A COMPARISON OF THE PHYSICAL AND CHEMICAL COMPOSITION OF UK WASTE STREAMS BASED ON HYPOTHETICAL COMPOUND STRUCTURE

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ABSTRACT

The suitability and effectiveness of a waste treatment process or strategy depends upon a waste stream's physical and chemical composition. Chemical properties of UK waste streams, particularly MSW, are limited while physical properties are better documented. Consequently this presents a degree of uncertainty with the waste's properties, manifesting itself as financial risk in the investment of new treatment or disposal plant. To mitigate this uncertainty, a number of UK waste surveys have been reviewed to determine if there is significant difference in the calorific value between waste streams. Ultimate and proximate analysis data from a number of sources have been collected and used to approximate the chemical composition of each waste fraction. To facilitate the comparison of each waste stream, a hypothetical compound of the form $C_6H_aO_b$ has been determined for each. Based on this analysis, all UK waste streams share the hypothetical formula $C_6H_{10}O_3$, indicating that on a dry basis, the composition of waste in the UK is fairly consistent. Monte Carlo analysis of the hypothetical compound structure revealed that for both household and civic amenity waste streams, the hydrogen and oxygen content only deviate slightly from the mean values. Since MSW is predominantly comprised of household and civic amenity waste, the hypothetical compound $C_6H_{10}O_3$ can be used to approximate UK MSW.

KEYWORDS

Energy from Waste, Hypothetical Compound, Monte Carlo Analysis, Municipal Solid Waste Management

INTRODUCTION

Historically, waste management routes in the UK have been dominated by landfill. Biodegradable waste decays in landfill sites generating methane, of which large proportions are vented to atmosphere. Methane is a potent greenhouse gas and to combat increasing emissions, the Landfill Directive (1999) was implemented by the EU and consequently, many new technologies and processes have been introduced to treat waste prior to disposal.

The effectiveness and suitability of a treatment process or strategy depends heavily upon a waste stream's physical and chemical properties (Tchobanoglous et al, 1993; McDougall et al, 2001), details of which for UK waste streams appear to be limited. This presents a degree of uncertainty over the waste's properties, which can manifest itself as financial risk in the investment of new treatment or disposal plant. For example, the output from a thermal treatment plant is dependent upon the calorific value of the feedstock, so any significant variation in the feedstock's properties will affect the plant's revenue streams, thus exposing an investor to financial uncertainty.

To mitigate this uncertainty, a number of UK waste surveys have been reviewed to determine if there is significant difference in the calorific value between waste streams. Ultimate and proximate analysis data has been collected and used to estimate the chemical composition of each waste fraction of the surveyed waste streams. To facilitate the comparison of each waste stream, a hypothetical compound of the form $C_6H_aO_b$ (Themelis et al., 2002) has been determined for each.

This paper attempts to review and collate the results of waste management surveys undertaken in the UK into one accessible source and provide upper and lower bounds to the physical composition of reported waste streams. The ultimate and proximate analyses of various waste streams and fractions have also been collated. The chemical composition of typical elements of the MSW stream is determined using methods described in Tchobanoglous et al. (1993). Finally, the hypothetical compounds are presented and discussed with specific relevance to recovering energy from waste.

REVIEW OF WASTE SURVEYS

Solid waste represents the largest input to the waste management system and its environmental impacts and economic and technical requirements can be evaluated based on the waste's physical and chemical composition (McDougall et al., 2001, Tchobanoglous et al., 1993, Chang and Davila, 2008). The physical composition of UK household waste has been determined in the past, but there is limited data on other waste streams (Burnley, 2007a).The most comprehensive analysis of UK MSW was undertaken for the Welsh Assembly(Poll, 2003, Burnley et al., 2007). However, the chemical composition of these streams is not reported.

The Landfill Directive (1999) is primarily aimed at diverting the biodegradable fraction of municipal solid waste (MSW) away from landfill. Recycling and recovery targets for MSW have been introduced nationwide in the

UK and in order to achieve compliance Local Authorities have been conducting waste surveys to determine the composition of MSW. Consequently, more data on the physical composition of UK MSW is available for analysis. This paper complements existing literature by reviewing these recent waste surveys and comparing the physical waste composition between them. A methodology is then presented for estimating the chemical composition based on the waste's physical composition.

Types of Waste Surveyed

Municipal solid waste (MSW) has a somewhat fuzzy definition. The Waste Strategy (2000) defines MSW as all waste under the control of local authorities. The Landfill Directive (1999), however, defines it as waste from households as well as other waste streams that are similar in composition. The surveys reviewed in this paper cover a range of waste streams that collectively can be considered as municipal waste (MSW)[1]. These include: household collected waste (HH), civic amenity waste (CA), litter bins (L), and street sweepings (SS). A summary of these surveys is reported in Table 1.

Table 1 : Waste Management Surveys used in this Paper

Location	Waste Streams	Date	Reference
Surrey	SS, L	2004	MEL(2004)
London	HH	2004	Poll (2004)
Cheshire	HH	2001	CLGA (2001)
Wales	MSW, HH, CA, SS, L	2003	Poll (2003)
North Yorkshire	HH	2006	Y&NY (2006)
Essex	HH, CA	2004	Leach (2004)
Merseyside	HH, CA	2006	Middlemas (2006)
Norfolk	CA	2006	Pawson & Morrin (2006)
UK	HH, CA	2002	Parfitt (2002)
UK	MSW	2006	Fisher et al. (2006)

The surveys detail waste collected from across the UK by various local authorities. However, the rationale used in collecting data varies between surveys. For example, the Merseyside and Essex waste surveys collected and reported waste composition on a seasonal basis, whereas the Cheshire survey was based on regional social demographic groupings. The London survey also used social demographic profiles, but further classified the waste based on ethnic classification. The waste collected in Surrey was reported based on rural, suburban and town centre locations and the Norfolk study reported waste arisings from mid-week and week-end surveys.

Waste Categories

Each survey collected data based on the fractions of waste that comprised the particular stream, which were then further aggregated into primary waste categories. These primary categories appear to have been assigned in an ad-hoc manner and thus vary across the surveys. In order to compare each survey, a list of sixteen primary waste categories were identified: paper, card, dense plastics, plastic film, textiles, combustibles, non-combustibles, glass, ferrous metal, non-ferrous metal, waste electrical and electronic equipment (WEEE), hazardous household, garden waste, kitchen waste, fines, and miscellaneous. The primary categories and sub-categories are presented in more detail in Appendix A and the mean values (percentage weight) of each primary category from each survey are presented in Appendix B on a stream by stream basis. It is assumed that all waste streams can be described by combinations of each of these categories; for example, household waste might consist of varying proportions of each category, but litter may be predominantly beverage containers (plastic and metal) and plastic/paper wrappings.

Physical Composition of UK Waste Streams

Of the data collected, only the compositions of household and civic amenity waste streams were reported in more than two surveys. Therefore, the remaining compositional analysis is focused on these two streams as no real meaningful statistical analysis is possible on the other waste streams. Since household and CA waste accounted for around 80% of the MSW stream in Wales (Poll, 2003), it is considered that the analysis of these two streams will be able to provide indicative results for the composition of UK MSW. The typical compositions of household and CA waste streams are presented in Table 2.

Variance in the Percentage Weight of Household Waste

Table 2 shows that paper, card, kitchen waste, and garden waste fractions have relatively large confidence intervals, indicating that there is some variance between the surveys. For the paper fraction, two surveys in particular contribute to the width of the confidence interval due to large percentages of paper being reported. The Cheshire survey reported that the quantity of paper being discarded across each borough was higher than the national average.

The North Yorkshire data reported paper and card as one single category, which in this analysis has been recorded arbitrarily in the paper fraction and consequently reports higher paper content. This also contributes to the variance in the card fraction too as zero (0%) card is recorded. However, assuming that paper is 70%

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[1] MSW can include commercial waste (Williams, 1998), but commercial waste arisings are not explicitly included in the surveys considered in this paper.

of the combined paper/card fraction does not affect the width of the confidence interval, suggesting that the Cheshire fractions skew the results, or that there is large variance in the sample.

Table 2 : Mean Compositions with 95% Confidence Intervals

	Household Waste		Civic Amenity Waste	
Waste Categories	**Mean %wt**	**95% CI**	**Mean %wt**	**95% CI**
Paper	16.28%	3.05%	2.73%	0.34%
Card	8.81%	2.08%	3.30%	0.76%
Dense Plastic	6.24%	1.71%	3.70%	1.94%
Plastic Film	4.86%	1.88%	0.71%	0.55%
Textiles	3.18%	0.58%	2.51%	0.40%
Combustibles	6.80%	2.07%	32.68%	9.26%
Non-Combustibles	2.01%	0.70%	16.23%	2.44%
Glass	6.76%	0.92%	1.78%	0.32%
Ferrous Metal	2.63%	0.94%	3.30%	1.72%
Non-Ferrous Metal	1.20%	0.77%	0.43%	0.32%
WEEE	1.22%	0.60%	5.65%	2.34%
Hazardous Household	0.44%	0.24%	1.24%	0.40%
Garden waste	10.18%	4.82%	17.85%	14.24%
Kitchen waste	25.98%	5.45%	0.61%	0.63%
Fines	2.65%	1.26%	0.98%	0.91%

In addition to the North Yorkshire data, the London and Wales surveys also contribute to the width of the confidence interval for the card fraction. Both surveys have relatively lower paper fractions and higher card fractions because of a secondary waste category that combines other paper and card. This category includes waste that is not recyclable paper, newspaper or magazines, or cardboard boxes and has been recorded in the primary card category in this analysis. This disparity affects the width of confidence intervals for both card and paper fractions.

Four waste surveys contribute to the relatively large confidence interval for the garden waste fraction. The Essex and Merseyside surveys report data on household residual waste arisings which do not include the waste separately collected. Kerbside collection of garden waste occurs in both regions and explains why the quantity of garden waste in each survey is relatively low. The London survey reports relatively low percentage of garden waste present in household waste, which is not unexpected due to the large number of residents compared to a small number of gardens. Conversely, the Cheshire survey reports that large quantities of garden waste are discarded into dustbins, rather than being taken to a local civic amenity site, which contributes to the relatively large percentages of garden waste and hence increases the width of the confidence interval.

The London survey reports relatively high quantities of kitchen waste being discarded whereas the Cheshire survey reports low quantities being discarded, which adds to the width of the confidence interval. Furthermore, the Cheshire survey recognised that all boroughs discarded kitchen waste at consistently lower quantities than the UK average, but no reason was provided.

Variance in the Percentage Weight of Civic Amenity Waste

Despite the increased number of household waste surveys available since Burnley (2007a) conducted his comparative study, there has not been quite the same reporting of CA waste. This inconsistency suggests that there are different driving factors for different local authorities in the UK and perhaps indicates the need for a unilateral standard in surveying and reporting waste compositions in the UK.

Table 2 shows that the garden waste and the combustibles fractions have relatively large confidence intervals, indicating some variance between surveys. The Merseyside and Norfolk surveys report relatively low percentages of garden waste, which has been attributed to the separate kerbside collection of garden waste resulting in its diversion away from civic amenity sites. However, Parfitt's survey reports relatively high quantities of garden waste, which may or may not include kerbside collected waste and or some commercial waste from professional gardeners, tree surgeons, etc.

The combustible fraction from Parfitt's survey is relatively low compared to the other surveys. This difference could arise because Parfitt's survey of CA waste is the earliest, which suggests that maybe there has been a change in public behaviour resulting in more recycling effort. A further possibility is that some disparity exists in the categorisation of wood between the surveys such that wood is recorded as garden waste, rather than as a combustible fraction or vice-versa – this would account for the fact that the combustible fraction in Parfitt's survey is much lower and that the garden waste is much greater than in the other surveys; but this is pure speculation.

HYPOTHETICAL COMPOUNDS THAT APPROXIMATE WASTE COMPOSITION

From the physical and chemical composition of each waste fraction, a hypothetical compound can be deduced for each waste stream and used to estimate chemical and biological transformations (Tsiliyannis, 1999, Vidal et al., 2001, Themelis et al., 2002, Themelis and Kim, 2002, Durmusoglu et al., 2005). Limited studies exist that report the chemical composition of UK MSW streams, but those that tend to be referenced are more than ten year's old (Burnley, 2007b).Furthermore, none of the waste surveys reviewed in this paper reported chemical composition, moisture content, calorific value, etc . To overcome this lack of UK data, ultimate and proximate analysis data of the primary waste categories has been collected from a number of sources.

Moisture Content

The mean, minimum, and maximum values of moisture content for each primary waste category was computed from these sources and the results are presented in Table 3. The Raw data from each source is tabulated in Appendix D.

Table 3 : Minimum, Maximum, and Mean Moisture Content of Waste Categories

Category	Min	Max	Mean
Card	4.00%	24.00%	11.08%
Combustibles	5.19%	30.00%	15.88%
Dense Plastic	1.00%	18.00%	7.50%
Ferrous Metal	2.00%	9.00%	4.50%
Fines	5.47%	41.00%	14.49%
Garden waste	30.00%	80.00%	55.16%
Glass	1.00%	4.00%	2.25%
Hazardous Household	13.00%	13.00%	13.00%
Kitchen waste	50.00%	80.00%	66.38%
Non-Combustibles	0.00%	0.00%	0.00%
Non-Ferrous Metal	2.00%	10.00%	5.50%
Paper	2.00%	16.00%	6.25%
Plastic Film	4.00%	24.00%	11.31%
Textiles	0.20%	28.00%	7.04%
WEEE	6.00%	25.30%	14.11%

Table 3 shows that the organic fractions that comprise the waste streams, i.e. kitchen and garden waste, have very high moisture content. Given that these two fractions contribute on average nearly 40% of the weight of household waste and around 15% of the weight of CA waste, the moisture content of MSW is likely to be quite high. Burnley (2007b) found in his study that half of the moisture present in UK MSW is from this biodegradable fraction. As the hypothetical compound structure is determined on a dry basis, knowledge of a waste stream's moisture content is paramount.

Determining the Chemical Composition of Waste Streams

In determining the hypothetical compound structure, the quantities of C, H, and O of each fraction are necessary. However, as with the proximate analysis data, it appears that limited sources exist that report the chemical composition of UK waste streams. Two sources of US data and one source of EU data was found that reported the ultimate analysis of waste streams. The average values for C, H, O, N, S, and ash content are presented in Table 4; the raw data from each source is tabulated in Appendix C.

Approximating the Chemical Structure of Each Stream

The percentage dry weight of each fraction is obtained by multiplying the percentage weight by (1- moisture content). As each waste stream is assumed to comprise of a combination of the primary waste categories, the percentage dry weight of each fraction is then multiplied by the percentage composition of each element to give the amount of that element present in each waste stream. This process is repeated for each fraction of the waste stream. The fractional component of each element is then summed to get the total quantity of that particular element in the waste stream.

The quantity of each element is divided by its molar mass to give the number of hypothetical moles of each element in the waste stream. Cellulose has a structure of $C_6H_{10}O_5$ and the organic fraction of waste can be approximated as $C_6H_{10}O_4$ (Themelis and Kim, 2002). As these make up a large proportion of the waste stream (paper, card, kitchen waste, garden waste, etc.) it is appropriate to compare the molecular ratio of each element with C=6 moles[2]. The chemical structure of the hypothetical compound, based on C=6, was deduced for each waste stream using each ultimate analysis dataset. The structures based on the mean values are shown in Table 5; the structures using each dataset are presented in Appendix B.

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[2] To normalise for C=6, the number of moles of each element is divided by one sixth of the number of moles of carbon.

Table 4 : Ultimate Analysis of Household Waste

	Mean Chemical content (percentage dry weight)					
Category	**C**	**H**	**O**	**N**	**S**	**Ash**
Paper	45.94%	6.35%	38.55%	0.48%	0.21%	8.47%
Card	44.85%	5.98%	43.38%	0.18%	0.20%	5.41%
Dense Plastic	73.81%	11.90%	4.83%	0.25%	0.13%	9.09%
Plastic Film	44.77%	6.08%	32.45%	1.74%	0.36%	14.60%
Textiles	47.64%	6.30%	35.46%	3.04%	0.23%	7.33%
Combustibles	45.35%	5.51%	32.45%	0.92%	0.37%	15.41%
Non-Combustibles	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
Glass	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
Ferrous Metal	4.50%	0.60%	4.30%	0.10%	0.00%	90.50%
Non-Ferrous Metal	4.50%	0.60%	4.30%	0.10%	0.00%	90.50%
WEEE	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
Hazardous Household	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
Garden waste	43.62%	5.55%	33.92%	2.21%	0.32%	14.38%
Kitchen waste	44.77%	6.08%	32.45%	1.74%	0.36%	14.60%
Fines	26.30%	3.00%	2.00%	0.50%	0.20%	68.00%
Miscellaneous	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%

Despite some of the surveys reporting data on residual household waste and each region employing different kerbside recycling strategies such that different materials are recycled and at different rates, the underlying chemical composition is fairly constant. Indicating that on a dry basis, the approximate chemical structure of UK waste has the formula $C_6H_{10}O_3$. The implications of this analysis suggest that based on the mean values of moisture content and chemical composition, energy recovery from waste will be influenced by those factors that do not contribute to the chemical structure such as moisture, metal, and glass content.

Table 5 : Variation in Hypothetical Compounds of Various Waste Streams

Stream	Survey	C	H	O	N
MSW	Wales (2006)	6	10	3	0
MSW	ERM (2006)	6	10	3	0
HH	Parfitt (2002)	6	10	3	0
HH	Cheshire (2001)	6	10	3	0
HH	Essex (2004)	6	10	3	0
HH	London (2004)	6	10	3	0
HH	Wales (2006)	6	10	3	0
HH	Merseyside (2006)	6	10	3	0
HH	North Yorks (2006)	6	10	3	0
HH	Mean	6	10	3	0
CA	Parfitt (2002)	6	10	3	0
CA	Essex (2004)	6	10	3	0
CA	Wales (2006)	6	10	3	0
CA	Merseyside (2006)	6	10	3	0
CA	Norfolk (2006)	6	10	3	0
CA	Mean	6	10	3	0
L	Wales (2006)	6	10	3	0
L	Surrey (2003)	6	10	3	0
SS	Wales (2006)	6	10	2	0

Fisher (2006), Patumsawad (2002), and Williams (1998) reported both physical and chemical composition of UK waste streams. A similar[3] methodology to that described above was used to determine a hypothetical compound of the form $C_6H_aO_b$ for each of these MSW streams. The hypothetical compounds for these streams, together with MSW streams from other locations around the world are presented in Table 6.

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[3] This was based on the ultimate analysis of the total waste stream rather than each individual waste fraction and is similar because the mass of each element (C, H, and O) is divided by its molar mass and then normalised to C=6. Whereas the methodology above computes the ultimate analysis of the total waste stream from each fraction first, before dividing by the molar mass and then normalising.

Table 6 shows that on a dry basis, the hypothetical compound structure for MSW is very similar in all of the studies, indicating that $C_6H_{10}O_3$ is a reasonable approximation. This further supports the interim findings of this study that physical parameters such as moisture content will influence the calorific value of waste, rather than the chemical composition. From the perspective of investing in energy from waste facilities, this result helps to reduce the uncertainty surrounding the calorific value of waste as only those factors that contribute to heat loss (moisture, metal, glass, etc) need be monitored, specified, or determined, which is more attractive than undertaking laboratory analysis of waste samples in order to estimate the heating value.

Table 6 : Hypothetical Compounds of MSW Streams

	C=6				Reference
EU	6	11	3	0	ECN (1997)
Kuala Lumpur	6	10	3	0	Sivapalan et al. (2002)
UK	6	10	3	0	Patumsawad (2002)
Thailand	6	10	3	0	Patumsawad (2002)
US	6	10	3	0	Cinergex (1998)
UK	6	10	4	0	Williams (1998)
Wales	6	10	3	0	Burnley et al. (2007)
UK	6	10	3	0	Fisher et al. (2006)

However, these findings are based on using mean values of chemical composition and moisture content all of which have upper and lower values. The next section uses these upper and lower values in conjunction with upper and lower values for the percentage weight of each fraction of household and CA waste to determine how sensitive the hypothetical compound structure is to these parameters in order to provide a more robust conclusion to the work.

MONTE CARLO ANALYSIS

Of the ten waste surveys reviewed in this paper, seven reported the composition of household waste and five reported the composition of CA waste. Monte Carlo simulation was undertaken to explore how the hypothetical compounds that describe these two waste streams behave under the uncertainty associated with the moisture content, percentage weight, and chemical composition of each waste fraction.

Monte Carlo simulation provides a method of estimating the expected value of a function based on the probability distributions of the function's parameters (Ross, 2000). As many of the parameters have identifiable limits (i.e. minimum and maximum values), a probability distribution with finite limits is a suitable choice (Johnson, 1997). The beta distribution is a typical example, but its parameters are seldom easily estimated and as a distribution function, it is poorly understood (Williams, 1992). Triangular distributions are also finite distributions and require estimates of upper, lower, and most-likely values, making them simpler than the beta distribution (Johnson, 1997). Further more, triangular distributions can model skewed density functions, they simplify the computational aspects of modelling, and the estimates required for the shape of the distribution are relatively easy to obtain (Chau, 1995). It is for these reasons that a triangular distribution has been deemed suitable for use in the Monte Carlo simulation.

Waste Stream Parameters

The waste stream parameters that are used to define the hypothetical compound are the moisture content, percentage weight, and chemical composition of each fraction. The moisture content and chemical composition of each fraction have been collected from a variety of sources and where minimum, maximum, and typical values of parameters have been reported they have been used to describe a triangular distribution. Where only singular data values have been available, a uniform distribution with an arbitrarily chosen tolerance of 10% either side of the typical value was used[4] – the effect of the tolerance is explored in the Monte Carlo simulation by examining the contribution made by these parameters to the variance of the forecast variables.

The percentage weight data for household and CA waste were tested to determine if both data sets came from a population that was normally distributed. The results from Anderson-Darling and Kolmogorov-Smirnoff tests revealed that there was no evidence to reject this hypothesis. However, on running the simulations, the percentage weight of some fractions was exceeding 100% and was lower than 0% in some trials due to the large variance in the samples. Triangular distributions were used instead based on the min, max, and mean values reported in the surveys to ensure that the percentage weight of each stream could not fall below 0% or exceed 100%.

Forecast Variables

The forecast variables are the moisture content, percentage weight, and chemical composition of each waste fraction and that are of interest to this study, i.e. the chemical structure of the hypothetical compound. As the

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[4] These parameters are typically the ultimate analysis data for metal and glass fractions of the waste, which arise from label/coating materials and therefore make a very small contribution to the waste stream's total moisture content, weight, or chemical composition.

thermal properties of each waste stream are of interest, the hypothetical compound is normalised to C=6 (Themelis et al., 2002) which closely approximates the combustible fractions of MSW (Themelis and Kim, 2002). The variation in waste stream parameters can be quantified as a change in hydrogen and oxygen content in the hypothetical compound. Since there are two waste streams under analysis (household and CA waste), there are four forecast variables: oxygen content and hydrogen content of each stream.

Because Monte Carlo simulations arise as a consequence of the strong law of large numbers (Ross, 2000),if the number of trials in the simulation is sufficiently large enough then the Central Limit Theorem dictates that the expected value of each forecast variable will be approximately normally distributed, regardless of the form of the distribution of each of the waste stream parameters (Hsu, 1997). Hence the shape of the forecast variables should resemble a normal distribution thus enabling statistical conclusions to be reached about each variable, such as mean values and confidence intervals.

RESULTS AND DISCUSSION

The need to explore how the uncertainty surrounding waste composition (physical and chemical) influences the structure of the hypothetical compounds used to approximate waste streams arises from the physical phenomenon that molecular structure determines the enthalpy of combustion. Therefore, if the structure varies significantly then the range of enthalpy of combustion will also vary, thus increasing the uncertainty associated with the quantity of energy that can be recovered from the waste stream. Conversely, if the structure appears to be fairly stable, i.e. not deviating from the mean greatly, then the enthalpy of formation is likely to be fairly constant supporting the claim that the compound $C_6H_{10}O_3$ can be used to approximate the chemical structure of UK MSW.

In this section, the results of the Monte Carlo simulation for household and CA waste are presented and discussed. The focus for the discussion is how the structures of the hypothetical compounds, i.e. the hydrogen and oxygen content, are influenced by perturbations to the waste stream's composition. Those parameters that contribute to the variance in hydrogen and oxygen content are also discussed, but in the context of addressing the assumption that a 10% interval either side of the mean is reasonable for those input parameters defined by a uniform distribution.

Household Waste

The frequency distributions from the simulation are presented in Figure 1. The area shaded in blue represents the 95% confidence interval for that variable after 100,000 trials. For the oxygen content the mean was 2.73 and the standard deviation was 0.20, hence the 95% confidence interval lies between 2.33 and 3.12. For the hydrogen content the mean was 9.87 and the standard deviation was 0.49, hence the 95% confidence interval lies between 8.94 and 10.87. Given that both variables are estimating molecular structure in moles, the oxygen content varies from 2 to 3 and the hydrogen content from 9 to 11.

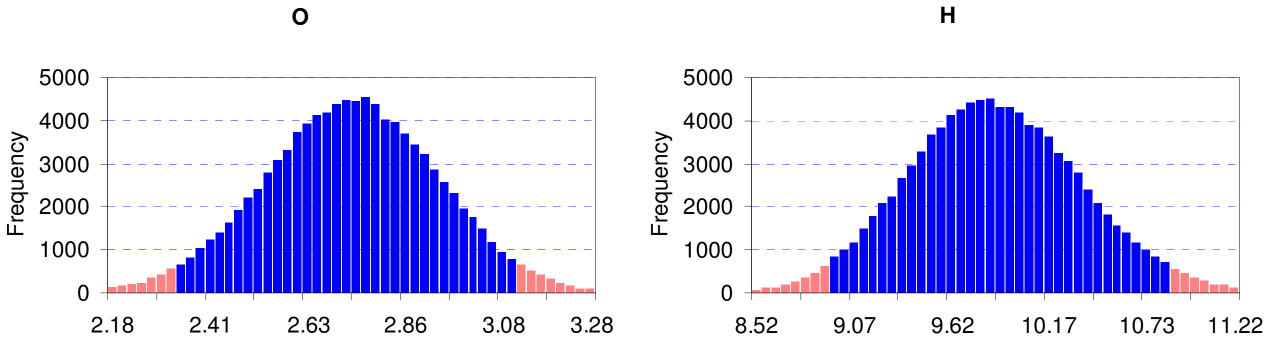

Figure 1 : **Results from the Monte Carlo Simulation for Oxygen and Hydrogen Content of Household Waste**

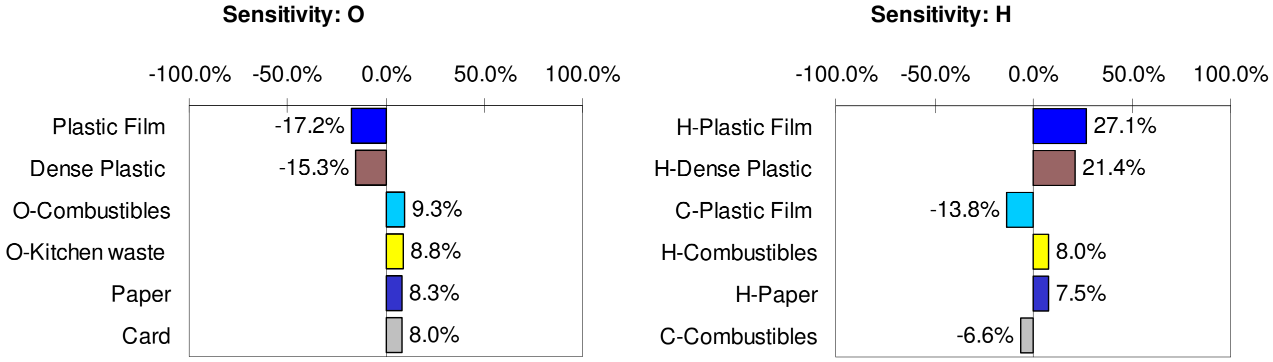

Figure 2: **Contribution to the Variance in Hypothetical Compound Structure of Household Waste**

Figure 2 shows the input parameters that have the greatest contribution to the variance of hydrogen and oxygen content, i.e. those parameters that influence the width of the confidence interval. It should come as no surprise that plastic content influences the hydrogen content; in particular that nearly 50% of the variance is explained by the reported values that the hydrogen content in the plastic streams can take. For the oxygen content, it is the physical quantities of plastics that contribute to the variance. This is because of the relatively low oxygen content reported in plastic film sub categories; particularly PVC, which has no oxygen content. So as the quantity of plastics increases in the waste stream, the oxygen content gets proportionally less. Combustibles and kitchen waste have relatively high oxygen content and also a relatively large range, thus contributing to the variance. The paper and card fractions also contribute because of the large variance in each category, as discussed earlier in the paper.

The overall structure of the household waste stream is fairly constant. Physically, it is also unlikely that the a structure with an odd number of hydrogen atoms would exist in a compound with carbon and oxygen as they both have even valances, hence the resulting compound would be electronegative like a free radical so using enthalpy of combustion data for this structure would be unrealistic. Hence an approximate structure is likely to be $C_6H_{10}O_a$, with the subscript a equal to 2 or 3. Given the effect that plastic content has on reducing oxygen content, the structure $C_6H_{10}O_3$ may be inappropriate to model waste streams with large quantities of plastic, e.g. greater than 30% by weight; but given the relatively low density of plastics, attaining such a high proportion in the waste stream maybe unrealistic.

Civic Amenity Waste

The frequency distributions for hydrogen and oxygen content are presented in Figure 3 and as with the household waste analysis, the area shaded in blue represents the 95% confidence interval. For the oxygen content the mean was 3.01 and the standard deviation was 0.4, hence the 95% confidence interval lies between 2.25 and 3.81. For the hydrogen content the mean was 9.17 and the standard deviation was 0.97, hence the 95% confidence interval lies between 7.31 and 11.16. Therefore, the number of moles of oxygen varies from 2 to 3 and moles of hydrogen from 7 to 11 moles.

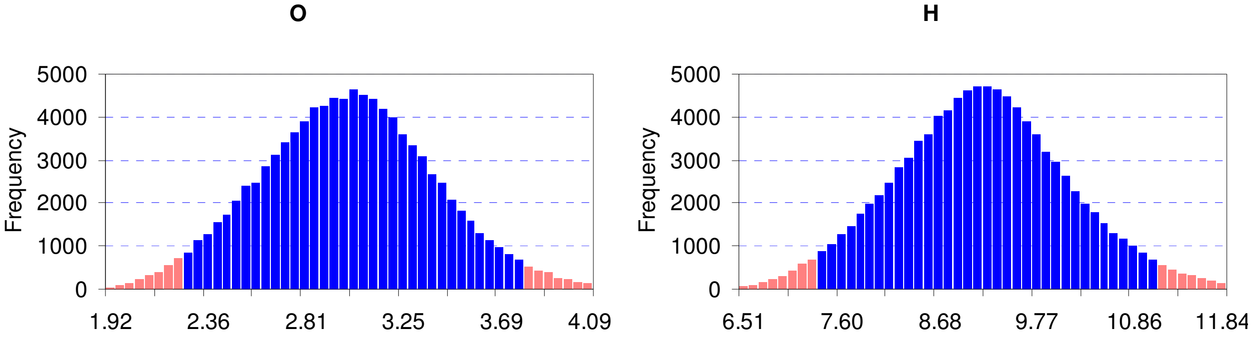

Figure 3 : **Results from the Monte Carlo Simulation for Oxygen and Hydrogen Content of CA Waste**

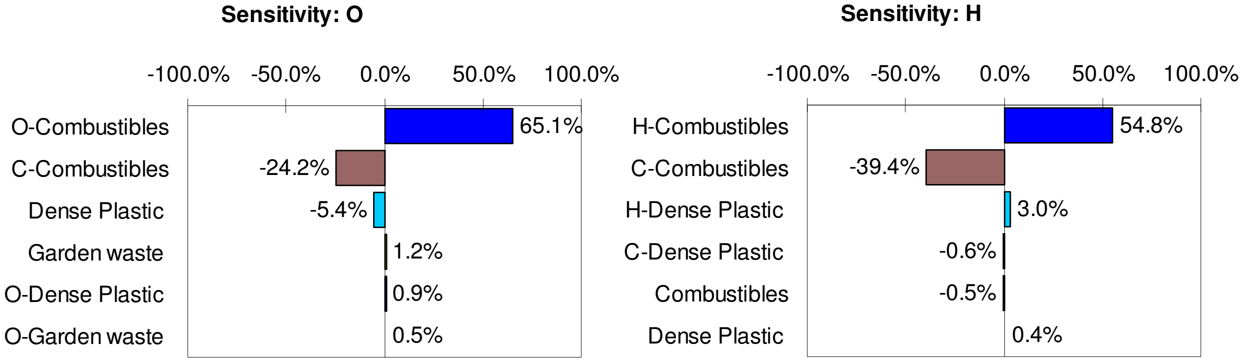

Figure 4: **Contribution to the variance in the Hypothetical Compound Structure of CA Waste**

The input parameters that have the greatest contribution to the variance of hydrogen and oxygen content in CA waste are presented in Figure 4. There are two reasons why the combustible fraction of the waste stream dominates the sensitivity charts. Firstly, the variance from the oxygen content of the combustible fraction accounts for 65% of the variance in oxygen content of the hypothetical compound. This is likely due to the fact that combustibles account for a third of the waste stream and have a relatively large standard deviation. Secondly, the moisture content is relatively low with a small range such that the dry mass of the fraction will be relatively large in comparison to other fractions with higher moisture content. As the combustible stream is also the largest fraction, on a dry basis, the percentage weight of the fraction will in effect be magnified such that perturbations to the oxygen content in the fraction will be translated to the hypothetical compound; this point is also applicable to the hydrogen content.

The ultimate analysis data used to determine the chemical composition of the combustibles fraction includes materials such as wood, leather and rubber, which have different chemical compositions, i.e. different ratios of C, H, and O. It is these differences that contribute to the range of values that each element can take in the simulation and thus affects the chemical composition of the fraction and therefore the structure of the hypothetical compound. If wood dominated the combustibles fraction, then the hypothetical compound structure will begin to approach the structure of wood (CH_2O) and given that the combustibles fraction comprises a large proportion of the CA stream the use of $C_6H_aO_b$ may not be appropriate.

Should an EfW facility accept MSW with a large proportion of CA waste, then the results from this work suggest that a detailed analysis of the combustible fraction of the feedstock should be undertaken to more accurately determine the components that comprise it. This would then reduce the uncertainty associated with the hypothetical compound structure and therefore calorific value of the feedstock.

All of the parameters that contribute to the variance in hypothetical compound structure of both streams have all been modelled with triangular distribution functions, indicating that hypothetical compound structure is not sensitive to the parameters modelled with a uniform distribution function. More data on these parameters would only improve the results from this analysis. However, as most of these parameters are inorganic and non-combustible (e.g. construction and demolition waste, metals, and glass) then their contribution to the hypothetical compound structure is likely to be negligible.

CONCLUSIONS

1. There is a need for a standard set of criteria for reporting waste categories, detailing the types of waste that make up each category and the parameters that need to be reported. The results from this work indicate that reliable, consistently measured moisture content and percentage weight of each fraction is required to make an informed decision regarding energy recovery from waste.

2. Despite the variation in waste composition, the structure of the hypothetical compound for household waste remains constant and does not deviate greatly from the structures associated with the major components of the waste stream, i.e. paper/card (cellulose) and putrescibles (food and garden waste).

3. The hypothetical compound structure of CA waste is highly sensitive to the chemical composition of the combustible fraction. Further analysis of this fraction to determine its principal components would greatly reduce this sensitivity.

4. The physical parameters, such as moisture, metal, and glass content, are likely to have more effect on the ‘useable’ quantity of energy recovered, because on a dry basis, the hypothetical compound structure is fairly stable suggesting that the enthalpy of combustion would be too. Therefore, any heat loss will be due to the heat ‘held’ by the metals and glass and the heat ‘lost’ from boiling off moisture.

5. Finally, the results from this analysis show that the hypothetical compound structures for household and CA waste are the same as other MSW streams from across the world, indicating that the structure $C_6H_{10}O_3$ can be used to approximate MSW waste streams. This approximation appears to be reasonable providing that the quantities of plastic products present in the waste stream do not exceed 30% by weight.

ACKNOWLEDGEMENTS

This research is sponsored by Biffa Waste Services with specific assistance from D Savory and the operational staff in his team. Additional funding and support has been provided by ATCO Power. The authors wish to thank G Paling and R Hodgson of ATCO Power for their valuable contributions to this work.

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APPENDIX A – WASTE CATEGORIES AND SUB-CATEGORIES USED IN THIS PAPER

Waste Category	Sub-category	Typical Examples:
Paper	Newspapers and magazines	Broadsheets & tabloids; non-glossy magazines, glossy magazines & glossy paper
	Recyclable paper	Copier / printer paper, letters, junk mail, books
Card	Cardboard boxes / containers	Heavy packaging card (corrugated card), thin packaging card (cereal boxed, egg boxes)
	Liquid cartons	All card liquid cartons, tetra packs
	Other paper & card	Paper bags, tissue paper, wall paper, contaminated paper, Birthday cards, toilet rolls, train tickets, beer mats, photographs
Dense Plastic	Dense plastic bottles	All plastic bottles
	Other packaging	Food trays, pizza bases, yoghurt pots, ready meal packets
	Other dense plastics	CD cases, CD's , toys, all non-packaging dense plastic
Plastic Film	Refuse sacks & carrier bags	
	Packaging film	Sweet wrap, bread bags, food wrapping film, gift wrap
	Other plastic film	Document wallets, polythene sheets
Textiles	Textiles	Clothing, rags, sheets, curtains, towels, off cuts
Combustibles	Shoes	All footwear
	Disposable nappies	
	Wood	Treated wood, untreated wood, DIY off cuts, boxes, fencing, shelves
	Carpet and underlay	Carpet, rugs, carpet samples, bath mats, underlay
	Tyres	
	Other MC	Fluff, sponges, soap, fake leather, foam, tyres
Non-Combustibles	C&D waste	Tiles, plaster, rubble, sawdust, gravel, sand, cement
	Bathroom Suites	Ceramic toilet bowels, sinks
	Other MNC	Stones, crockery, porcelain, flower pots, cinders
Glass	Packaging glass	Bottles, jars
	Non-packaging glass	Light bulbs, drinks glasses, mirrors, window glass
Ferrous Metal	Food and beverage cans	Magnetic cans
	Other ferrous metal	Aerosols, coat hangers, screws, cutlery, car parts
Non-Ferrous Metal	Food and beverage cans	Not magnetic cans
	Other non-ferrous metal	Tin foil, aerosols, copper pipe, jewellery
WEEE	White goods	Fridges, cookers, dishwashers, microwaves, heaters
	Large electronic goods	Hoovers, computers, hi-fi's, printers, radios
	TVs and monitors	TV's and monitors, cathode ray tubes
	Other WEEE	Keyboards, wires, lamps, kettles, cables, personal stereos
Hazardous Household	Lead/acid batteries	Car batteries
	Household batteries	TV remote control batteries
	Oil	Bottles/cans of oil
	Paint	Tins of paint, dried up or useable
	Identifiable clinical waste	Drugs & packaging, dressings, syringes, blood soiled waste
	Other potentially hazardous	Thinners, smaller batteries, insecticides, bleach, asbestos
Garden waste	Garden waste	Twigs, leaves, grass cuttings, cut flowers
Kitchen waste	Kitchen waste	Processed & non-processed food waste
Fines	< 10mm diameter particles	Dirt, ash, etc.
Miscellaneous	Other	Any waste not of the other categories

[Adapted from Williams (1998), Poll (2003) and Pawson & Morrin (2006)]

APPENDIX B – COLLECTED WASTE DATA, CATEGORISED BY STREAM

	MSW – (municipal solid waste)		CA – (civic amenity waste)				
Waste Categories	ERM (2006)	Wales (2006)	Essex (2004)	Merseyside (2006)	Norfolk (2006)	Parfitt (2002)	Wales (2006)
Paper	18.32%	11.04%	3.33%	2.56%	2.25%	2.48%	3.03%
Card	0.00%	9.96%	4.19%	3.11%	3.34%	1.77%	4.07%
Dense Plastic	3.72%	4.48%	5.24%	2.99%	7.12%	0.91%	2.24%
Plastic Film	2.75%	2.78%	0.63%	0.28%	1.95%	0.33%	0.36%
Textiles	2.48%	1.84%	3.09%	2.62%	2.86%	2.01%	1.96%
Combustibles	7.51%	12.05%	35.98%	44.84%	40.89%	15.76%	25.93%
Non-Combustibles	12.09%	7.99%	19.68%	16.63%	11.63%	14.98%	18.22%
Glass	6.50%	5.79%	1.41%	1.59%	2.32%	1.48%	2.11%
Ferrous Metal	2.04%	4.83%	4.67%	3.60%	2.51%	0.00%	5.72%
Non-Ferrous Metal	0.53%	0.81%	0.89%	0.00%	0.32%	0.11%	0.84%
WEEE	3.95%	1.99%	5.74%	4.78%	1.44%	9.69%	6.62%
Hazardous Household	1.06%	0.75%	1.42%	1.56%	1.48%	0.34%	1.40%
Garden waste	17.81%	14.79%	12.72%	4.92%	5.18%	48.93%	17.50%
Kitchen waste	17.28%	15.65%	0.41%	0.00%	2.02%	0.31%	0.33%
Fines	3.96%	5.24%	0.61%	0.00%	2.98%	0.91%	0.40%
Miscellaneous	0.00%	0.00%	0.00%	10.53%	11.72%	0.00%	9.28%

HH – (household waste)

Waste Categories	Cheshire (2001)	Essex (2004)	London (2004)	Merseyside (2006)	North Yorks (2006)	Parfitt (2002)	Wales (2006)
Paper	22.79%	14.07%	12.03%	16.69%	27.99%	17.41%	11.40%
Card	10.77%	6.16%	11.81%	7.02%	0.00%	5.31%	12.22%
Dense Plastic	10.23%	7.72%	5.61%	2.86%	6.23%	4.86%	6.14%
Plastic Film	2.62%	4.89%	4.20%	10.42%	3.93%	3.97%	4.01%
Textiles	4.35%	2.88%	2.31%	4.09%	3.04%	3.19%	2.42%
Combustibles	3.64%	6.74%	12.28%	5.18%	5.56%	6.02%	8.20%
Non-Combustibles	0.58%	1.51%	2.35%	3.41%	1.42%	2.07%	2.77%
Glass	4.79%	7.33%	6.39%	7.56%	5.65%	8.45%	7.15%
Ferrous Metal	2.50%	2.64%	2.78%	3.00%	3.91%	0.00%	3.60%
Non-Ferrous Metal	0.68%	1.17%	0.90%	1.23%	0.00%	3.37%	1.04%
WEEE	1.28%	0.93%	0.90%	1.29%	0.47%	2.95%	0.73%
Hazardous Household	0.09%	0.54%	6.76%	0.82%	0.75%	0.00%	0.62%
Garden waste	21.00%	3.91%	30.52%	3.47%	9.80%	16.46%	10.15%
Kitchen waste	13.16%	37.08%	0.00%	27.11%	26.79%	22.22%	24.97%
Fines	0.00%	2.44%	1.16%	2.25%	4.47%	3.70%	4.55%
Miscellaneous	1.52%	0.00%	0.00%	3.61%	0.00%	0.00%	0.00%

CA – (civic amenity waste)

Waste Categories	Essex (2004)	Merseyside (2006)	Norfolk (2006)	Parfitt (2002)	Wales (2006)
Paper	3.33%	2.56%	2.25%	2.48%	3.03%
Card	4.19%	3.11%	3.34%	1.77%	4.07%
Dense Plastic	5.24%	2.99%	7.12%	0.91%	2.24%
Plastic Film	0.63%	0.28%	1.95%	0.33%	0.36%
Textiles	3.09%	2.62%	2.86%	2.01%	1.96%
Combustibles	35.98%	44.84%	40.89%	15.76%	25.93%
Non-Combustibles	19.68%	16.63%	11.63%	14.98%	18.22%
Glass	1.41%	1.59%	2.32%	1.48%	2.11%
Ferrous Metal	4.67%	3.60%	2.51%	0.00%	5.72%
Non-Ferrous Metal	0.89%	0.00%	0.32%	0.11%	0.84%
WEEE	5.74%	4.78%	1.44%	9.69%	6.62%
Hazardous Household	1.42%	1.56%	1.48%	0.34%	1.40%
Garden waste	12.72%	4.92%	5.18%	48.93%	17.50%
Kitchen waste	0.41%	0.00%	2.02%	0.31%	0.33%
Fines	0.61%	0.00%	2.98%	0.91%	0.40%
Miscellaneous	0.00%	10.53%	11.72%	0.00%	9.28%

	L – (litter)		SS – (street sweepings)
Waste Categories	Surrey (2003)	Wales (2006)	Surrey (2003)
Paper	24.12%	12.99%	7.15%
Card	6.85%	17.98%	2.60%
Dense Plastic	10.21%	12.49%	5.54%
Plastic Film	5.28%	7.79%	2.19%
Textiles	1.64%	1.90%	1.18%
Combustibles	4.19%	4.10%	2.00%
Non-Combustibles	0.86%	0.80%	0.07%
Glass	10.97%	8.39%	4.32%
Ferrous Metal	2.49%	4.20%	1.95%
Non-Ferrous Metal	2.40%	3.70%	2.38%
WEEE	0.11%	0.20%	0.00%
Hazardous Household	0.07%	0.30%	0.00%
Garden waste	3.87%	8.49%	20.33%
Kitchen waste	21.00%	14.99%	4.52%
Fines	5.95%	1.70%	45.76%
Miscellaneous	0.00%	0.00%	0.00%

APPENDIX C – ULTIMATE/PROXIMATE ANALYSIS DATA SOURCES

Reference Category:			Chemical content by percentage dry weight					
Cinergex (1998)	Waste Category	Moisture	C	H	O	N	S	Ash
Corrugated	Card	20.12%	46.06%	6.36%	44.33%	0.14%	0.29%	2.83%
Rubber/leather	Combustibles	14.97%	50.68%	6.32%	13.61%	1.58%	1.38%	26.45%
Wood	Combustibles	16.09%	49.10%	5.99%	41.18%	0.29%	0.08%	3.36%
Plastics	Dense Plastic	18.00%	68.82%	9.50%	9.82%	1.04%	0.35%	10.48%
Yard Waste	Garden waste	45.13%	42.45%	5.34%	31.97%	1.62%	0.27%	18.35%
Food waste	Kitchen waste	60.38%	45.25%	6.44%	32.43%	2.85%	0.15%	12.87%
Newsprint	Paper	25.11%	48.90%	6.22%	42.41%	0.15%	0.25%	2.07%
Magazines	Paper	16.13%	39.26%	5.53%	39.17%	0.13%	0.25%	15.66%
Other paper	Paper	23.61%	42.43%	5.90%	39.15%	0.41%	0.25%	11.86%
Textiles	Textiles	25.27%	49.82%	6.72%	36.28%	4.16%	0.37%	2.65%

Reference Category:			Chemical content by percentage dry weight					
ECN (1997)	Waste Category	Moisture	C	H	O	N	S	Ash
Cardboard	Card	-	44.50%	5.68%	41.20%	0.10%	0.12%	8.40%
Wood	Combustibles	-	51.40%	5.88%	42.20%	0.10%	0.10%	0.32%
Rubber	Combustibles	0.4%	25.30%	2.46%	24.80%	0.14%	0.19%	47.11%
LDPE	Dense Plastic	-	85.70%	14.30%	0.20%	0.00%	0.00%	0.00%
HDPE	Dense Plastic	0.2%	85.60%	14.20%	0.30%	0.00%	0.00%	0.00%
Mixed Plastics	Dense Plastic	10%	81.10%	13.33%	0.00%	0.11%	0.01%	5.45%
Organic HH waste	Kitchen waste	-	48.10%	5.91%	40.70%	0.69%	0.04%	4.56%
Paper	Paper	-	49.00%	6.86%	35.00%	0.45%	0.08%	8.61%
Waste Paper	Paper	5.2%	49.30%	7.07%	34.90%	0.70%	0.15%	7.88%
PVC	Plastic Film	-	38.00%	5.00%	0.00%	0.00%	0.00%	57.00%
PE	Plastic Film	-	86.00%	14.00%	0.00%	0.00%	0.00%	0.00%
Carpet Grains	Textiles	13.5%	45.10%	5.78%	30.10%	2.77%	0.12%	16.13%

Reference Category:			Chemical content by percentage dry weight					
Tchobanoglous et al (1993)	Waste Category	Moisture	C	H	O	N	S	Ash
Cardboard	Card	5%	44.00%	5.90%	44.60%	0.30%	0.20%	5.00%
Dirt, Ash, etc.	Fines	8%	26.30%	3.00%	2.00%	0.50%	0.20%	68.00%
Glass	Glass	2%	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
INERT	Non-Combustibles	2%	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
INERT	WEEE	2%	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
INERT	Hazardous Household	2%	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
INERT	Miscellaneous	2%	0.50%	0.10%	0.40%	0.10%	0.00%	98.90%
Mixed Food Waste	Kitchen waste	70%	48.00%	6.40%	37.60%	2.60%	0.40%	5.00%
Mixed Metals	Ferrous Metal	2%	4.50%	0.60%	4.30%	0.10%	0.00%	90.50%
Mixed Metals	Non-Ferrous Metal	2%	4.50%	0.60%	4.30%	0.10%	0.00%	90.50%
Mixed Paper	Paper	10%	43.40%	5.80%	44.30%	0.30%	0.20%	6.00%
Mixed Plastics	Dense Plastic	0.2%	60.00%	7.20%	22.80%	0.00%	0.00%	10.00%
PVC	Plastic Film	0.2%	45.20%	5.60%	1.60%	0.10%	0.10%	2.00%
Textiles	Textiles	10%	48.00%	6.40%	40.00%	2.20%	0.20%	3.20%
Textiles	Combustibles	10%	48.00%	6.40%	40.00%	2.20%	0.20%	3.20%
Yard Waste	Garden waste	50%	46.00%	6.00%	38.00%	3.40%	0.30%	6.30%

APPENDIX D – MOISTURE CONTENT OF WASTE FRACTIONS

Category	Coleman et al. (2008)	Tchobanoglous et al, (1993)			Cinergex (1998)	ECN (1997)	Leio et al (2007)	Williams (1998)
		Min	Typ	Max				
Card	24.00%	4.00%	5.20%	8.00%	20.10%			5.20%
Combustibles	16.00%	10.00%	15.00%	30.00%	15.00%		20%	5.19%
Dense Plastic	10.00%	1.00%	2.00%	4.00%	18.00%	10%		
Ferrous Metal	9.00%	2.00%	3.00%	4.00%				
Fines	41.00%	6.00%	8.00%	12.00%				5.47%
Garden waste	58.00%	30.00%	60.00%	80.00%	45.10%		44%	69.00%
Glass	2.00%	1.00%	2.00%	4.00%				
Hazardous Household	13.00%							
Kitchen waste	63.00%	50.00%	70.00%	80.00%	60.40%		63%	78.29%
Non-Combustibles	6.00%	2.00%	4.00%	10.00%				
Non-Ferrous Metal	16.00%	2.00%	3.00%	4.00%				
Paper	24.00%	4.00%	6.00%	10.00%	21.00%	5.20%	10%	10.24%
Plastic Film	28.00%	1.00%	2.00%	4.00%				0.20%
Textiles	19.00%	6.00%	10.00%	15.00%	25.30%	13.50%		10.00%
WEEE	10.00%	0.00%	1.00%	2.00%				

APPENDIX E – HYPOTHETICAL COMPOUNDS FROM EACH DATA SET

Data Source:		Tchobanoglous et al (1993)			ECN (1997)			Cinergex (1998)		
Stream	Survey	C	H	O	C	H	O	C	H	O
MSW	Wales (2006)	6	10	3	6	10	2	6	10	3
MSW	ERM (2006)	6	10	3	6	10	2	6	10	3
HH	Parfitt (2002)	6	10	3	6	10	2	6	10	3
HH	Cheshire (2001)	6	10	4	6	12	2	6	10	3
HH	Essex (2004)	6	10	3	6	10	2	6	10	3
HH	London (2004)	6	10	4	6	12	2	6	10	3
HH	Wales (2006)	6	10	3	6	10	2	6	10	3
HH	Merseyside (2006)	6	10	3	6	10	2	6	10	3
HH	North Yorks (2006)	6	10	3	6	10	2	6	10	3
HH	Mean	6	10	4	6	12	2	6	10	3
CA	Parfitt (2002)	6	10	4	6	12	1	6	10	3
CA	Essex (2004)	6	10	4	6	10	2	6	10	3
CA	Wales (2006)	6	10	4	6	10	2	6	10	4
CA	Merseyside (2006)	6	10	4	6	10	3	6	10	4
CA	Norfolk (2006)	6	10	3	6	10	2	6	10	3
CA	Mean	6	10	4	6	10	2	6	10	3
L	Wales (2006)	6	10	3	6	12	2	6	10	3
L	Surrey (2003)	6	10	3	6	10	2	6	10	3
SS	Wales (2006)	6	10	2	6	10	1	6	10	2