Thermal methods of
municipal waste treatment

BIFFAWARD PROGRAMME ON SUSTAINABLE RESOURCE USE

OBJECTIVES

This report forms part of the Biffaward Programme on Sustainable Resource Use. The programme aims to provide accessible, well-researched information about the flows of different resources through the UK economy, based either singly, or on a combination of regions, material streams or industry sectors.

BACKGROUND

Information about material resource flows through the UK economy is of fundamental importance to the cost-effective management of resource flows, especially at the stage when the resources become waste.

In order to maximise the programme's full potential, data will be generated and classified in ways that are consistent with each other and with the methodologies of the other generators of resource flow/waste management data.

In addition to the projects having their own means of dissemination to their own constituencies, their data and information will be gathered together in a common format to facilitate policy making at corporate, regional and national levels.

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INTRODUCTION

The need for a critical review of thermal waste-treatment options

Recent studies show that the present level of landfill disposal for municipal solid waste (MSW), sewage sludge and other organic combustible waste is not a sustainable option.[1] In many areas of the UK, the availability of landfill sites is limited and, consequently, costs are high and rising. Figures 1 and 2 show data for waste arisings and disposal.
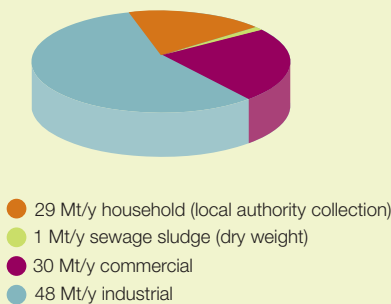

● 29 Mt/y household (local authority collection)
● 1 Mt/y sewage sludge (dry weight)
● 30 Mt/y commercial
● 48 Mt/y industrial

Figure 1: Recent data for total waste arisings from England and Wales.

● 2.3 Mt/y household (local authority collection)
● 0.1 Mt/y sewage sludge (dry weight)
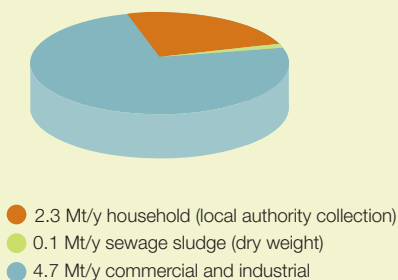● 4.7 Mt/y commercial and industrial

Figure 2: Data for waste arisings in Scotland.

The European and UK governments have a common policy of minimising waste production and recycling as much of it as practicable. Where organic waste cannot be eliminated at source or recycled, there is the option of recovering energy from it. Europe and the UK favour the energy-recovery option and have written it into government targets for waste processing.

Specific targets for UK waste treatment

- By 2005, there will be 40% energy recovery, including at least 25% recycling or composting.
- By 2010, there will be 45% energy recovery, including at least 30% recycling or composting.
- By 2015, there will be 67% energy recovery, including at least 33% recycling or composting.

To meet these specific UK targets, local authorities and waste management companies will need to invest in new plant. If central government applies pressure to invest too soon, however, then the mainstay technology for energy recovery will be incineration. Other emerging technologies such as gasification, pyrolysis, hydrolysis, fermentation and anaerobic digestion may not get full consideration.

Therefore, before making large-scale investment in new waste-treatment plant, a critical review of other emerging technologies is recommended. Such technologies could

- recycle material rather than recover energy
- have lower potential for creating toxins
- recover energy more efficiently
- give energy efficiency on a small scale, thereby reducing transportation costs.

Focus on mass balance

This report sets out critical data for the relative study of different thermal technologies.

The last 40 years of waste studies have produced a considerable amount of literature about individual treatment methods and thermal technologies such as incineration, gasification and pyrolysis. However, few of them give data that enable the direct

comparison of technologies on environmental merit. There are several reasons for this:

- different studies use different waste feeds
- most gasification and pyrolysis processes have only been proven at the pilot scale
- different gas clean-up technologies are used
- new processes are developed without much comparison with the best-performing, competing technologies
- operators are secretive about operating costs and parameters.

The report focuses on a standard composition for waste and assesses the theoretical performance of different technologies. The standard composition will be MSW, which is predominately household waste. Commercial waste has a similar composition to household waste and so the derived mass balances will be applicable. The report also gives selected mass balance information for several specific processes, as provided by the operators.

Electricity generation, rather than combined heat and power, is described for energy recovery. Combined heat and power is more energy efficient than power generation but currently has limited applicability. Moreover, a successful heat and power scheme needs a customer base that can take heat at a commercial rate, 24 hours a day, 365 days a year, for the lifetime of the plant.

"THE PRESENT LEVEL OF LANDFILL DISPOSAL FOR MUNICIPAL SOLID WASTE, SEWAGE SLUDGE AND OTHER ORGANIC COMBUSTIBLE WASTE IS NOT A SUSTAINABLE OPTION"

WASTE COMPOSITION – INPUT

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The starting point for a mass balance study is the composition of waste. The study must consider what goes in, what is added during processing, what the final components are, and where they end up. What goes in can be classified in various ways – material or substance type, elemental composition or combustion properties (fixed carbon, volatile organics, ash and moisture).

Oxygen is the principal addition during combustion. For gasification and hydrolysis, steam may be added and the waste may be co-combusted with natural gas. During the gas clean-up stage, lime and activated carbon might be added, and water could be used to cool and stabilise the fly ash. The principal final products will be carbon dioxide, water vapour and ash.

Variations in composition

Household and commercial waste content varies with lifestyle, location, season, trends in packaging, local recycling schemes and local authority collection policy. One significant policy is the acceptance of garden waste. Table 1 gives data from various sources showing the percentage content of waste using a few broad classifications.[2, 3, 4]

The 1992–93 data from the Department of Environment's National Household Waste Analysis Programme (NHWAP, a study run between 1991 and 1995) represent waste content with little or no recycling and no added garden waste.[5] The data from Nuneaton & Bedworth Council reflect the waste content subject to effective paper and glass recycling schemes. Nuneaton & Bedworth Council accepts some garden waste mixed with household waste; therefore, the putrescible food and garden waste content is high. These data also show some seasonal variation. The data gathered from the Isle of Wight show content subjected to coarse screening; consequently, the proportion of fines is high.

Detailed definition

To define the input for a mass balance study precisely, a more detailed breakdown is required. Such a breakdown is available from the 1992 Warrington (Cheshire) segment of the NHWAP study and is detailed by Williams.[3] This breakdown is reproduced in the dry weight column in Table 2.

It is possible to calculate the overall content of the waste using the data shown in Table 2 and knowledge gained from detailed analyses of separate components. The content can be recalculated for different components as determined by recycling and lifestyle (see wastebase.xls www.capenhurst.com) .[6]

Table 3 uses published information to give a combustion analysis for each waste component.[3] The combustion analysis gives moisture, volatile organic, fixed carbon, ash content and calorific value. The data analysis assumes that the waste is dry – household waste is invariably wet when collected. In order to apply the data in Table 3 to the composition shown in Table 2, a correction must be made to obtain the correct moisture content (31.56%). This is done by adding more water (waste water). The wet-weight column in Table 2 renormalises percentages in the dry-weight column by including added water. This allows the percentages to add up to 100%. When moisture-content data in Table 3 are applied to the wet-weight data in Table 2, a moisture content of 31.56% is achieved.

Table 2 shows the calorific value of each type of dry component. The contribution made by each component to the calorific value of the total waste is given by multiplying the wet-weight value by the calorific value. The wet-weight values shown represent the amount of dry material in the wet waste. The dry-weight values are the amounts of dry material in dried waste.

The elemental composition of waste also needs consideration. Data are available for the carbon, hydrogen, oxygen, nitrogen and sulphur content of many of the material and substance subcategories shown in Table 2.[3]

For thermal treatment plant emissions and ash, elemental composition requires a broader consideration. Table 4 shows a breakdown for 28 elements expressed as ranges.[5]

Critical data for the potential environmental impact caused by incineration or thermal destruction are the quantities of chlorine, sulphur, fluorine and heavy metals. Table 4 relates typical elemental composition to their abundance in the earth's crust – this gives an approximate measure of their potential environmental impact.[7]

Many of the heavy metals listed are toxic when ingested in significant quantities, but they are also essential to a healthy diet in trace quantities. Lead, mercury and cadmium do not have any biological function and are undesirable even in trace quantities. Phosphorus was not given in the source data, but is a vital component of bones and protein. In Table 4, it is assumed that its ratio to the abundance of calcium is 1:25.

" EUROPEAN AND UK GOVERNMENT POLICY IS TO RECYCLE AS MUCH WASTE AS IS PRACTICABLE "

Category	Warrington 1992, %	DoE NHWAP (1992–1993), %	Nuneaton & Bedworth March 1998, %	Nuneaton & Bedworth August 1998,%	Isle of Wight, %
Paper/board	27.4	33.2	11.9	16.0	27.1
Plastic	9.8	11.2	8.8	8.2	9.2
Glass	9.7	9.3	3.8	5.0	4.2
Metals	7.8	7.3	4.0	4.1	5.0
Food scraps/garden waste	21.7	20.2	38.3	36.6	21.5
Textiles	1.9	2.1	3.2	3.4	3.2
Other	18.0	–	–	–	–
Misc. combustibles	10.3	8.1	6.8	6.5	3.5
Misc. noncombustibles	4.6	1.8	20.4	13.3	–
Fines	6.8	6.8	2.9	4.8	23.7

Table 1: Comparative data for household waste composition – percentages of each type of component (NHWAP survey).

Category	Subcategory	Dry weight, %	Wet weight, %	Calorific value, MJ/kg
Paper	Newspapers	8.6	7.68	18.55
	Magazines	4.3	3.84	17.07
	Other paper	6.8	6.07	15.75
	Liquid cartons	0.6	0.54	26.35
	Card packaging	3.3	2.95	16.38
	Other card	3.8	3.39	16.38
Plastic	Bags and film	3.8	3.39	41.50
	Bottles	1.7	1.52	22.00
	Food packaging	1.6	1.43	38.00
	PVC	1.5	1.34	22.59
	Other dense plastic	1.2	1.07	40.32
Textiles	Textiles	1.9	1.70	16.12
Miscellaneous combustibles	Disposable nappies	7.1	6.34	4.00
	Other	3.2	2.86	20.14
Putrescible	Dry garden waste	3.6	3.21	18.49
	Wet putrescible	18.1	16.16	4.17
Fines	10-mm combustibles	3.4	3.04	14.79
	10-mm noncombustibles	3.4	3.04	0
Glass	Brown	0.4	0.36	0
	Green	1.5	1.34	0
	Clear	4.0	3.57	0
	Broken glass	3.8	3.39	0
Ferrous metal	Beverage cans	0.8	0.71	0
	Food cans	4.2	3.75	0
	Other cans	0.3	0.27	0
	Other ferrous	0.8	0.71	0
Non-ferrous metal	Beverage cans	0.4	0.36	0
	Foil	0.5	0.45	0
	Other non-ferrous	0.8	0.71	0
Miscellaneous noncombustibles		4.6	4.11	0
Waste water		+12.0	10.71	0

Table 2: Waste breakdown from Warrington (NHWAP survey, 1994). The collective properties of the waste sampled were moisture 31.56%, ash 25.12%, gross calorific value 10.05 MJ/kg.

Component	Moisture, %	Volatiles, %	Fixed carbon, %	Ash, %	Calorific value, kJ/g
Paper and card	5–10	76–81	8–12	2–5	15.7–18.6
Waxed cartons	3.4	90.9	4.5	1.2	26.4
Vegetable (food) waste	78.3	17.1	3.5	1.1	4.2
Fried fats	0.0	97.6	2.4	0.0	38.3
Grass	75.2	18.7	4.5	1.6	4.8
Plants and shrubs	50–69	25–42	5–8	1–2	4.8–8.6
Wood	20	67.9	11.3	0.8	19.6
Rubber	1.2	84.0	4.9	9.9	25.9
Upholstery	6.9	76.0	14.5	2.6	16.1
Polystyrene	0.2	98.7	0.7	0.4	38.0
PVC	0.2	86.9	10.8	2.1	22.6
Vacuum cleaner dirt	5.5	55.7	8.5	30.3	14.8

Table 3: Combustion analysis (percentages) of waste components.

Element	Range	Major sources or typical consumption for a healthy diet	Abundance in crustal rocks
Oxygen	20–40%	Water, oxides, protein, cellulose	37.0%
Carbon	18–31%	Paper, plastic, food	–
Hydrogen	2.5–8%	Water, plastics and organics	–
Silicon	1.5–4.5%	Earth	27.0%
Iron	0.3–7.3%	Cans	5.8%
Sodium	0.2–1.2%	Salt	2.3%
Aluminium	0.8–1.5%	Cans	8.0%
Calcium	0.7–1.3%	Bones and organics	5.1%
Nitrogen	0.3–0.8%	Organic material	–
Sulphur	0.04–0.12%	Organic material	0.03%
Chlorine	0.21–0.97%	Salt and PVC	0.02%
Bromine	0.01%	–	4 ppm
Phosphorus	0.03–0.05%	Bones and organics	0.1%
Fluorine	0.01%	–	0.05%
Magnesium	0.17–0.28%	Mineral supplement (300 mg)	2.8%
Potassium	0.22–0.42%	Mineral supplement (40 mg)	1.7%
Manganese	372–572 ppm	Mineral supplement (2.5 mg)	1000 ppm
Zinc	140–320 ppm	Mineral supplement (15 mg)	82 ppm
Lead	33–247 ppm		10 ppm
Copper	40–100 ppm	Mineral supplement (2 mg)	58 ppm
Chromium	24–62 ppm	Mineral supplement (25 µg)	96 ppm
Nickel	17–105 ppm	Mineral supplement (5 µg)	72 ppm
Arsenic	1.8–10 ppm	Micro-mineral	2 ppm
Molybdenum	1.9–2.8 ppm	Mineral supplement (25 µg)	1.2 ppm
Antimony	0.6–3.7 ppm	–	0.2 ppm
Silver	0.3–4.6 ppm	–	0.08 ppm
Cadmium	0.4–1.9 ppm	–	0.18 ppm
Mercury	0.02–0.12 ppm	–	0.02 ppm

Table 4: Elemental composition of household waste (NHWAP survey, 1994).

2.1 WASTE COMPOSITION AFTER RECYCLING

European and UK government policy is to recycle as much waste as is practicable. The ease with which materials can be recycled often depends on the effort necessary to separate them from other materials within the waste stream. Materials such as glass, paper and textiles are collected separately by most local authorities and can be recycled with minimal expense. It is important to consider thermal treatment with respect to waste composition after achieving government recycling targets, which will remove most of the glass, paper, discarded clothing and possibly cans.

Plastic problem

About 10% of our waste is plastic and this presents more of a problem for recycling. A breakdown of the types of plastic in household waste is shown:

- 60–65% polyolefins (42 MJ/kg)
- 15–20% polystyrene (40 MJ/kg)
- 10–15% PVC (18 MJ/kg)
- 8% (approximately) composites (20 MJ/kg).[8]

Polyolefins include polyethylene and polypropylene (PP). Composite materials are those made of two or more materials. This list

does not include polyethylene terephthalate (PET), which is a growing component of the plastics waste stream.

Plastics are only easily recycled when they are clean, free of fillers and coatings, and have been separated into different types. As an example, recycling facilities are available for clear PET bottles without tops.

Automated separation of plastics is difficult, and users cannot easily sort different plastics into their respective bins without product labelling. The pyrolysis of plastics to produce chemical feedstock has been extensively researched.[8] This route for recycling plastics

produces a tar with a commercial value less than crude oil at a much higher cost. Consequently, mixed plastics are likely to remain a major waste component after recycling.

putrescibles are removed from the fuel. This process will typically give a damp RDF with a moisture content of 20%. If the fuel is to be stored or transported, it will typically be dried to 10% moisture content.

When the 33% recycling target level scenario is achieved, the net calorific value will reduce by 14% and the moisture content will increase to 45%. Wet putrescible waste is included in this scenario.

Recycling options

Table 5 shows different recycling options for the percentage of waste recycled – 9.5%, 25%, 30%, 33% and 37%. The options are set using targets for individual components. For example, the 9.5% recycling scenario requires 50% of newspaper to be collected and recycled.

Refuse-derived fuel (RDF) content is manipulated to give it a high calorific value. Paper is included because it has a high calorific value. The waste is sorted over a coarse screen so that surplus water and wet

How green is composting?

Government policy highlights composting as a green alternative applicable to wet putrescible waste. Removing this would leave a superior fuel for thermal treatment. Unfortunately, composting is not environmentally friendly. It produces carbon dioxide, a greenhouse gas, with no associated energy recovery. Open composting can spread harmful airborne spores and bacteria, and the final residue will be unsuitable for land spreading if the original waste contained raw meat scraps. The green alternative to composting is anaerobic digestion to produce methane, preceded by thermal treatment to sterilise the waste and hydrolyse the complex organics.

Component	Material	Total amount recycled					Damp refuse-derived fuel
		9.50%	25%	30%	33%	37%	
		Fraction of each component recycled					
Newspapers		0.5	0.8	0.9	0.9	0.9	0
Magazines		0.5	0.7	0.9	0.9	0.9	0
Other paper	Mixed paper	0	0.4	0.6	0.6	0.5	0
Liquid cartons		0	0	0	0	0	0
Card packaging	Corrugated	0	0.3	0.4	0.8	0.8	0
Other card		0	0	0.3	0.3	0.3	0
Bags and film	Polyolefins	0	0	0	0	0	0.2
Bottles	PET	0	0	0	0.8	0.8	0.2
Food packaging	Polystyrene	0	0	0	0	0	0
Other dense plastic, PVC		0	0	0	0	0.3	0.8
Other dense plastic, PP		0	0	0	0	0.6	0.8
Textiles	Upholstery	0	0	0.3	0.5	0.8	0
Disposable nappies		0	0	0	0	0	0
Other miscellaneous combustibles	Wood	0	0	0	0	0	0
Garden waste	Leaves	0	0.7	0.94	0.95	0.95	0.9
Other putrescibles	Veg. waste	0	0	0	0	0.2	0.9
10-mm fines combustibles	Vacuum cleaner dirt	0	0	0	0	0	0.98
10-mm fines noncombustibles		0	0	0	0	0	0.98
Brown glass		0.7	0.9	0.9	0.9	0.9	0.9
Green glass		0.7	0.9	0.9	0.9	0.9	0.9
Clear glass		0.7	0.9	0.9	0.9	0.9	0.9
Broken glass		0	0	0	0	0	1.0
Beverage cans, ferrous		0	0.9	0.9	0.9	0.9	0.9
Food cans, ferrous		0	0.9	0.9	0.9	0.9	0.9
Other cans, ferrous		0	0.9	0.9	0.9	0.9	0.9
Other ferrous		0	0.9	0.9	0.9	0.9	0.9
Beverage cans, aluminium		0	0.9	0.9	0.9	0.9	0.9
Foil		0	0	0	0	0	0
Other non-ferrous		0	0.9	0.9	0.9	0.9	0.9
Miscellaneous noncombustible		0	0	0	0	0	0
Waste water		0	0	0	0	0	0.9
Recycling/rejection, %		9.45	25.00	30.34	33.11	37.29	49.94
Moisture, %		34.50	40.73	43.29	44.95	43.95	20.12
Ash, %		23.55	18.79	19.94	20.66	21.96	13.81
Gross recycled calorific value, MJ/kg		**9.96**	**10.02**	**9.49**	**9.10**	**8.96**	**15.057**
Net recycled calorific value, MJ/kg		**9.09**	**9.00**	**8.40**	**7.98**	**7.86**	**14.554**

Table 5: Calorific value of waste after certain fractions have been recycled. Gross/net calorific value before recycling = 10.05/9.27 MJ/kg, moisture = 31.56%.

EXISTING AND EMERGING TECHNOLOGIES

The most common systems for treating waste are landfill and mass burn. They are universally applicable but both systems are wasteful of resources – neither recovers energy particularly efficiently. New and emerging technologies – tested, pilot-scale plants with commercial solutions in development – offer the possibility of enhanced material recovery, enhanced energy recovery and reduced landfill. The important technologies are

- **incineration**
- **gasification**
- **pyrolysis**
- **hydrolysis**
- **anaerobic digestion**
- **fermentation**
- **cryogenics.**

Gasification, pyrolysis, hydrolysis and anaerobic digestion produce a gas. In principle, this could be burnt in a gas turbine instead of fuelling a boiler, which enhances electricity generation efficiency. Fermentation provides a liquid fuel. Research groups that promote gasification and pyrolysis often claim that these techniques are less polluting and potentially less expensive than the competing mass burn technologies.

Gasification, pyrolysis and hydrolysis differ from mass burn because the waste is heated with insufficient oxygen for complete combustion. Pyrolysis heats waste in the virtual absence of air to create a gas and a tar or char. Where a mixed waste is pyrolysed, the resulting mixture of tars and char often contains many complex, toxic organic substances, acids and heavy metals, which can be problematic. Gasification resolves this problem by allowing sufficient air or oxygen into the reaction zone for most of the tars and char to be reduced to a syngas, which contains carbon monoxide and hydrogen as its major components.

Gasification processes may use either air or oxygen to reduce the organic content of the waste. Oxygen reduction has the advantage of preventing the syngas from becoming diluted with nitrogen.

Hydrolysis uses high-temperature steam rather than air or oxygen to reduce the organics; this also avoids the problem of diluting the resultant syngas with nitrogen. To create a syngas using steam, heat must be added.

Other key issues attracting current research interest are recycling, detoxification and reuse of ash, and energy recovery efficiency and overall cost.

Incineration

Incineration is the combustion of waste in an excess of oxygen. Incineration is used throughout industry, particularly for medical waste and high-hazard material. Incineration and other thermal waste treatments can reduce the volume of MSW by 90% and its weight by 75%.

The UK has about 60 incinerators burning MSW, chemicals, clinical waste and sewage sludge. Thirteen of these burn MSW, and two use RDF. There are no commercial facilities for the pyrolysis or gasification of MSW.

After incineration, the wastes are converted to carbon dioxide, water vapour and ash (this varies in chemical composition). To cope with the differences in initial waste composition, incinerators will be equipped with secondary treatment units such as scrubbers or filtration systems. These will often include secondary combustion chambers and economisers to maximise by-product gas destruction and useful heat recovery. For the purpose of this study, we are interested in three designs: moving grate, rotary kiln and fluidised bed.

The advantage of moving grates and rotary kilns is that they can handle large volumes, have higher operating temperatures and are very flexible on waste composition. For example, they can accept non-uniform-sized wastes, such as cans and large solids.

Fluidised beds units require more uniform-sized waste – generally less than $400\,mm^3$ – operate at lower temperatures and cannot accept materials that form large amounts of slag, which disrupts fluidisation. They are typically fed with pre-dried RDF; however, they offer much better heat recovery than rotary or moving grate kilns.

The UK's first commercial fluidised bed MSW incinerator was commissioned two years ago in Dundee, Scotland. The plant processes 120,000 t/y of MSW and produces 8.3 MW of electricity (MWe), which it sells to the National Grid. Fluidised-bed technology has the benefits of coping with higher moisture levels in the waste and being easier to control when the calorific value of the waste is changing from minute to minute. These advantages come from the thermal mass and heat retained in the fluidising medium (sand). Mass burn does not offer either of these benefits.

Gasification and pyrolysis

Gasification and pyrolysis are thermal reactions carried out to less than full oxidation by restricting the available oxygen (or air). These processes always produce gas. Moreover, they can be optimised to produce mainly syngas, which has a significant fuel value. Gasification reactions are typically exothermic. The energy given off can be used to heat the input waste fuel to the gasification temperature, thereby maximising energy efficiency.
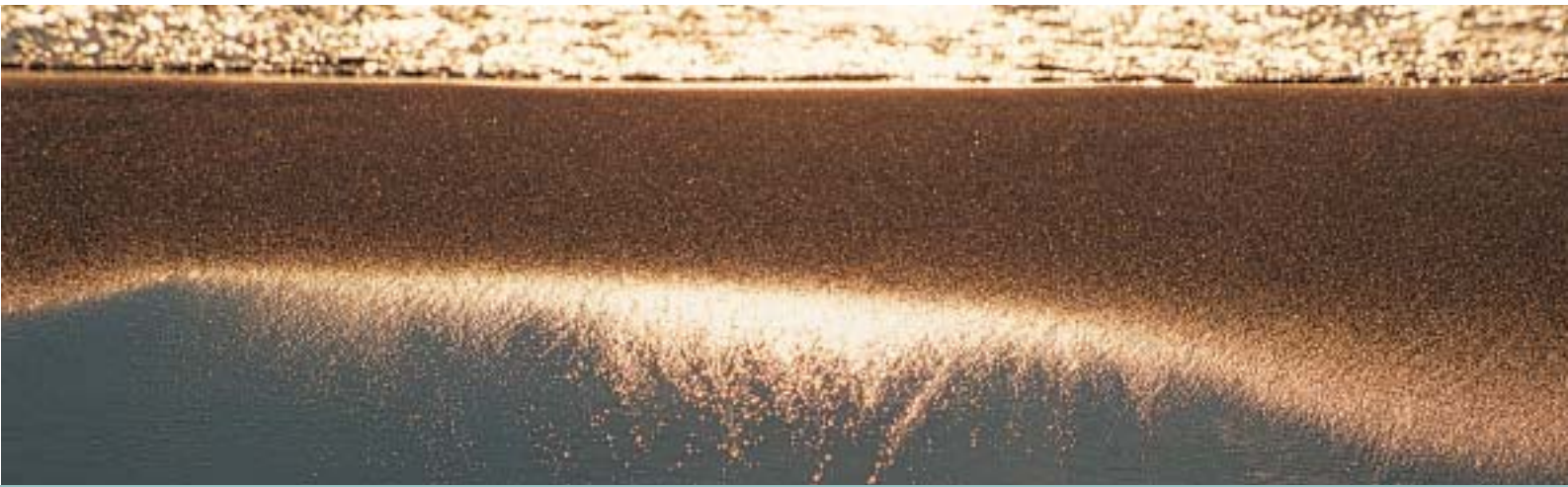
When syngas is produced, it contains virtually all of the energy in the original fuel. The syngas can then be burnt at a temperature of 850°C to provide an exhaust gas with all the energy of the original fuel.

Current gasification technologies generally utilise processed waste or RDF with 6 to 7% moisture content to produce syngas. This moisture content enables hydrolysis and gasification to occur together. Temperatures used for gasification are in the range 600 to 1200°C. Conversion efficiency varies, but it can be as high as 87%. Several pilot gasification plants were constructed and operated in Europe, the USA and Japan during the 1990s.

Pyrolysis is a specialised form of gasification and is carried out in the absence of oxygen (or air). This process is always endothermic and requires an energy input. The major advantage of pyrolysis is the recovery of useful by-products (such as metals or chemicals), energy recovery being a marginal benefit.

Pyrolysis for commercial treatment of RDF is a long way from being an economically viable option. A few commercial-scale processes do exist, but it is unlikely that pyrolysis will ever be a viable option for thermal treatment of MSW.

" **THE IMPORTANT TECHNOLOGIES ARE INCINERATION, GASIFICATION, PYROLYSIS, HYDROLYSIS, ANAEROBIC DIGESTION, FERMENTATION AND CRYOGENICS** "

EXAMPLES OF GASIFICATION TECHNOLOGIES AND INSTALLATIONS

Bergau, Germany. Built 17 years ago, this plant is based on rotating-kiln pyrolysis and complies with German and European emission requirements. The syngas output is burnt in a boiler. The fact that this process has not been adopted elsewhere suggests that its construction and operating costs are higher than for mass burn incineration. It is likely that this economic disadvantage will reverse in the future with the availability of efficient gas turbines for burning syngas.[9]

Thermoselect. This pyrolysis and gasification process is close to commercial application.[10] The plant pyrolyses compressed waste in a tunnel. It then adds oxygen in a reaction chamber at the end of the tunnel to gasify the waste. This technology is relatively expensive – the use of oxygen in preference to air does not justify the extra cost against the added value of the syngas produced. The process also uses considerable amounts of energy to vitrify the ash at very high temperatures (up to 2000°C). This energy usage is difficult to defend as the ash can be sintered at 850°C to give a relatively stable residue for non-hazardous landfill. When testing began in 2000, the Thermoselect plant did not meet the strict emission limits imposed by the German licensing authority. Since then the combustion chamber has been redesigned and other modifications made. Currently the plant has one gasification line running at its capacity of 720 t/d, and two more lines are planned at the same site. A mass balance for the Thermoselect process is available.[11]

Rowitec.[12] This circulating fluidised bed system is based on an inclined bubbling bed marketed by MG Engineering (Lurgi Energie). The system reportedly allows large particles (400 mm^3) to be fed to the bed, which significantly minimises pretreatment, making it particularly suited to MSW. There are several successful installations, the largest of which treats 300,000 t/y of MSW with availability figures of over 91%.

Compact Power.[13] The process uses pyrolysis followed by gasification. The pyrolysis section is made up of a number of modular tubes each capable of processing 500 kg/h into simple gases, char and inerts. The gasifer uses a water–gas reaction to produce hydrogen and carbon monoxide, which are then oxidised at high temperature in the thermal section. The gas is exhausted through a heat-recovery boiler, which generates steam

to power a turbine thus providing the energy recovery. This system claims to be more adaptable to changing demand because of the modular pyrolysis section. As a result, such plants are suitable for smaller sites and are a more-distributed approach to waste management.

SWERF™ (solid waste and recycling facility).[14] Pyrolysis and gasification are used in this process. However, the gasifier in this design acts as a steam reformer feeding syngas back to fuel the pyrolysis section. This syngas is then used directly to fire a turbine.

WasteGen.[9] In this system, materials and energy are recovered from the incoming waste stream in a conventional materials-segregation process, followed by a pyrolysis gas-production process. This pyrolysis is carried out in an externally heated rotary kiln. The gas is subsequently burned in a gas turbine or is used to fuel a burning chamber to raise steam to drive a steam turbine. The segregation process is designed to remove unsuitable materials – compostibles and recyclable content – both mechanically and, if required, by manual selection. The process can be custom designed to maximise the amount of recycling and composting required, and varied in operation to respond to changing market opportunities. The pyrolysis process is capable of significant variations in fuel input and is able to exceed the requirements of all known and anticipated legislative requirements.

Energos.[15] The system uses a double pyrolysis combustion furnace, operated in semi-batch mode. The combustion furnace has primary and secondary chambers. The combustion of the solid-fuel fractions takes place in the primary chamber, while combustible gases released in the primary chamber are burned in the secondary chamber. A flue-gas boiler that recovers the energy from the flue gas is connected downstream of the combustion furnace. The flue-gas boiler is a combined smoke-tube and water-tube technology used to control the outlet flue-gas temperature by preheating the feed water. The flue gas enters the flue-gas cleaning system downstream of the boiler. The cleaning system is equipped with a bag-house filter, a silo for lime, a storage unit for active carbon and a filter-dust silo. The filter cake is removed mechanically from the bottom of the bag-house filter and transported pneumatically to the filter-dust silo.

Co-incineration

Co-incineration at coal power stations is an emerging technology applicable to sewage sludge. The Longannet power station, Falkirk, Scotland, has recently been equipped and licensed to burn dried sewage sludge (10% moisture). A maximum of 10% sewage sludge can be mixed with the coal for incineration, although, more typically, the mix will contain 4% dried sewage sludge. The risk for the power-station operator is the cost of additional boiler maintenance, which might exceed the fuel bill savings. The attraction of co-incineration for the waste industry is the economy of scale – power stations are huge compared with incineration plants. Co-incineration is only a sensible option for waste streams that have a similar elemental composition to coal so that expensive upgrading of the emission control plant is not required.

There is also the possibility of co-gasification with coal. The economics of this process have been considered and look quite favourable.[16]

Anaerobic digestion

Anaerobic digestion can produce combustible gas suitable for driving a gas turbine. The gas is free of hydrogen chloride and other acidic gases. Anaerobic digestion does not require heating of the waste fuel to a high temperature, converting the moisture content to steam, and then cooling it down again while trying to recover its energy.

Another important advantage of anaerobic digestion is that the nitrate content of the fuel is not destroyed. Nitrates are retained in the final, indigestible sludge, allowing it be used as a soil fertiliser. Retaining nitrates in the sludge may be energy efficient – the average natural gas consumption for anhydrous ammonia production is approximately 35 MJ of gas for 1 kg of fertiliser. The energy content of wet putrescibles is typically 4 MJ/kg.

The most significant disadvantage of anaerobic digestion is that it is only effective for the putrescible part of the waste. If other waste, such as fragmented plastics and metal, is mixed in with the putrescibles, then the final sludge is unsuitable for land spreading and its fertiliser content is lost.

Anaerobic digestion is not very good at breaking down the cellulose in paper and wood; therefore, it can only extract a limited amount of the stored energy. However, if the waste is thermally treated before anaerobic digestion takes place, the cellulose is more easily digested.[17]

It is estimated that 1 kg of organic solids derived from municipal waste digested at between 35 and 40°C will yield up to 0.35 m^3 of gas, with about 58% methane within 15 to 30 days.[18] The energy content of methane gas at 20°C is 33 MJ/m^3; hence, the potential energy output per kilogram of organic solids is 6.8 MJ/kg. This number is consistent with the calorific values of wet putrescible waste.

The Steinmüller Valorga process, which has been operating in France since 1988, demonstrates that anaerobic digestion can be applied effectively to the organic screenings of an RDF or waste recycling plant.[19]

Fermentation

Fermentation is an alternative digestion process for cellulosic materials that can yield liquid fuel in the form of ethanol rather than methane gas. The ethanol is extracted by distillation. The fermentation process has to

be proceeded by an enzymatic hydrolysis of the cellulosic material to produce sugars.

Hydrolysis

Hydrolysis has been applied to sewage sludge on a pilot scale but not to MSW or RDF; hence, an example output gas constitution is not available. Where hydrolysis does take place it is endothermic – energy is not lost, as the final syngas will have a higher calorific value.

Where hydrolysis requires higher temperatures, using an RDF feed for example, the overall process is likely to be less efficient, as there will be greater heat losses from the reactor.

Alternatively, hydrolysis of sewage sludge at 150 to 180°C and 5 to 10 bar is particularly effective at breaking down complex organic materials such as proteins, lipids and cellulose fibres to more-readily digestible substances. Hydrolysis combined with anaerobic digestion has been used to process 70 t/d of sludge at Hamar, Norway.[20] The high-pressure hydrolysis process destroys all the pathogens in the sludge, making the solid residue from anaerobic digestion safe for land spreading.

Cryogenics

Cryogenic technologies have been used as a waste management route for hazardous waste such as paints, resins and glues. However, this route has limited usefulness with mixed-waste streams and little or no application to MSW.

Calculating mass balance

A set of spreadsheets (wastebase.xls) is available for use with this report, see www.capenhurst.com.[6] The spreadsheets allow many of the mass balance calculations to be repeated with alternative input data.

PRIMARY THERMAL-TREATMENT TECHNOLOGIES

Public concern about the protection of our environment has put the waste industry under intense scrutiny. Considerable amounts of money have been made available by European governments and the European Commission (EC) for research into the interaction of waste with the environment and new technologies aimed at alleviating the problems associated with waste and waste treatment. As a result, the disposal of waste is now tightly regulated; coal power stations have been fitted with desulphurisation plant, landfill sites are lined and managed to collect gas, and old incineration plants with unacceptably high emissions have been shut down.

This section sets out some of the remaining issues for the thermal treatment of waste, reviews current research and highlights emerging technologies that may have a future impact. Key issues attracting current research interest are recycling, detoxification and reuse of ash, and efficiency of energy recovery and overall cost.

4.1 THE CHEMISTRY OF PRIMARY TREATMENT TECHNOLOGIES FOR COMBUSTIBLE WASTE

To consider the chemical detail of gasification, pyrolysis and hydrolysis reactions, it is necessary to have a chemical formula for the carbon, hydrogen and oxygen content of the waste to be used.

Gasification, pyrolysis and hydrolysis are typically performed at slightly lower temperatures than those used for combustion. Reaction rates are slower; therefore, it is usually necessary to use RDF rather than raw waste.

Williams gives the atomic composition by weight of completely dry RDF as 55% carbon, 7.3% hydrogen and 35.9% oxygen.[3] Converting from weight fraction to number fraction, the fuel can be modelled by a

stoichiometric composition: $C_{20}H_{32}O_{10}$. Table 6 shows the atomic composition of a range of waste components in a similar form.

From Table 6 it can be seen that $C_{20}H_{32}O_{10}$ is not a bad match for many of the waste components. A more precise match for paper might be $C_{20}H_{30}O_{13}$.

4.2 GENERALISED CHEMICAL REACTIONS AND ENERGY BALANCES

Using an appropriate chemical formula for waste as derived in the last section, a general chemical equation encompassing gasification, pyrolysis, hydrolysis and combustion reactions may be written as
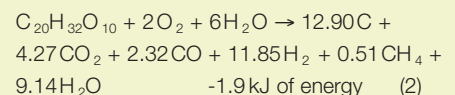
$$C_{20}H_{32}O_{10} + x_1O_2 + x_2H_2O \rightarrow y_1C + y_2CO_2 + y_3CO + y_4H_2 + y_5CH_4 + y_6H_2O + y_7C_nH_m \quad (1)$$
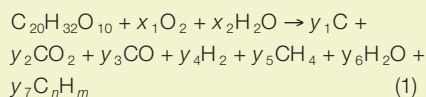
The coefficients x and y are chosen to balance species on either side of the equation. C_nH_m typically includes C_2H_2, C_2H_4, C_2H_6, C_3H_8, C_4H_{10}, C_5H_{12} and C_6H_6.

Water is included on both sides of the equation – for hydrolysis it is an input and for combustion an output.

The precise combination of gases on the right-hand side of the equation depends on the temperature at which the reaction takes place and how quickly the gases are cooled. A good indication of the gaseous output can often be determined from the chemical equilibrium of the atomic species at the reaction temperature.

Figure 3 gives equilibrium diagrams for the gasification of $C_{20}H_{32}O_{10}$ with 6 moles water and 2 moles of oxygen ($x_1 = 2$ and $x_2 = 6$ in the generalised equation). Specific reactions that might take place at differing temperatures are defined. The specific reaction is defined by the values of y_n in the general equation for the reaction. At 600°C the reaction can be written as
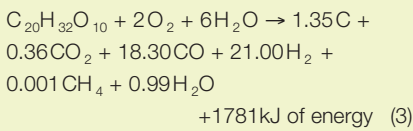
$$C_{20}H_{32}O_{10} + 2O_2 + 6H_2O \rightarrow 12.90C + 4.27CO_2 + 2.32CO + 11.85H_2 + 0.51CH_4 + 9.14H_2O \qquad -1.9\,kJ \text{ of energy} \quad (2)$$

Material	Carbon	Hydrogen	Oxygen
Newspapers	20.00	29.79	13.13
Magazines	20.00	32.69	15.07
Mixed paper	20.00	32.18	15.31
Liquid cartons	20.00	37.51	7.64
Corrugated card packaging	20.00	31.28	15.41
Other card	20.00	31.28	15.41
Upholstery	20.00	31.08	13.89
Leather shoes	20.00	30.39	8.15
Vacuum cleaner dirt	20.00	31.81	8.44
Vegetable food waste	20.00	32.38	11.48
Cooked meat scraps	20.00	38.14	6.20
Fried fats	20.00	37.87	3.04
Lawn grass	20.00	30.97	11.83
Leaves	20.00	28.12	8.73
Green logs	20.00	30.65	12.65
Evergreen shrubs	20.00	32.36	12.50
Flowering plants	20.00	34.01	12.92
Wood	20.00	28.39	12.60
Refuse-derived fuel	20.00	31.85	9.79

Table 6: Stoichiometric composition of organic materials.

and at 1200°C, as

$$C_{20}H_{32}O_{10} + 2O_2 + 6H_2O \rightarrow 1.35\,C + 0.36\,CO_2 + 18.30\,CO + 21.00\,H_2 + 0.001\,CH_4 + 0.99\,H_2O$$
$$+1781\,kJ \text{ of energy} \quad (3)$$

The equations also give the energy associated with the reaction as a final term. The value given is nominally the amount of energy added or subtracted from the output components on the right-hand side so that they are formed at the same temperature and pressure as the input components on the left-hand side. If the value is negative, the reaction is exothermic and if the value is positive, the reaction is endothermic.

The energy balance referenced to room temperature and pressure can be determined simply by balancing the energy of formation for each of the components. Appropriate values are given in Table 7.

The energy of formation of the model RDF – $C_{20}H_{32}O_{10}$ – has been derived on the assumption that the calorific value of dry, ash-free RDF is 20.85 MJ/kg. The heat of formation of newsprint, designated as $C_{20}H_{30}O_{13}$, has been derived on the assumption that the calorific value of dry, ash-free RDF is 20.03 MJ/kg. Other values have been taken from Kaye and Laby.[7]
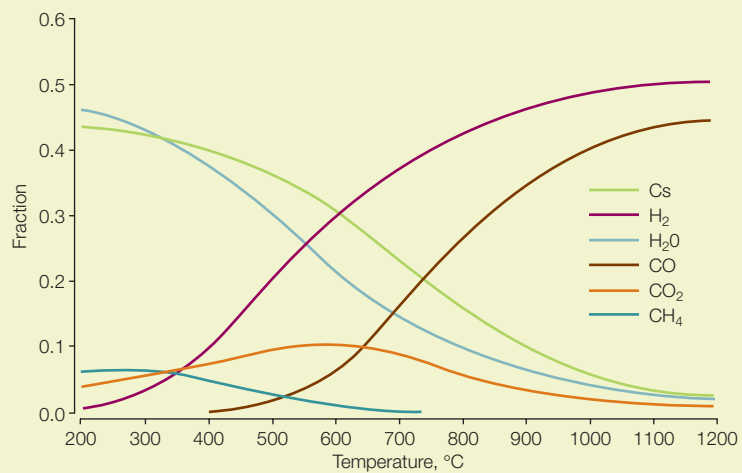

Figure 3: Equilibrium diagram for gasification of RDF with one part oxygen to three parts steam.

Molecule	Energy of formation, kJ/mole	Molecule	Energy of formation, kJ/mole
C	0.0	C_2H_6	-84.7
CO	-110.5	C_3H_8	-103.8
CO_2	-393.5	C_4H_{10}	-126.1
H_2	0.0	C_5H_{12}	-146.4
H	218.0	C_2H_2	226.7
H_2O (gas)	-241.8	C_2H_4	52.3
H_2O (liquid)	-285.8	C_6H_6 (gas)	82.9
O_2	0.0	$C_{20}H_{32}O_{10}$	-2731.8
CH_4	-74.8	$C_{20}H_{30}O_{13}$	-1921.0

Table 7: Energies of formation.

4.3 THE NATURE OF THE CHEMICAL EQUILIBRIUM FOR GASIFICATION

By referring back to Figure 3 for the gasification of RDF with oxygen and steam and the detailed reactions given at 600 and 1200°C, more can be learned about the nature of the reactions. The reaction at 600°C is slightly exothermic and thus requires no energy addition. The reaction at 1200°C exhibits a considerable degree of hydrolysis. This reaction is strongly endothermic and a large amount of heat must be supplied to make the reaction take place. The necessary energy for a hydrolysis process is not lost, as it is retained in the syngas, giving it a higher calorific value. For an efficient gasification process that uses a high degree of hydrolysis, effective heat recovery from syngas combustion is required to fuel the endothermic hydrolysis reaction.

Figure 3 does not show the equilibrium molecular fractions of higher hydrocarbons designated as C_nH_m with $n>1$ because they are typically small. In practice, the production of both methane and higher hydrocarbons is increased and the production of carbon char is reduced, compared with that suggested in Figure 3. This is because the final composition is determined by reaction rates rather than the chemical equilibrium after an infinite time.

Although equilibrium calculations do not give precise compositions, they do show important tendencies. Figure 3 shows that

- at low temperatures, carbon and oxygen prefer to exist as carbon dioxide and carbon char
- at high temperatures, when there is an excess of carbon, the carbon dioxide breaks down to form carbon monoxide. (Although not shown by the figure, carbon monoxide can be eliminated at all temperatures with sufficient oxygen.)
- low-temperature oxygen would rather react with hydrogen to form water than with carbon or carbon monoxide to form carbon dioxide
- at high temperatures, oxygen would rather react with carbon to form carbon monoxide or carbon dioxide than with hydrogen to form water. (This means that hydrogen is produced at high temperatures when there is a shortage of oxygen.)

- methane and other hydrocarbons tend to decompose at temperatures above 500°C
- char formation is almost inevitable, even at high temperatures. (The formation of char and its loss with rejected ash can represent a significant loss of efficiency for many of the gasification processes.)

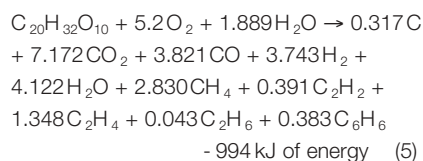## 4.4 TYPICAL CHEMICAL REACTIONS AND ENERGY BALANCES

Combustion

Mass burn combustion generally operates at temperatures between 850 and 1100°C with a large excess of oxygen. The chemical reaction is

$$C_{20}H_{32}O_{10} + 23\,O_2 \rightarrow 20\,CO_2 + 16\,H_2O$$
$$- 9007\,kJ\ of\ energy\quad (4)$$
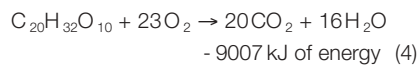
In a typical incinerator where waste forms a packed bed on the grate, this reaction proceeds in several stages. The first stage is low-oxygen pyrolysis, the second is gasification, and the third is an immediate combustion of the gas as it leaves the bed. Thermal radiation from the flame heats the bed.

Gasification with air or oxygen

Current gasification technologies generally utilise processed waste or RDF containing 6 to 20% moisture. The moisture gives a hydrolysis reaction as well as the gasification reaction. Temperatures used for gasification are in the range 600 to 1200°C. The chemical reaction is shown as

$$C_{20}H_{32}O_{10} + 5.2\,O_2 + 1.889\,H_2O \rightarrow 0.317\,C$$
$$+ 7.172\,CO_2 + 3.821\,CO + 3.743\,H_2 +$$
$$4.122\,H_2O + 2.830\,CH_4 + 0.391\,C_2H_2 +$$
$$1.348\,C_2H_4 + 0.043\,C_2H_6 + 0.383\,C_6H_6$$
$$- 994\,kJ\ of\ energy\quad (5)$$

These data relate to the TPS gasification plant at Grève (see page 24). The gasification temperature was 850°C and there would normally be a larger carbon term on the right-hand side. However, at the Grève plant, char is reduced in a catalytic-cracking stage following the gasification stage. The water component on the left-hand side corresponds to 6.5% moisture in the RDF fuel, which also contains 11% ash.

The energy given out by gasification can be used to heat the input RDF. The energy balance in equation 5 has been referenced back to 25°C. Therefore, to find out how much of the heat given out is needed to raise the temperature of the right-hand side to the gasification temperature it is necessary to know its heat capacity. Heat capacities of the gases in equation 5 at 25°C are given in Table 8.

Using Table 8, the heat capacity of the right-hand side is 1408 JK^{-1}. Adding an allowance for heating the ash, which represents 11% of the wet fuel mass, this rises to 1451 JK^{-1}. This value will increase slightly with temperature. However, using this value it is possible to estimate that the excess energy of 994 kJ in equation 5 will give a temperature rise of 685°C. This means that some additional heating is needed to reach a gasification temperature of 850°C.

When syngas is produced, it contains virtually all the energy in the original fuel. In principle, the syngas could then be burnt at a temperature of 850°C to provide an exhaust gas with all the energy of the original fuel.

Gas produced from RDF is likely to have a significant concentration of hydrogen chloride, which is very corrosive for gas turbines with metal-alloy blades. It is invariably necessary to clean the syngas after production, and this has to be done at a temperature lower than 850°C. To ensure that very little of the original energy in the fuel is lost, it is desirable to cool the gas in a boiler to provide steam for a steam turbine (or perhaps hot water for a heating system). To enhance the economy of scale for a steam turbine, the boiler tubes cooling the syngas should be on the same steam circuit as boiler tubes extracting heat from the exhaust of the gas turbine.

Once the syngas from 1 mole of $C_{20}H_{32}O_{10}$ has been cooled to 25°C, it has an energy content of 7805 kJ. This is the amount of energy available for driving an engine or gas turbine to produce electricity. The energy content of 1 mole of $C_{20}H_{32}O_{10}$ that is released on combustion is 8924 kJ. The difference is equivalent to the energy extracted from the syngas as it is cooled minus the heat added to attain the gasification temperature. In this case, the efficiency of converting the RDF fuel to syngas fuel is 87.5%.

Molecule	C	CO	CO_2	H_2	O_2	H_2O	CH_4	C_2H_2	C_2H_4	C_6H_6
C_P, JK^{-1}mole^{-1}	8.5	29.1	37.1	28.8	29.4	33.6	35.3	43.9	43.6	81.7

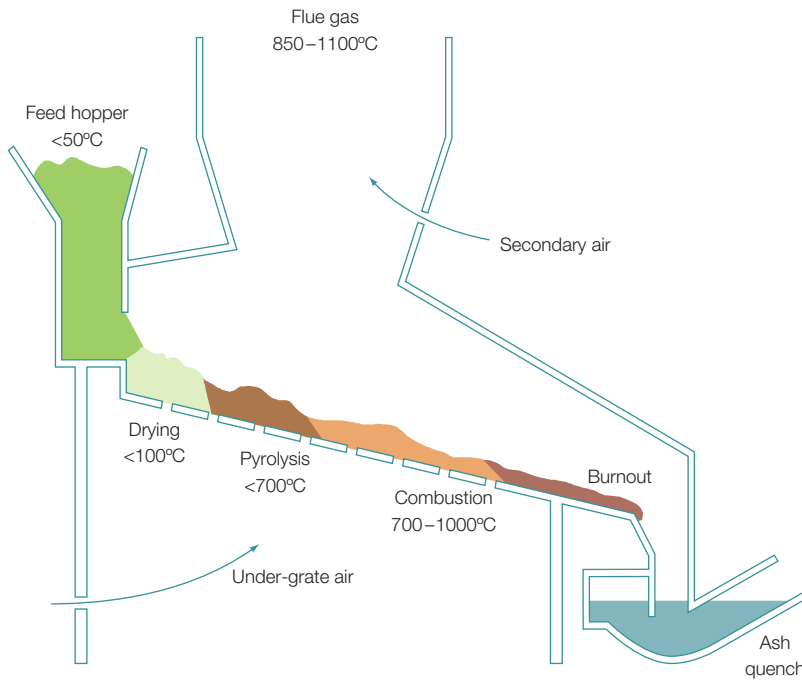Table 8: Heat capacity of gases at constant pressure at 25°C.

Figure 4: Combustion processes for mass burn incineration.

4.5   TECHNOLOGY OPTIONS

Incineration

Incinerators can be classified by the manner in which they move waste through the combustion zone. There are three types in common usage:

- **moving grate**
- **rotary kiln**
- **fluidised bed.**

Most European MSW incinerators are the moving-grate type. Systems commonly used for MSW are reciprocating grates, rocking grates, travelling conveyor grates and roller grates. The combustion processes on a mass burn grate system are shown in Figure 4.

The grate supports the bed of waste and allows air to be drawn from underneath to initiate gasification and combustion processes. This air also cools the grate. The grates are inclined at an angle so that waste tumbles under the action of gravity as the grate elements are manipulated.

The second type of incinerator, the rotary kiln, has an inclined, rotating drum. The incline causes waste to tumble down the length of the drum as it rotates. Rotary kilns are popular for small incineration systems.

The fluidised bed is the third type of incinerator. It floats waste in a bed of sand that is fluidised by the air needed for combustion. The fluidised bed typically

cannot support large, heavy particles, and these must be shredded or removed before waste is fed to the bed.

An important distinguishing feature between incinerator designs is the way that the temperature is controlled. Temperature can be controlled either by variation of excess air to the combustion zone, by heat extraction from the combustion zone, or both. Modern incineration systems try to minimise airflow through the grate to reduce particle entrapment in the exhaust and subsequent fly ash loading on the pollution-control system, therefore temperature control is predominately by varying heat extraction from the combustion zone.

For grate incineration systems, boiler pipes are embedded in the furnace walls. Variation of the flow to these pipes changes the wall temperatures and hence the radiant loss from the combustion bed. Increasing radiant losses from the bed reduces its temperature.

In fluidised bed systems, boiler pipes pass through the fluidised bed. Heat extraction is controlled by varying flow.

Rotary kilns tend to be controlled by excess air supply rather than heat extraction.

In addition to incinerators being classified by the way waste is transported, they are classified as modular and non-modular. Modular incinerators have two or more combustion zones. Commercially successful modular incinerators typically operate the first chamber in a starved-air mode. This reduces

entrainment of fly ash in the exhaust. The second chamber completes combustion of the gases generated in the first chamber. Starved-air modular incinerators are less expensive to build and operate, but their energy recovery efficiency is lower as significant quantities of char are left in the bottom ash.

Mass and energy balances for mass burn incineration

The principal factors in the mass balance for incineration are the input of organics and air, and the output of ash, carbon dioxide and water vapour.

Excess air is required to ensure that combustion is complete and that the concentration of carbon monoxide in the exhaust gases is minimised; therefore, the oxygen concentration in the exhaust needs to be significant. Table 9 shows the effect of using excess air for the incineration of MSW with 9.5% recycling.

Air volume in (NTP), m³	Exhaust volume out (NTP), m³	Oxygen content of exhaust, %	Maximum theoretical flame temperature, °C
2.57	3.33	0	1663
2.87	3.63	1.76	1545
3.45	4.21	4.38	1365
4.02	4.78	6.37	1222
4.56	5.36	7.93	1107
5.17	5.93	9.19	1012
5.74	6.51	10.23	932
6.32	7.08	11.10	865

Table 9: Exhaust volume, oxygen concentration and maximum temperature at normal temperature and pressure (NTP) as a function of air intake for MSW with 23.55% ash and 34.50% moisture.

Typical oxygen concentrations for incineration of MSW are in the range 7 to 10%. This implies an air intake volume between 4.4 and 5.8 m³ and an exhaust volume in the range 5.2 to 6.6 m³ per kg of waste. Chandler gives the air consumption of typical mass burn incinerators as 5 m³ per kg waste, with older incinerators operating at 6 m³ per kg waste and new incinerators at 4 to 4.5 m³ per kg waste.[21]

Ash

Table 4 shows that MSW contains abundant elements that include silicon, iron, sodium, aluminium, calcium, magnesium and potassium, as well as carbon, hydrogen and oxygen. Following incineration, these elements form a variety of high-melting-point oxides and complex minerals. The bulk of these end up in the grate ash. This continues to the end of the grate and is quenched in the sump.

Not all the ash from a mass burn incinerator ends up as bottom ash delivered to the quench tank (Figure 4). Ash also collects in other locations (Table 10).

- Grate siftings are the ashes that fall between the grate elements and are collected in hoppers under the air intake. This ash is mixed with the bottom ash before disposal.
- Bottom ash is also called grate ash. Bottom ash represents the largest bulk residue from the incineration process. Ideally, the incineration process should be designed so that bottom ash has a low level of toxic metals and organics. This allows disposal as a non-hazardous, inert, high-density landfill product suitable for reclamation projects.
- Boiler ash collects in hoppers under the boiler tubes.
- Boiler clinkers are hard deposits that form on the boiler tubes and the boiler walls. High-velocity air jets or mechanical rappers remove some of the loose deposits during plant operation. These deposits mix with the boiler ash. Some deposits harden on the boiler pipe and have to be removed during shutdown. A typical mass burn plant has two to four shutdowns per year. Several tonnes of material can be removed on each shutdown. This material is referred to as clinker. It is typically held together by metal chlorides that solidify at temperatures in the range 700 to 400°C.

Dust filters and scrubbers are available to remove virtually all the remaining particulates, acid gases and toxic vapours.

Exhaust gases

From knowledge of permissible emission concentrations, their total mass can be determined in exhaust gases. The values in Table 6 can be taken as approximate atmospheric emissions levels, as the licensed UK incinerators are expected to stay within the emission limits virtually all the time. In most modern incinerator facilities, the exhaust is filtered at temperatures below 200°C.

		Typical, kg	Range, kg
Grate siftings	Ash that falls through the grate. Will include low-melting point-metals such as aluminium and lead	5	5–12
Bottom ash	Ash that stays to the end of the grate and is quenched in the sump	300	210–360
Boiler ash	Ash that settles into hoppers under the boiler tubes	5	2–12
Boiler clinker	Ash that forms hard deposits on the boiler tubes and walls	–	–
Filter ash	Ash that is collected from the exhaust stream after the boiler by a bag filter or an electrostatic precipitator	20	10–40
Particulate emission	Escape of particulates up the chimney stack to the atmosphere	0.005	<0.05
TOTAL			**225–420**

Table 10: Ash residues for mass burn incineration per 1000 kg of waste.

> ## "PUBLIC CONCERN ABOUT THE PROTECTION OF OUR ENVIRONMENT HAS PUT THE WASTE INDUSTRY UNDER INTENSE SCRUTINY"

Therefore, most of the heavy metal compounds that existed as vapours in the exhaust end up in the fly ash. The relative amount of heavy metals that ends up in the fly ash, as opposed to ending up in the bottom ash, depends strongly on the chlorine and fluorine content of the waste. If no chlorine and/or fluorine are present, most of the heavy metals end up as oxides in the bottom ash.

In the UK, there are 13 facilities burning MSW and two using RDF with a capacity to process 2.9 Mt/y. If emissions from the facilities were at the maximum level permitted by EU Directive 2000/76/EC,[22] then total emissions for the UK can be determined from Table 9. Collective data are given in Table 11.

Figure 5 shows a mass balance for incineration based on an input of 1000 kg of typical organic waste as detailed in Table 5.

Table 11: Collective, permissible, maximum annual emissions from UK incinerators processing 2.9 Mt/y of waste.
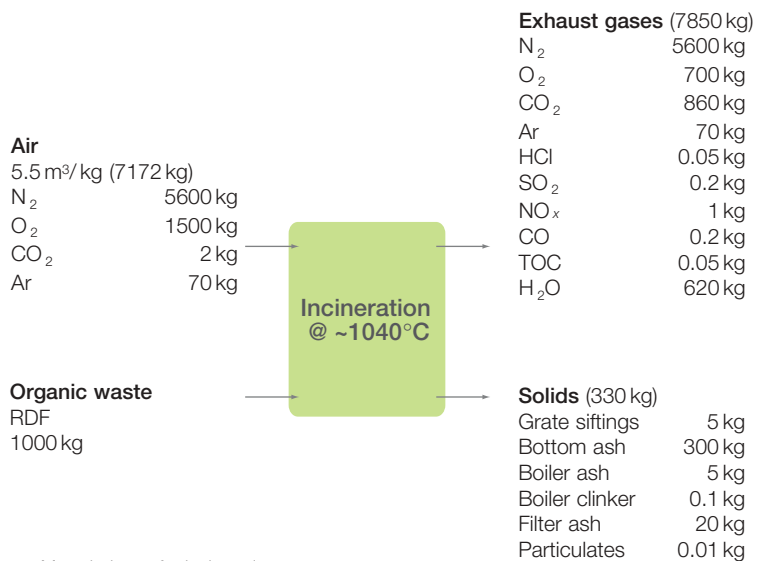
Air
5.5 m³/kg (7172 kg)

N_2	5600 kg
O_2	1500 kg
CO_2	2 kg
Ar	70 kg

Organic waste
RDF
1000 kg

Incineration @ ~1040°C

Exhaust gases (7850 kg)

N_2	5600 kg
O_2	700 kg
CO_2	860 kg
Ar	70 kg
HCl	0.05 kg
SO_2	0.2 kg
NO_x	1 kg
CO	0.2 kg
TOC	0.05 kg
H_2O	620 kg

Solids (330 kg)

Grate siftings	5 kg
Bottom ash	300 kg
Boiler ash	5 kg
Boiler clinker	0.1 kg
Filter ash	20 kg
Particulates	0.01 kg

Figure 5: Mass balance for incineration.

	Collective, maximum-permitted, annual UK emission
Dust	131.66 t
Total organic carbon (TOC)	131.66 t
Hydrogen chloride (HCl)	131.66 t
Hydrogen fluoride (HF)	13.66 t
Sulphur dioxide (SO_2)	658.3 t
Oxides of nitrogen (NO_x)	2633.2 t
Carbon monoxide (CO)	658.3 t
Mercury (Hg)	658 kg
Cadmium/thallium	132 kg
Heavy metals	6458 kg
Dioxins and furans	1.346 g

Energy efficiency for mass burn incineration

The initial loss of energy is released from the furnace by the ash. Good design can limit heat losses from the furnace to about 1%.

Assuming an oxygen concentration of 6.37% in the exhaust, Table 9 indicates that the flue gas would heat to 1222°C. To avoid the formation of dioxin, the boilers should not cool the exhaust below 400°C. This means that the maximum amount of energy the boilers can extract from the hot exhaust is 68.3%. Therefore, the maximum energy that can be delivered to the steam is 6.05 MJ/kg. Energy losses from the boiler tubes en route to the steam turbine can be made negligible.

The second law of thermodynamics limits the efficiency of converting steam energy to mechanical energy. The maximum steam temperature is likely to be 480°C. At higher temperatures, corrosion of the boiler tubes becomes excessive. If steam is ejected from the turbine at 100°C, this defines a maximum Carnot efficiency of about 50%. A practical Rankine cycle with heat

losses from the turbine would only have about 80% of the Carnot efficiency; hence, the overall turbine efficiency is 40%. The mechanical energy available on the shaft of the gas turbine is just 2.42 MJ/kg. Friction losses in the electrical generator and dissipation in the windings will reduce the electricity output by a further 2% to 2.37 MJ/kg.

Not all this electricity is available for export. Some will be needed to drive the water pumps on the steam circuit (about 1%), some may be needed for exhaust fans (assume 0%) and some will be needed to generate the magnetic field in the generators (about 0.5%). Other electrical plant could consume a further 1%; hence, the electrical output for export will be reduced to 2.31 MJ/kg. The overall efficiency is 25.4%.

Plants that achieve a better efficiency level extract heat from the exhaust at temperatures below 400°C and run the risk of creating dioxins. Table 12 summarises the energy balance.

	Efficiency, %	Losses	Remaining energy, MJ/kg
Net calorific value	–	–	9.09
Energy lost with hot ashes	–	0.14 MJ/kg	8.95
Thermal losses from furnace		1.0%	8.86
Boiler efficiency (quenching at 400°C)	68.3	–	6.05
Turbine efficiency (steam at 480°C)	40.0	–	2.42
Generator efficiency	–	2.0%	2.37
Electrical energy to drive water pumps	–	1.0%	2.34
Other electrical plant	–	1.5%	2.31
Overall efficiency	25.4	–	–

Table 12: Electrical generation efficiency of mass burn incineration.

Gasification

Gasification is an established and well-researched technology for coal, lignite and wood. A considerable amount of data on gasifier design and performance is available in texts on industrial chemistry.[23] The application of gasification technology for the thermal treatment of waste became of interest in the late 1970s when scientific evidence revealed the extent to which emissions from waste incinerators could be damaging our health and environment. An emerging concern of that era was the increasing level of dioxins in the environment.

Initial research work on the gasification of municipal waste was supported on the basis that it might lower emissions and reduce environmental impact in comparison with mass burn incineration. Arguments that gasification might be a cleaner technology than mass burn incineration are now not so strong, because both technologies can meet the stringent emission regulations when appropriate flue gas and waste water cleaning technologies are applied.

Most of the work undertaken on applying gasification technology to MSW was published before 1999, and many commercial organisations investigating such technologies have either switched their interest to gasifying biofuels or abandoned it altogether.

The various reactor technologies that have been applied to gasification are described by Bridgewater.[24] Technologies include updraught, downdraught, bubbling fluidised bed, circulating fluidised bed and rotary kiln reactors.

There are three modes of operation for these reactors:

- **partial oxidation with air**
- **partial oxidation with oxygen**
- **gasification with steam.**

Partial oxidation with air produces a gas that is diluted with atmospheric nitrogen and has a low heating value in the range 4 to 8 MJ/m^3. In the past, this energy value was too low for effective utilisation in gas turbines. Alstom has now demonstrated, and is further developing,

new-generation gas turbines for effective combustion of syngas with low calorific values.[25]

Partial oxidation with oxygen produces a syngas that is free of nitrogen and with heating values in the range 8 to 14 MJ/m^3. The additional cost of producing oxygen for the reaction is difficult to justify against the increased value of the fuel.

Gasification with steam produces gas that is free of nitrogen and can have heating values in the range 14 to 20 MJ/m^3.

Examples of the various modes of operation are the TPS Termiska Processer circulating fluidised bed reactor (partial oxidation with air), the Proler rotary kiln (partial oxidation with oxygen) and the SilvaGas circulating fluidised bed reactors by Future Energy Resources (FERCO) (using steam).[26,27] Table 13 summarises the three examples.

Company	Reactor gas	Reactor type	Feature	Gas energy value, MJ Nm^{-3}	Flame temperature,°C
TPS Termiska	Air	Circulating fluidised bed	Char cracker	7.2	1723
Proler	Oxygen	Rotary kiln	Vitrifier	10.6	1775
FERCO	Steam	Circulating fluidised bed	Char combustor	18.5	1965

Table 13: Selected gasification examples for mass and energy balance analysis.
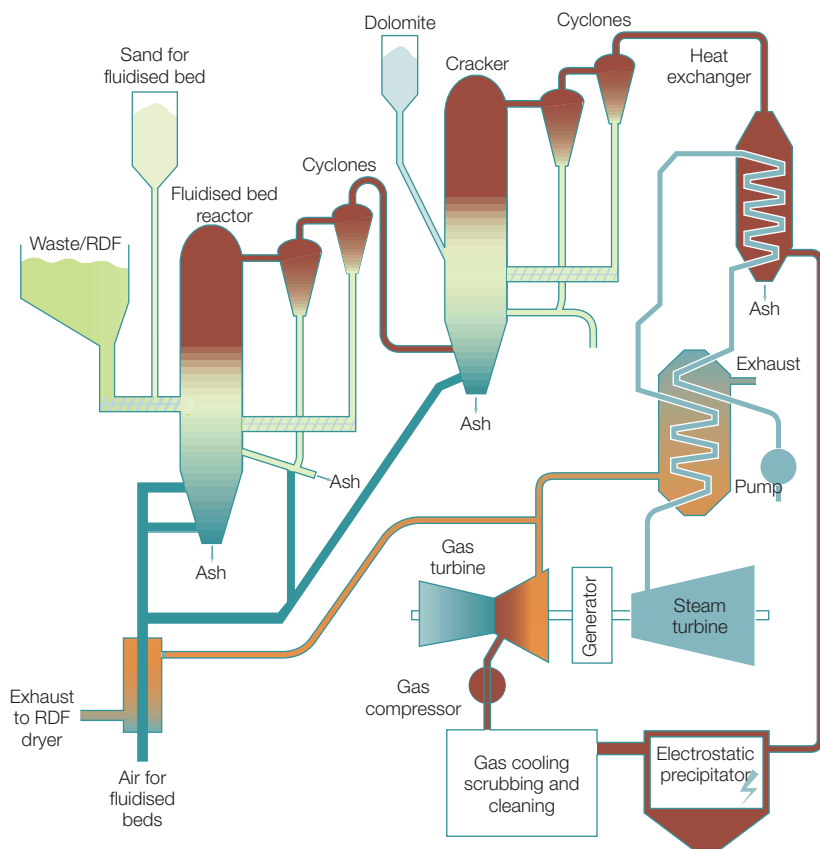
Figure 6: TPS circulating fluidised bed gasification plant and gas cleaning plant.

Although steam is used as the fluidising gas for the SilvaGas process, temperatures are too low and residence times too short for steam hydrolysis reactions to take place. The process is really a pyrolysis reaction. No pilot-scale examples of high-temperature steam hydrolysis could be found in the literature on MSW and RDF gasification. This is probably because such processes are likely to be uneconomic and consequently have not been studied in detail.

An additional mode of operation applicable to fluidised bed reactors is pressurised operation. Pressurised gasifiers are used commonly in the chemical industry, but no experimental data exist for their application to MSW.

Bridgewater has rated the various technologies against technology strength and market attractiveness.[24] The circulating fluidised bed reactor is ranked the highest on both criteria. The bubbling fluidised bed reactor and the rotary kiln are only given high technology strengths. All three technologies are applicable to the mass throughputs required for municipal waste thermal treatment.

The TPS Termiska Processer AB air gasification process

The basic technology being developed by TPS Termiska Processer can be applied to air gasification, oxygen gasification or steam gasification.[26] The company focuses on gasification with air. TPS began developing a circulating fluidised bed gasifier in 1984. A pilot-scale plant based on this technology was commissioned at Grève, Chianti, Italy in 1988 to process RDF. The low-quality syngas from this plant is burnt directly, either in a steam boiler or in cement kilns. The tar content of the syngas from a circulating fluidised bed is typically in the range 2 to 100 g/m^3 equivalent gas volume at 20°C/Nm^3. The maximum acceptable tar content for gas engines is in the range 20 to 500 mg/Nm^3.

TPS has recognised that the future of the process is integrated gasification combined cycle (IGCC). Aiming for a higher-quality syngas, TPS enhanced its gasification process by adding a second fluidised bed reactor in series with the first. In this reactor, tars are broken down to lower-molecular-weight hydrocarbons (cracked) using calcined dolomite as a catalyst. Dolomite is a mineral containing calcium and magnesium carbonate. The activity of the dolomite is thought to be related to the formation of calcium oxide at high temperatures. Differing sources of dolomite have differing catalytic activities. Dolomite also reacts with hydrogen chloride in the flue gas to form magnesium and calcium chloride. This eases the burden of the following gas clean up. An example layout for the TPS IGCC process is shown in Figure 6.

The waste is delivered to the first fluidised bed gasifer by a screw feed. This allows the gasifer to operate at a pressure slightly above atmospheric pressure.

Particles of waste are heated rapidly in the fluidised bed. Depending on the size of the waste feed, the resonance time in the fluidised bed can range from a few seconds to a few minutes. The first gasifier operates at a temperature between 830 and 900°C. This temperature is chosen to optimise gas production. Most of the heat required to maintain the temperature of the fluidised bed comes from the exothermic gasification reaction. Additional heat is supplied by preheating the air input used for gasification. Typically, this air is heated to about 400°C. The heat is supplied from the gas turbine exhaust.

High gas velocities in the circulating fluidised bed reactor carry sand particles and ash out of the reactor with the product gas. The ash and sand need to be separated from the syngas. The sand is returned to the reactor and the ash is discarded – two cyclones are used for these processes. The first cyclone removes coarse particles, which then undergo an air separation so that most of the coarse sand is returned but large, dense, sintered ash granules are rejected. The second cyclone recovers all the fine sand and ash and returns it to the gasifier. Very heavy particles in the waste fall out of the bottom of the gasifier.

The syngas produced typically contains a few percent tar and char. The tar and char are gasified in a second circulating fluidised bed reactor called the cracker.

The syngas leaves the cracker at a temperature of about 900°C. At this temperature, the syngas carries about 15 to 25% of its total energy as heat. Recovery of this heat is critical to overall efficiency. If the syngas has a very low concentration of hydrogen chloride and heavy metals, the gas can be cooled in a heat exchanger to 120°C or less, recovering 80% of the heat energy. The gas would then be filtered using a bag filter before the final gas cleaning stage.

If the gas has a significant concentration of hydrogen chloride, oxygen, and heavy metals there will be a risk of forming dioxins by de-novo synthesis. These dioxins cannot escape to atmosphere, as they would be destroyed in the gas turbine. However, they could contaminate the water used for final gas clean up.

In this instance, an operator may choose to cool the gas to 400°C, recover just over 50% of the heat energy, remove particulates in an electrostatic precipitator and then cool very rapidly before the final gas cleaning stage. The final gas cleaning stage will need to remove sulphur dioxide, hydrogen disulphide, ammonia and possibly hydrogen chloride. The ammonia must be removed, as it will be converted to oxides of nitrogen in the gas turbine.

Before the syngas can be injected into the gas turbine, it must be compressed. As the gas has a low calorific value, a much larger volume must be injected into the turbine relative to other fuels. Consequently, the gas compressor is a substantial item consuming a considerable amount of energy. It is usually necessary to cool the gas as it is compressed.

If the syngas contains high-molecular-weight hydrocarbons such as naphtha that would condense in the compressor, these components must be removed beforehand, unless the compressor has a facility for handling the condensate.

The steam cycle illustrated in Figure 6 is simplified, as it is normal to have several turbine inlets and to reheat the steam between them.

Mass balance

TPS has published mass, energy and cost analyses for plant similar to that shown in Figure 6 for a green wood crop, verge grass and organic domestic waste.[26] Table 14 reproduces the company's process data for 1 kg of wet fuel input.

Mass balance data for the gasification of RDF can be deduced from knowledge of the syngas produced at the Grève plant. The syngas and RDF compositions have been published in a National Renewable Energy Laboratory report.[11] The data indicated a balance of 4.88% hydrocarbons other than methane (C_xH_y x>1). The calculation assumed the composition of this

†LHV = lower heating value. The lower heating value is the heat of combustion when all the water that is formed is in the vapour state.

		Green wood crop	Verge grass	Organic domestic waste
Fuel data	Moisture content, % wet fuel	50	60	54
	Ash content, % dry fuel	1.3	8.4	18.9
	LHV (as received), MJ/kg	7.7	5.4	6.4
Composition, % by weight dry, ash-free fuel	Carbon	49.10	48.70	51.90
	Hydrogen	6.00	6.40	6.7
	Oxygen	44.30	42.50	38.70
	Nitrogen	0.48	1.90	2.20
	Sulphur	0.01	0.14	0.50
	Chlorine	0.10	0.39	0.30
Gasifier air	Flow rate, kg/kg wet fuel	1.4	1.48	1.6
	Temperature, °C	400	400	400
Dolomite	Flow rate, kg/kg wet fuel	0.0268	0.0279	0.0279
Syngas product	Flow rate, kg/kg wet fuel	2.37	2.40	2.42
	Temperature, °C	900	900	900
Syngas composition, %vol wet gas	CO	17.22	14.94	13.98
	H_2	13.25	12.42	11.27
	CH_4	2.82	2.61	2.81
	C_2H_4	0.94	0.87	0.77
	C_2H_6	0.02	0.02	0.02
	CO_2	12.22	12.09	11.80
	H_2O	13.55	14.49	13.71
	N_2	39.20	41.64	44.59
	NH_3	0.27	0.33	1.00
	H_2S	0.00	0.03	0.03
	HCl	0.03	0.07	0.00
g/kg wet fuel	Tar residue	12	11	10
kg/kg wet fuel	Filter ash	0.036	0.083	0.152
% wt fly ash	Filter ash composition	65	87	95
MJ/Nm³	LHV† (wet gas)	5.22	4.74	4.39
	LHV (30°C)	5.77	5.31	4.86
Gasifier ash	Flow rate, kg/kg wet fuel	0.0158	0.0158	0.0357
	Ash:sand ratio, %	90	90	90

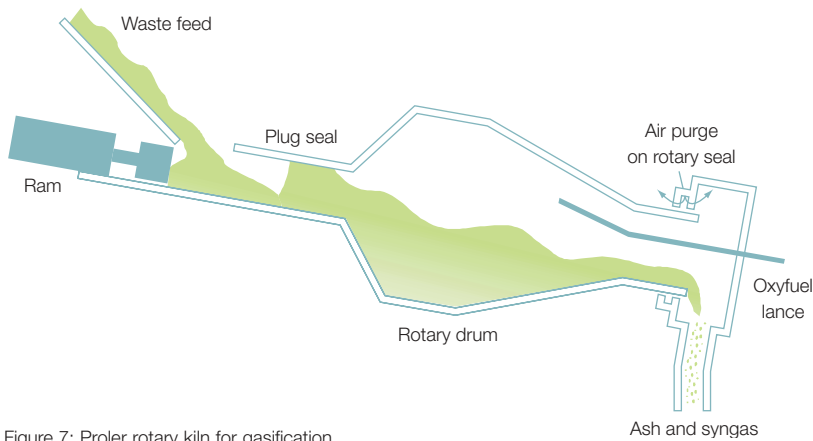Table 14: Mass balance data for TPS Termiska plant gasifying organic fuels.

Figure 7: Proler rotary kiln for gasification.

fraction to be 0.1% C_2H_6, 0.90% C_2H_2, 3.10% C_2H_4 and 0.88% C_6H_6. This ratio is consistent with data from other gasification processes. The carbon dioxide level in the output gas was increased from 15.65% in the experimental data to 16.50% for the calculation, and the tar residue was set at 7.3 gm/kg RDF. Otherwise, the calculated data for the model RDF closely match the experimental data. The mass balance data for RDF are shown in Table 15.

The syngas derived from the RDF has a very different composition to that derived from the fuels shown in Table 14. It has a high hydrocarbon content and a reduced carbon monoxide and hydrogen component. The difference can be explained in part by the lower gasification temperature. The remainder of the difference arises because less heat is needed to raise the dryer RDF to temperature; hence, less oxygen is delivered to promote exothermic oxidation and the production of carbon

monoxide. To use the syngas for running a gas turbine would probably require gasification at a higher temperature to reduce the production of naphtha.

The overall efficiency of producing electricity by gasifying RDF will depend on the energy required to make the RDF.

The Proler oxygen gasification process

The Proler International Corporation began developing a gasification process for automobile shredder waste in 1989 and undertook work on gasifying RDF. Two distinguishing features of the Proler process are that it uses a rotary kiln and oxygen instead of air. Proler is not currently promoting its process for the gasification of RDF. The data published allow a mass balance analysis for gasification with oxygen.

The rotary kiln is illustrated in Figure 7. Waste is fed in through a long, narrow tunnel. A ram is used to compress waste in this tunnel so that it forms an airtight seal. The rotary seal on the outlet of the drum has an air purge to eliminate unwanted gaseous emissions. Trials were performed with 6-cm RDF containing 15% moisture. On scale up, RDF shredding would only need to reduce the maximum size to about 15 cm.

Natural gas and oxygen are introduced into the gasifier vessel through an oxyfuel burner lance. The energy input associated with the natural gas is about 14% of the energy in the fuel. The benefit of a small addition of natural gas to the reactor is not entirely apparent.

Table 15: Calculated mass balance data for the TPS Termiska plant gasifying model RDF.

		Pelletised RDF
Fuel data, % weight of fuel	Moisture content	6.49
	Volatile matter	71.1
	Fixed carbon	11.4
	Ash	11.0
	Sulphur	0.5
	Chlorine	0.5
MJ/kg	LHV	17.04
Gasifier air, kg/kg RDF	Flow rate	1.366
Syngas product (wet)	Flow rate, kg/kg RDF	2.248
	Temperature, °C	850–900
Syngas composition, %vol wet gas		
	CO	8.79
	H_2	8.61
	CH_4	6.51
	C_2H_2	0.90
	C_2H_4	3.10
	C_6H_6	0.88
	CO_2	16.50
	H_2O	9.48
	N_2	45.13
	Tar residue, gm/kg RDF	7.3
	LHV (wet gas), MJ/kg syngas	6.626
	LHV (wet gas), MJ/Nm^3	7.46

Mass balance

A mass balance for the Proler gasification process has been calculated for an RDF feed with 15% moisture, 22% ash and a nominal fuel based on $C_{20}H_{32}O_{10}$. Process input data have been matched as closely as possible to data in reference 11. A spreadsheet – proler.xls – is set up to perform the calculation on the website.[5] The computed mass and energy balance is set out in Figure 8.

The moisture content of the fuel, the input of natural gas, the output of rocks and metals, the ratio of char to ash, and the ash-content setting were based on Niessen et al.[11] This reference source is also used to determine the amount of air needed to air the seal for setting the nitrogen concentration in the syngas.

The RDF feed used in the calculation corresponds to a shredded waste stream after 10 to 12% recycling and drying from 35 to 38% moisture to 15% moisture. The energy requirement for this drying process is about 1140 MJ and, therefore, could be taken from energy recovered on cooling the syngas. The overall efficiency of converting the energy in the low-heating-value waste to energy in a fuel that can be burned in a gas turbine is 66%.
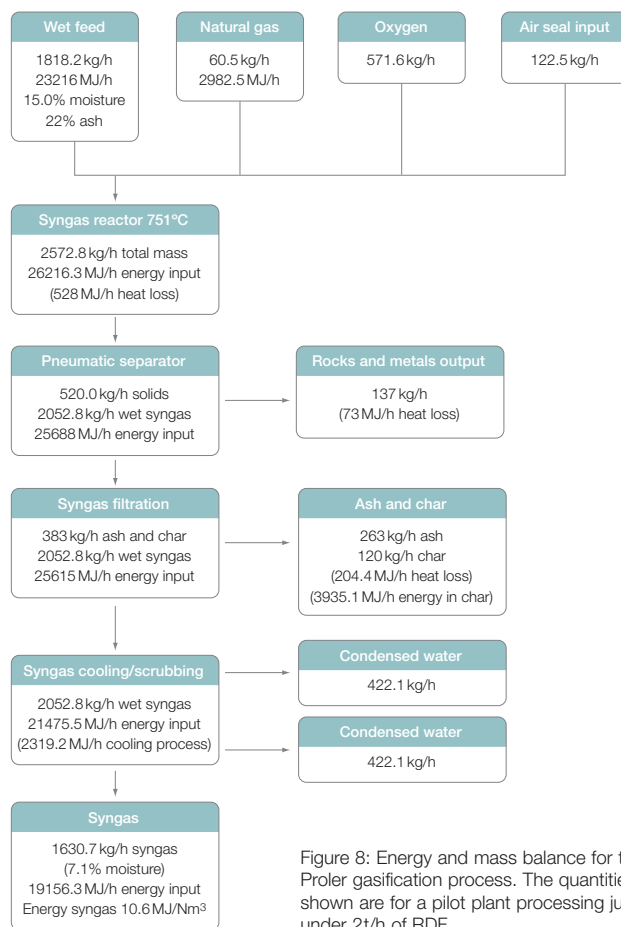
Wet feed
1818.2 kg/h
23216 MJ/h
15.0% moisture
22% ash

Natural gas
60.5 kg/h
2982.5 MJ/h

Oxygen
571.6 kg/h

Air seal input
122.5 kg/h

Syngas reactor 751ºC
2572.8 kg/h total mass
26216.3 MJ/h energy input
(528 MJ/h heat loss)

Pneumatic separator
520.0 kg/h solids
2052.8 kg/h wet syngas
25688 MJ/h energy input

Rocks and metals output
137 kg/h
(73 MJ/h heat loss)

Syngas filtration
383 kg/h ash and char
2052.8 kg/h wet syngas
25615 MJ/h energy input

Ash and char
263 kg/h ash
120 kg/h char
(204.4 MJ/h heat loss)
(3935.1 MJ/h energy in char)

Syngas cooling/scrubbing
2052.8 kg/h wet syngas
21475.5 MJ/h energy input
(2319.2 MJ/h cooling process)

Condensed water
422.1 kg/h

Condensed water
422.1 kg/h

Syngas
1630.7 kg/h syngas
(7.1% moisture)
19156.3 MJ/h energy input
Energy syngas 10.6 MJ/Nm³

Figure 8: Energy and mass balance for the Proler gasification process. The quantities shown are for a pilot plant processing just under 2t/h of RDF.

		Wet, refuse-derived-fuel feed
Fuel data, % weight of fuel	Moisture content	15.0
	Volatile matter/carbon	63.0
	Ash	22.0
MJ/kg	LHV	12.77
Gas/oxygen input, kg/kg RDF	Oxygen flow rate	0.3092
	Air flow rate	0.0642
	Natural gas flow rate	0.0333
Syngas product (wet)	Flow rate, kg/kg RDF	0.8547
Syngas composition, % vol wet gas at 75ºC (after condensation)	CO	31.8
	H_2	30.8
	CH_4	5.7
	C_2H_2	0.5
	C_2H_4	1.7
	C_2H_6	0.1
	C_6H_6	0.5
	CO_2	17.8
	H_2O	7.10
	N_2	4.6
gm/kg RDF	Tar residue	80.3
MJ/Nm^3	LHV (wet gas)	10.6

Table 16: Calculated mass balance data for the Proler rotary gasifier.

This figure does not include the energy needed to produce the 572 kg of oxygen per hour. If this process is to have any chance of competing with mass burn incineration for producing electricity, then the combined-cycle gas turbine burning the syngas will need to be at least 38% efficient before the cost of the oxygen is taken into account.

Table 16 expresses the input:output mass balance for the Proler process on the same basis as was used for the TPS in Table 15. Measurements of the composition of syngas were made after cooling to 75°C. On cooling, much of the water in the original syngas condenses.

The SilvaGas steam gasification process

Battelle started developing the SilvaGas steam gasification process in 1977 and undertook tests in 1989 with a highly prepared RDF using a process research unit with a capacity of 30 kg/h. FERCO has since acquired the SilvaGas process from Battelle and developed the technology on a commercial scale for the gasification of wood chips.

The process configuration is illustrated in Figure 9. Like the TPS gasification system, two fluidised beds are used. In the first fluidised bed, the SilvaGas system gasifies with steam. The system burns the char with air in the second fluidised bed, and syngas is drawn off after the first fluidised bed. The SilvaGas system recycles sand as the fluidising medium from the second fluidised bed back to the first.
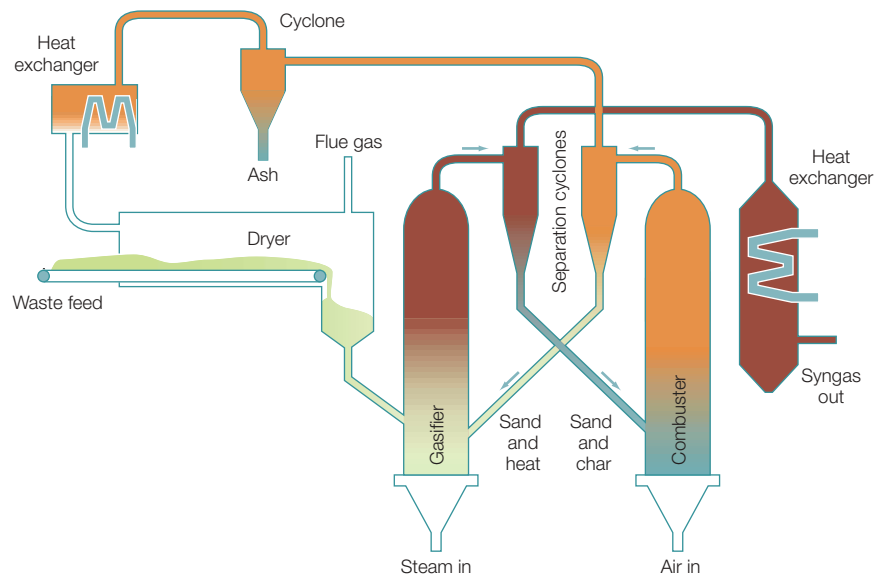
The SilvaGas system has two gas streams that need cleaning, syngas from the gasifier and exhaust from the combustor. As acid gases and heavy metal chlorides are taken away with the syngas, exhaust from the combustor is relatively clean and usually only requires filtration for particulates.

Figure 9 shows that exhaust gas from the combustor is used to dry the raw waste forming the RDF feed. This will need cleaning and deodorising after exiting the dryer.

The syngas will need to be scrubbed to remove acid gases and passed over a cracking catalyst to remove residual tar before it can be burned in a gas turbine. At a demonstration plant in Burlington, Vermont, USA, syngas is burned directly in a boiler and tar cracking is not necessary.

Mass balance

Battelle has published data on the gasification of RDF and wood chip feeds. However, the RDF gasification data do not provide enough information to be able to reconstruct a detailed mass balance.[11] The constitution of

Figure 9: The SilvaGas process for steam gasification.

		Wood feed	Refuse-derived-fuel feed	Refuse-derived feed equilibrium
Fuel data, % weight of fuel	Moisture content	15.0	15.0	15.0
	Volatile matter/carbon	63.0	63.0	63.0
	Ash	22.0	22.0	22.0
	Model	$C_{20}H_{28.4}O_{12.6}$	$C_{20}H_{32}O_{10}$	$C_{20}H_{32}O_{10}$
MJ/kg	LHV	13.44	12.77	12.77
Steam input, kg/kg RDF	Steam flow rate	0.3026	0.3026	0.3026
	Air purge	0.0072	0.0072	0.0072
Syngas output	Flow rate (7.5% moisture), kg/kg RDF	0.479	0.502	0.861
	Reaction energy released, MJ/kg RDF	0.293	-1.944	-3.494
	LHV (7.5% moisture), MJ/Nm^3	17.17	15.07	8.93
	Total syngas energy, MJ/kg RDF	8.77	10.31	13.51
Syngas composition, % vol wet gas at 75ºC (after condensation)	CO	16.2	16.2	21.41
	H_2	7.2	20.26	46.80
	CH_4	6.5	6.5	0.09
	C_2H_2	0.0	0.0	0.00
	C_2H_4	4.1	4.1	0.00
	C_2H_6	0.0	0.0	0.00
	C_6H_6	0.2	0.2	0.00
	CO_2	4.2	4.2	7.13
	H_2O	61.2	53.24	15.62
	N_2	0.4	0.4	0.00
Tar/char	Tar/char residue, gm/kg RDF	133.4	133.4	83.9
	Carbon conversion, %	61.9	61.9	76.0
	Combustion energy, MJ/kg RDF	4.38	4.40	2.75

Table 17: Heat and mass balances for the Battelle steam gasification process.

RDF was approximately $C_{20}H_{30.3}O_{12.5}$, giving a syngas composition of 15.7% H_2, 43.9% CO, 11.1% CO_2, 16.3% CH_4, and 11.2% C_2H_4. The Battelle RDF constitution is, therefore, significantly different to our model RDF $C_{20}H_{32}O_{10}$.

A mass:energy balance has been calculated to analyse the SilvaGas steam gasification process on a similar basis to that used for TPS and Proler. A spreadsheet – Battelle_wood.xls5 – analyses the gasification process for a standard 15% moisture and 22% ash feed.[5] The composition of the syngas output for a wood-chip fuel was taken as given by Niessen et al.[11] The fuel model used was $C_{20}H_{28.4}O_{12.6}$, as this gave the measured syngas composition after adjustment of the steam input. Data for the analysis are given in Table 17.

The lower heating value for the wood-chip feed was 13.44 MJ/kg. The gasification reaction is slightly exothermic, with 1 kg of wood chip yielding 0.293 MJ of energy. This will heat the wood-chip feed and the added steam by 150°C. The gasification temperature is 800°C; hence, an additional 1.23 MJ/kg of heat is needed to raise the gasifier temperature to 800°C. The energy available from burning the char is 4.38 MJ/kg and this provides the heat needed to attain the gasification temperature. Some of the heat evolved from burning the char in the combustor is used to raise steam for the gasifier. This steam carries some part of the additional 1.23 MJ/kg of heat required by the gasifier.

The combustor operates at a temperature of 970°C; hence, the maximum temperature to which the exhaust gases can heat steam is about 900°C. (A steam temperature of 900°C could only be achieved at low pressures. In practice, it is unlikely that the steam would be heated above 500°C.) Steam is added at a rate of 0.3026 kg per kg of wood chip. If exhaust from burning the char raises steam to 900°C, then the available heat above 20°C from 0.3026 kg of steam is about 0.5 MJ. This is not enough heat to raise the gasifier feed to 800°C.

The SilvaGas steam gasification process is innovative in the way in which heat is carried from the combustor to the gasifier. Most of the heat required for gasification is carried by the fluidising medium (sand) that circulates through the combustor back to the gasifier. An important parameter for the control of temperature is the rate at which sand is recycled to the gasifier.

To compare the SilvaGas steam gasification process with the TPS and Proler gasification processes it is necessary to consider the mass and energy balances for identical feeds. This is difficult to do, as the resulting syngas composition in the SilvaGas gasifier is unknown for the waste feeds used by Proler and TPS.
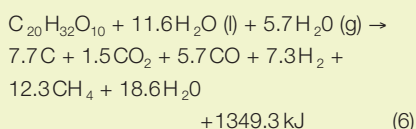
A naive method of estimation might be to suppose that the RDF feed $C_{20}H_{32}O_{10}$ gives the same syngas composition as the wood chip feed $C_{20}H_{28.4}O_{12.6}$. This of course is not possible, as the number of carbon, hydrogen and oxygen atoms must balance before and after the reaction. To obtain a balance, two components of the syngas need changing – output of water vapour and hydrogen – leaving the other components unaffected.

Once an elemental balance has been achieved, it is apparent that the gasification process is strongly endothermic. For the reaction to proceed, 1.944 MJ must be added per kg of RDF. This energy is in addition to the energy needed to heat the feed. The energy balance for the 12.77 MJ feed per kg RDF is 10.31 MJ to the syngas, 4.40 MJ to the char and -1.944 MJ for the endothermic reaction. The volume of syngas increases from 0.479 kg per kg RDF to 0.502 kg per kg RDF. The compensation for this is a reduced calorific value – from 17.17 to 15.0 MJ/Nm^3. For this gasification process to work, the sand must carry almost 3.5 MJ of energy from the combustor to the gasifier for each kilogram of RDF feed.

Pyrolysis

Typically, a pyrolysis process will produce char, oil, steam and syngas. A second look at the SilvaGas process for RDF shows that it is really a pyrolysis process. The chemical equation for the SilvaGas (Battelle) process derived from Table 17 is

$$C_{20}H_{32}O_{10} + 11.6H_2O\ (l) + 5.7H_2O\ (g) \rightarrow 7.7C + 1.5CO_2 + 5.7CO + 7.3H_2 + 12.3CH_4 + 18.6H_2O$$
$$+1349.3\,kJ \qquad (6)$$

There are more water molecules on the right-hand side of the equation than on the left-hand side. Hence, the steam input was not essential to the mass and energy balance and can be subtracted from both sides. The result defines the pyrolysis reaction as

$$C_{20}H_{32}O_{10} \rightarrow 7.7C + 1.5CO_2 + 5.7CO + 7.3H_2 + 12.3CH_4 + 1.3H_2O + 1.4C_2H_4$$
$$+1349.3kJ \qquad (7)$$
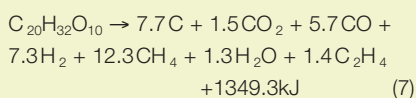
Pyrolytic processes are always endothermic. They are typically performed in packed beds, fluidised beds or rotary kilns. Where a fluidised bed is used, a fluidising gas is necessary. Many experimental studies use nitrogen, but this would not be economic for a commercial plant. Practical choices for a commercial plant would either be steam or exhaust gases from the syngas combustor (which may be a gas turbine). Exhaust gases primarily contain steam and carbon dioxide, but also some oxygen. The use of exhaust gases would alter the process from being a pure pyrolytic process to a partial air gasification process.

Examples of potential commercial processes of pyrolysis for MSW include Nexus and Thide Environnement technologies. The Nexus process pyrolyses unsorted MSW waste in containers at 500°C. This should be equivalent to pyrolysis on a packed bed. Heating can take many hours. The gaseous output is 64%, including steam and oil

vapour. The remainder is classified as solids. The solids contain carbon char, metals, glass and ash. The gaseous output is burnt in a boiler without treatment or cooling. Exhaust gases from the boiler are filtered and scrubbed to remove acid gases. Because of the high oil content, it is probably not practical to cool and clean the syngas for use in a gas turbine.

In the Thide Environnement process, pyrolysis also occurs at 500°C.[31] Pyrolysis takes place in an externally heated rotating drum. Heat and mass balance data for this process have not been published.

Pyrolysis processes are already in commercial use by the metals industry for treating contaminated non-ferrous scrap.[30] An example of this is the Alcan process for delacquering aluminium cans.[32] Two options exist therefore for recovering contaminated metals – separate then pyrolyse, or pyrolyse then separate. The first is probably cheaper but the second may recover more metal.

Pyrolysis has been extensively researched with respect to the conversion of polymers back to petrochemical feedstocks. Polyethylene (PE) and polypropylene (PP) decompose rapidly at temperatures between 400 and 600°C to give a complex mixture of olefins and alkanes. At 400°C, the yield is mainly waxes. The gaseous fraction increases with temperature.

Polystyrene (PS) initially decomposes at 290°C to yield styrene, diphenylbutene and triphenylbutene. After prolonged heating, or at higher temperatures, these components primarily form toluene, ethylbenzene, cumene and triphenylbenzene.

PVC begins to degrade rapidly above 250°C, yielding hydrogen chloride gas. In addition to hydrogen chloride, small quantities of benzene and other hydrocarbons are released. At

higher temperatures, the dehydrochlorinated polyene undergoes further cracking to yield a mixture of aliphatic and aromatic compounds and a carbonaceous char.

PET degrades at about 300°C to yield a mixture of terephthalic acid monomer and vinyl ester oligomers. Longer reaction times and higher temperatures produce volatiles, including formic acid, acetaldehyde, carbon oxides, ethylene and water.

The pyrolysis of plastics with a high PVC content requires special techniques. One approach is to add lime. The lime reacts with the PVC to form calcium chloride. In a fluidised bed, the calcium chloride forms undesirable agglomerates.

Hydrogen chloride is released from PVC at temperatures well below pyrolysis temperatures where the bulk of the hydrocarbon gases are formed. It is therefore possible to cleave most of the chlorine from PVC at a temperature just above 300°C and collect it separately.

As not all the chlorine will be removed in this way, further treatment is needed. Ammonia can be added as an alternative to lime and this forms ammonium chloride. Ammonium chloride is less of a problem in a fluidised bed.

Pyrolysis of mixed plastics produces oils that typically contain between 50 and 500 ppm organic-bound chlorine. Fortunately no chlorinated dibenzodioxins can be detected in the organochlorides.[8] If the feed stock initially contains dioxins then fluidised bed pyrolysis at 700°C will reduce levels by about 75%. For the produced oils to be acceptable for use by a petrochemical plant, the levels of organochlorides would need to be less than 10 ppm. This can be achieved by introducing sodium vapour to the syngas at 500°C.
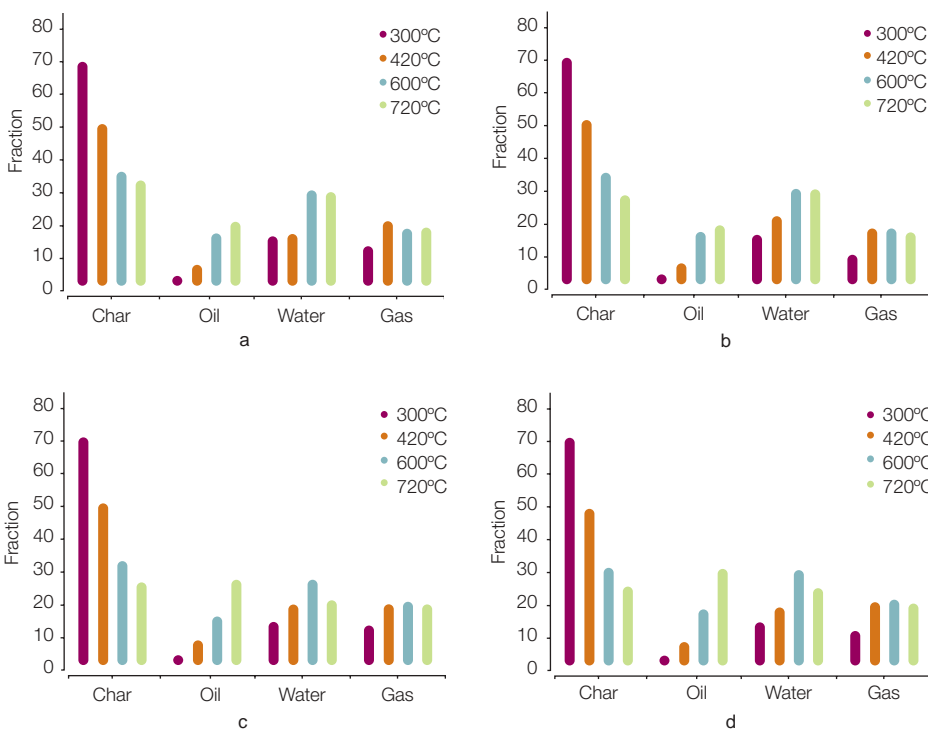
a

b

c

d

Figure 10: Product yield from the pyrolysis of RDF on a packed bed at various heating rates:
a – 5°C/min
b– 20°C/min
c – 40°C/min
d – 80°C/min

Mass balance

Final product analyses from pyrolysis thermal degradation processes show sensitivities to temperature and heating rates. Williams and Besler have undertaken a systematic analysis of product yield from RDF pyrolysis for temperatures between 300°C and 720°C and for various heating rates.[33] Their results are shown in Figure 10.

Figure 10 shows that increasing the temperature for pyrolysis decreases char production and increases oil and water production. Gas production increases between 300 and 420°C, but then stays constant. The variation of yield with heating rate was much smaller than the variation with temperature. As heating rates were increased, char production fell slightly and oil production increased. The heating rates used in this experiment were quite small. Yield changes are significant for very fast heating rates of the order of 700°C per second. Heating at these rates is termed flash pyrolysis. For flash pyrolysis at temperatures less than 600°C, the production of oil is very high; moreover, at temperatures above 700°C gas production is very high.

Gas evolution during pyrolysis is also dependent on the processing method. In a separate study, Williams reports much higher gas evolution from an RDF fuel when it is processed in a fluidised bed than when it is processed in a packed bed.[34] Figure 11 gives the product yield for RDF processed using a fluidised bed reactor, with syngas yields increasing to 75%. The RDF used in this study was different to that used for the study in Figure 10, but pyrolysis of the former on a packed bed at 700°C gave 48.6% condensates and only 16.6% gas.
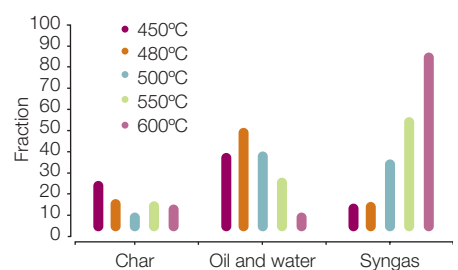

Figure 11: Product yield from the pyrolysis of RDF in a fluidised bed.

Table 18 gives a quantitative analysis of the pyrolysis products of the above plastics in a fluidised bed at 550°C.[35] The gas composition as associated with gas production in Table 18 is given in Table 19. When plastics are mixed and pyrolysed together, there are interactions between the components; hence, the composition of the syngas cannot be predicted from data for the pyrolysis of individual plastics. Table 20 shows that mixing plastics in the ratios found in municipal waste gives gas compositions that are a function of pyrolysis temperature.[35] Gaseous output increases with temperature.

The pyrolysis of mixed and separated plastic waste for the temperature range 600 to 800°C has been studied extensively by the University of Hamburg, Germany, using a laboratory-scale plant.[8] The process utilised a fluidised bed, with clean pyrolysis gas as the fluidising gas. Data from the university show that the pyrolysis of mixed plastic waste at 735°C gives a more complete breakdown of the organic gases and liquid formed by the process (Table 21). The gaseous output shown in Table 21 is similar to the gaseous output in Table 20, but it should be noted that there is no definitive mass balance for the pyrolysis of plastic waste. The data shown in Table 21 do not give the hydrogen chloride concentration.

Product	HDPE††, %wt	LDPE††, %wt	PP, %wt	PS, %wt	PVC, %wt	PET, %wt
Gas	11.4	21.4	6.5	0.7	3.9	49.1
Oil	36.8	17.8	31.5	59.0	22.1	23.5
Wax	29.9	35.4	38.3	12.4	0.0	15.9
Char	0.0	0.0	0.0	0.0	13.5	12.8
HCl	0.0	0.0	0.0	0.0	31.7	0.0

Table 18: Yields (%wt) for fluidised bed pyrolysis of individual plastics at 550°C. ††HDPE – high-density polyethylene. LDPE – low-density polyethylene.

Gas	HDPE	LDPE	PP	PS	PVC	PET
Hydrogen	0.13	0.23	0.24	0.01	0.20	0.06
Methane	0.86	1.52	0.44	0.08	0.79	0.41
Ethane	0.90	1.71	0.45	<0.01	0.55	0.20
Ethylene	3.01	5.33	1.48	0.09	0.51	1.27
Propane	0.79	0.84	0.67	<0.01	0.28	0.00
Propene	2.26	4.80	1.08	0.02	0.54	1.60
Butane	0.35	0.55	0.26	0.00	0.11	0.00
Butene	2.34	6.40	1.95	0.02	0.92	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	24.28
CO	0.00	0.00	0.00	0.00	0.00	21.49
HCl	0.00	0.00	0.00	0.00	31.70	0.00

Table 19: Gas yield (%wt) for fluidised bed pyrolysis of individual plastics at 550°C.

Temperature, °C	500	550	600	650	700
Hydrogen	0.35	0.22	0.32	0.75	0.62
Methane	0.70	2.87	4.09	12.56	11.09
Ethane	0.97	2.39	4.44	8.93	5.66
Ethylene	1.56	5.65	8.98	25.11	26.67
Propane	0.72	1.26	1.47	1.18	0.98
Propene	9.35	5.53	9.65	22.92	16.46
Butane	0.22	0.24	0.34	0.18	0.06
Butene	1.43	6.35	6.46	13.64	4.68
CO_2	–	–	5.00	3.47	1.93
CO	<0.10	<0.10	<0.10	<0.10	<0.10
HCl	1.76	1.42	4.13	0.80	0.51
TOTAL	17.06	25.93	48.88	89.54	68.66

Table 20: Gas yield (%wt) for fluidised bed pyrolysis of mixed plastics.

Feedstock	Mixed plastic (7.39% Cl)	Mixed plastic no PVC	Car shredder waste
Hydrogen	0.2	0.5	0.7
Methane	7.8	15.8	12.1
Ethane	2.5	4.2	2.4
Ethylene	7.1	10.8	3.7
Propane	0.2	0.3	0.3
Propene	2.7	3.5	1.8
Other aliphatic compounds	0.3	3.0	0.8
Benzene	5.8	9.1	5.5
Toluene	2.4	7.4	5.1
Xylenes, ethyl benzene	1.4	0.4	0.9
Styrene	4.4	6.9	0.6
Indane, indene	0.7	1.2	0.1
Naphthalene	1.0	2.1	1.2
Methyl naphthalene	0.4	0.9	0.4
Diphenyl	0.1	0.4	0.3
Fluorene	0.1	0.2	0.1
Phenanthrene/anthracene	0.3	0.5	0.3
Pyrene	–	0.1	0.1
Other aromatic compounds	12.3	11.0	11.8
Carbon monoxide	4.9	2.7	4.8
Carbon dioxide	7.2	1.0	1.8
Water	3.0	3.0	1.8
Hydrogen sulphide	–	–	0.01
Thiophene	–	–	0.02
Soot	5.2	8.4	27.6
Fillers/metals	28.4	4.9	14.0

Table 21: Products of the pyrolysis of plastic waste in a fluidised bed at 735°C. The mixed plastic waste input was sorted from domestic waste. Column three is the same waste as column two with the PVC removed. The reduced filler and metal content for the PVC-free waste implies additional sorting of non-plastic material.

ENVIRONMENTAL CONSIDERATIONS AND BENEFITS

05

Toxin removal

Since the early 1990s, detailed research has revealed the mechanisms by which dioxins and furans are formed during the incineration of materials containing chlorine. These chemicals are destroyed at normal incineration temperatures of 900°C. The problem they present is that they form in trace quantities when exhaust gases containing chlorine, carbon and heavy metal catalysts are cooled slowly between 400 and 250°C. The maximum rate of formation is at 300°C. As these chemicals are exceptionally toxic, even trace quantities can pose a danger to health. Recent research work has provided better analytical techniques for detecting dioxins and furans, computer models that can accurately predict the rate at which they are formed, and strategies to eliminate their formation.[10]

Recent technological advances have made it possible to reduce flue-gas dioxin emissions from incineration plant to less that half a part in a thousand billion. A remaining issue is the somewhat higher levels found in fly ash filtered from the exhaust gases. Fly ash also tends to contain most of the lead, cadmium and mercury present in the original waste. Currently, fly ash is buried at designated landfill sites appropriate for hazardous waste.

A more environmentally friendly approach is to treat the fly ash, destroying dioxins and recovering heavy metals. The treated ash is then sent to a landfill site that only contains inert, dense, non-toxic waste. Many of the proposals for treating fly ash recommend vitrification at high temperatures to destroy dioxins and seal in the heavy metals. Most of these processes are energy intensive and have penalties both in cost and carbon dioxide emission.

Another important area for research is the treatment of exhaust gases. Many of the basic treatments such as filtration and

scrubbing to remove acid gases are mature technologies. One important area of research for the immediate future will be instrumentation that can accurately measure exhaust emissions at the new levels set by European Union legislation.[22]

Exhaust typically leaves the final boiler stage at a temperature near to 400°C. This stage is usually the economiser that preheats water going to the boiler. At temperatures below 400°C, it is possible for toxic dioxins to form by de-novo synthesis. Modern practice is to cool the gases as quickly as possible between 400 and 250°C to minimise synthesis. Before the mechanism of de-novo synthesis of dioxin was known, standard practice would have been to allow exhaust gases to cool in the economiser to about 200°C.

Filtration and scrubbing can provide process advantages if these operations are performed at much higher temperatures. It has been postulated that high-efficiency filtration at temperatures above 450°C would remove virtually all the catalytic heavy metal particles and carbon char particles on which dioxins may form. With the risk of dioxin formation removed, gases could be cooled with efficient heat transfer through the temperature range 400 to 250°C. More-effective heat recovery boosts overall plant efficiency. Ceramic filters have been developed for high-temperature filtration.

However, there are significant problems to be solved with deposits that condense and stick within the pores of the filters and are resistant to reverse flow cleaning.[16]

Removing acidic gases

As well as removing particles at high temperatures, acidic gases such as sulphur dioxide and hydrogen chloride must also be removed. This has particular benefit for gasification processes.

Most gasification processes currently have to cool the syngas to 60°C for conventional gas scrubbing. Significant energy losses can be associated with the cooling of the syngas. For some energy recovery processes, there is an efficiency advantage in cleaning hot gas and then burning it hot in a boiler or gas turbine. The use of liquid metals may offer the possibility of scrubbing gases at high temperatures or integrating the gasification process with the absorption of sulphur and chlorine.[36]

An exception to scrubbing at 60°C has been demonstrated at the Varnamo pilot plant in Sweden.[26] Trials at this plant gasified a 50:50 wood chip:RDF mixture in a pressurised system. Production of hydrogen chloride was reduced by adding lime to the feed. The syngas was filtered at 350°C using sintered metal filters and then burnt directly in a gas

Emissions

It is of interest to see how dioxin emissions spread over the UK land mass. The total dust emission from incinerators would give a layer 0.22 nm thick.

However, the impact of dioxin emission is a significant concern for the public. It is thought that dioxins have a half-life of about 40 years in the soil. Typical soil concentrations of dioxin in UK rural areas are in the range 0.7–17ng which corresponds to a range of 1,680–40,800 ng/m³.[37] It is apparent from the analysis that emission limits have been set at a level where compliance ensures environmental effect is minimal.

turbine. By keeping the gas temperature at 350°C, tar condensation was not a problem. This temperature was also low enough to remove alkali metal chlorides. The use of ceramic filters was also investigated, but problems were experienced.

Correct selection of the bed material in a fluidised bed gasifier can greatly reduce the quantities of acid gases found in the syngas. Work is also under way by VTT in Finland on hot gas cleaning and catalytic conversion techniques.[38] As well as extending gas cleaning to higher temperatures, there is also the opportunity for intensification. An example of intensification would be the use of the V-tex™ advanced scrubbing system developed by the UK Atomic Energy Authority.[39] In this system, opposed jets of scrubber solution produce optimised droplet sizes with high tangential velocities through a circulating exhaust stream.

In a selective non-catalytic reduction (SNCR) process (Figure 12), gases are cooled in the boiler before entering a spray reactor. Reactions in the spray reactor convert hydrogen chloride and sulphur dioxide gases to solid reactants that can be collected in the

"RECENT RESEARCH WORK HAS PROVIDED BETTER ANALYTICAL TECHNIQUES "

subsequent bag filter. The most widely used reactant for the spray reactor is hydrated lime (calcium hydroxide, $Ca(OH)_2$), which is formed by reacting lime (calcium oxide) with water. Where hydrated lime is introduced as wet slurry, it provides rapid cooling of the exhaust. Rapid cooling from 400 to 250°C greatly reduces the de-novo synthesis of dioxins.

In addition to using lime slurry to remove acid gases, the advanced pollution control system injects activated carbon to remove mercury and dioxins. The amount of carbon used depends on the concentrations of mercury and dioxin.

The gas cleaning technology illustrated is somewhat wasteful of neutralising chemicals as the excess hydrated lime used in the reactor is typically 250%. Wet scrubbing of the exhaust gases can achieve better removal of acid gases with the minimum use of chemicals. The simplest application of wet scrubbing would be to filter the exhaust with either a bag filter or an electrostatic precipitator and cool the exhaust to about 60°C in a heat exchanger. The exhaust gas then passes through an acidic scrubber to remove hydrogen chloride and an alkali scrubber to remove sulphur dioxide. It is then reheated in the heat exchanger before being expelled by a large fan.

Wet scrubbing usually consumes more energy than semi-wet scrubbing, as more power is needed to drive the exhaust through the additional scrubbers and to expel the cooler exhaust. An additional potential problem with wet scrubbing is that the liquids in the scrubbing columns must be treated before discharge. A cost-effective method of disposing of the effluent from the wet scrubbers is to inject it into the exhaust gases to provide rapid cooling from 400 to 200°C before entry to the bag filter. Excess chemicals can then contribute to the exhaust treatment. Dry residue is collected in the bag filters as described. A typical process layout for achieving the described treatment is
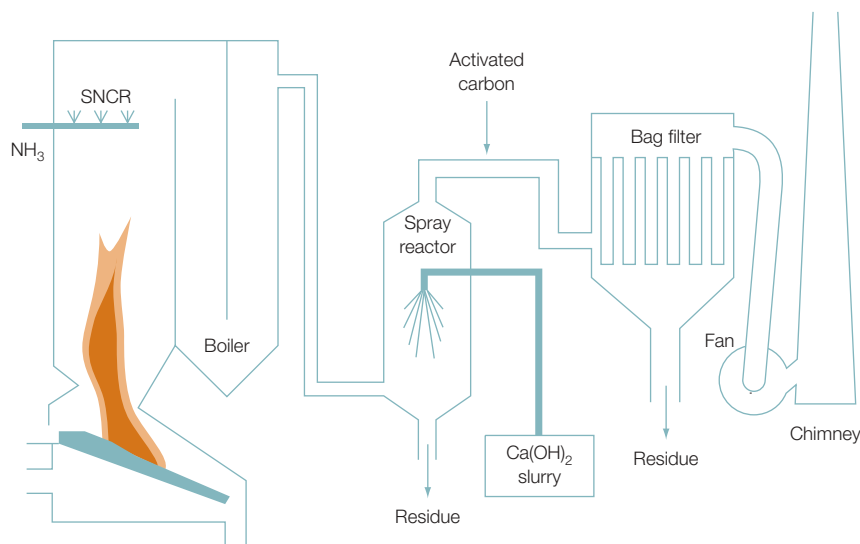

Figure 12: A simplified advanced pollution control system utilising a semi-wet reactor.

illustrated in Figure 13. Note that there are two fans for moving the exhaust.

The principal mineral phases found in the electrostatic precipitator and bag filter residues include sodium chloride, potassium chlorate, calcium sulphite, magnesium sulphate and other complex salts of potassium, calcium, aluminium, silica,

phosphorus and magnesium. Advanced pollution control residue collected in the bag filter would additionally include calcium chloride following the disposal of wet scrubbing residue. The residue following a semi-dry or semi-wet scrubber is more likely to contain calcium hydroxychloride than pure calcium chloride.

Emission limits, atmospheric pollution and quantities in perspective

Implementation of EU directive 2000/76/EC (applicable to new UK installations from 28 December 2002 and existing UK installations from 28 December 2005) sets daily maximum emission levels for all significant environmental pollutants from thermal municipal waste treatment plants.[40] These limits are shown in Table 22.

EU directive 2000/76/EC will be implemented in the UK by a regulator who licenses incinerators and waste thermal treatment processes for the production of fuel according to Integrated Pollution Prevention and Control regulations.[42]

Dust	Total organic carbon	HCl	HF	SO_2	NO_x	CO	Hg	Cd/Tl	Heavy metals	PCDD/PCDF
10	10	10	1	50	200*	50	0.05	0.01	0.5	0.0000001

Table 22: Average daily emission limits in mg/m^3 as set by EU directive 200/76/EC

for plants burning more than 6 t/h ~ 50,000 t/y.

Heavy metals includes antimony (Sb), arsenic (As), lead (Pb), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), nickel (Ni) and vanadium (V). Cadmium (Cd), thallium (Tl) and mercury (Hg) have separate limits. PCDD (dioxins) and PCDF (furans) – differing species contribute to the total figure with weightings less than or equal to one, depending on their toxicity. The legislative document has various limited exemptions and extended periods for compliance. In addition to daily rates, it gives half-hourly rates and frequency of measurement. It also sets limits on water contamination, general plant operation and ash disposal.
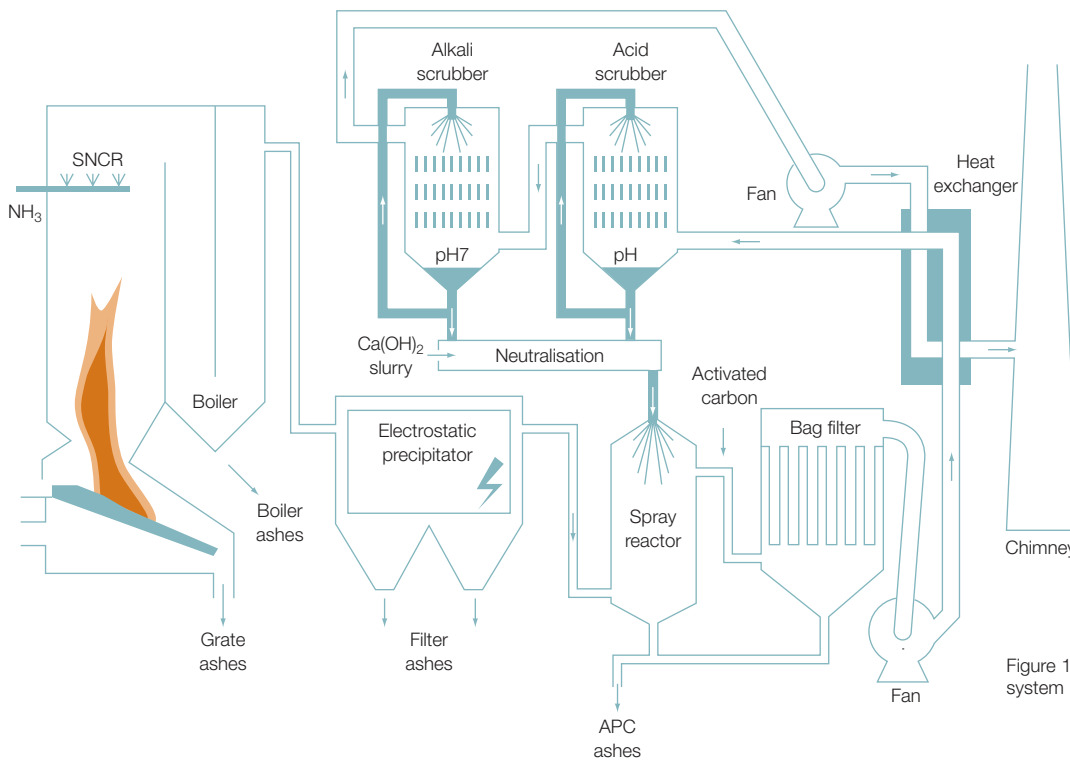
Figure 13: Advanced pollution control system utilising wet scrubbing.

5.1 MASS BALANCES FOR THE POLLUTION CONTROL SYSTEM

As emissions from incinerators would be above permissible limits, pollution control schemes are used. Estimates of the concentration range of controlled components within the exhaust at the exit of the boiler are given in Table 23. [3,41]

Oxides of nitrogen (NO$_x$)

In advanced pollution control processes, ammonia is injected into the flue gas at a point just before the boiler where temperatures are close to 850°C (see Figure 12). The ammonia reduces the NO$_x$ to produce nitrogen gas and water vapour. Typically, the reaction proceeds as

$$4NH_3 + 6NO \rightarrow 5N_2 + 6H_2O \qquad (8)$$
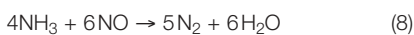
Four moles of ammonia are required for each 6 moles of nitrogen oxide in the exhaust. In terms of mass, 68 kg of ammonia are needed to neutralise 180 kg of nitrogen oxide.

From Table 4, the anticipated nitrogen content of the waste is 0.3 to 0.8%. It is apparent from Table 22 that not all of this nitrogen becomes converted to nitrogen oxide. A concentration range of 150 to 600 mg/m^3 is equivalent to a concentration range of 0.015 to 0.03%. This means that only 5% of the organic nitrogen is converted to NO$_x$. Accordingly, the minimum amount of ammonia that must be added to the exhaust will be in the range 57 to 227 mg/m^3. One kilogram of waste typically produces 5.5 m^3 of exhaust; hence, the minimum addition of ammonia must be in the range 0.31 to 1.2 gm/kg waste to eliminate the emission of NO$_x$.

Data for the waste facility at Bremerhaven, Germany, indicate that the typical ammonia utilisation can be seven times the stoichiometric ratio.[21] For an NO$_x$ concentration of 400 mg/m^3 in a gas flow of 78,000 m^3/h (31.2 kg/h), the ammonia utilisation was 82 kg/h, with an additional 6 kg/h recovered from a final scrubbing column and then recycled with steam injection.

Hydrogen chloride

The reaction that removes hydrogen chloride gas is represented by the equation

$$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O \qquad (9)$$

One mole of calcium hydroxide removes two moles of hydrogen chloride. In terms of mass, 1 kg of calcium hydroxide can remove 0.985 kg of hydrogen chloride. In practice, the spray reactors are not effective unless there is a considerable excess of the calcium hydroxide reactant. Typically, the usage of calcium hydroxide is two and a half times higher than the minimum quantity. This means that 2.5 kg of calcium hydroxide are needed for every kilogram of hydrogen chloride. From Table 23, the typical flue gas concentration of hydrogen chloride is 648 mg/m^3 and the exhaust volume for the incineration of 1 kg of waste is about 5.5 m^3. It follows that about 9 kg of calcium hydroxide are required for each tonne of waste incinerated.

Figure 14 sets out the overall mass balance for chlorine for a 1-t input of raw waste.

Emissions	Mean, mg/m^3	Range, mg/m^3
Particulates	3000	1500–8000
Hydrogen chloride	648	345–950
Hydrogen fluoride	9	5–20
Sulphur oxides	425	180–670
Nitrogen oxides	250	150–650
Lead	30	6–55
Cadmium	1.8	0.3–3.6
Mercury	0.5	0.1–1.1

Table 23: Concentration range of acid gases in exhaust from incineration facilities without gas clean up.
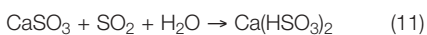
Oxides of sulphur (SO$_x$)

A similar analysis can be performed for sulphur dioxide. Sulphur dioxide can be removed through several reactions. The most important is

$$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O \qquad (10)$$

forming calcium sulphite and then followed by the reaction

$$CaSO_3 + SO_2 + H_2O \rightarrow Ca(HSO_3)_2 \qquad (11)$$

forming calcium bisulphite.

One mole of calcium hydroxide can, in principle, remove two moles of sulphur dioxide. Stated in terms of mass, 1 kg of calcium hydroxide can remove 1.73 kg of sulphur dioxide. Again, assuming calcium hydroxide usage is two and a half times the minimum quantity, then 1.45 kg of calcium hydroxide is needed for every kilogram of sulphur dioxide. From Table 23, the typical flue gas concentration of sulphur dioxide is 425 mg/m^3, which equates to about 2.3 kg per tonne of waste. This is inconsistent with the sulphur content for typical household waste as defined in Table 4. Alternative mass balances can be calculated on the assumption that 35% of the sulphur ends up in the bottom ash and 40% is carried in the exhaust as sulphur dioxide.[21] On this basis, Figure 15 gives the overall mass balance for sulphur.
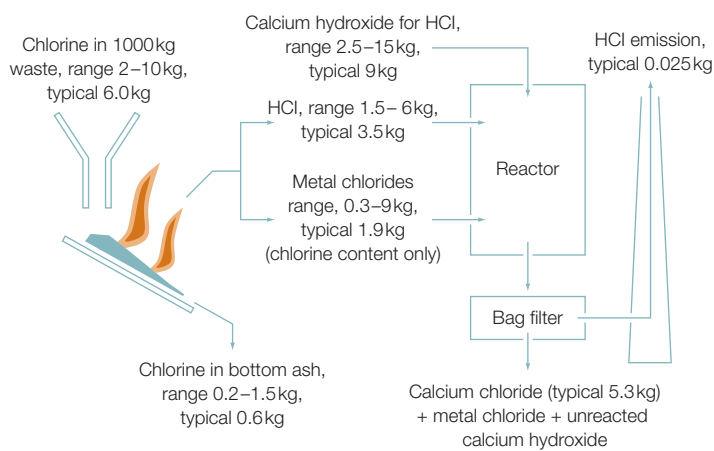

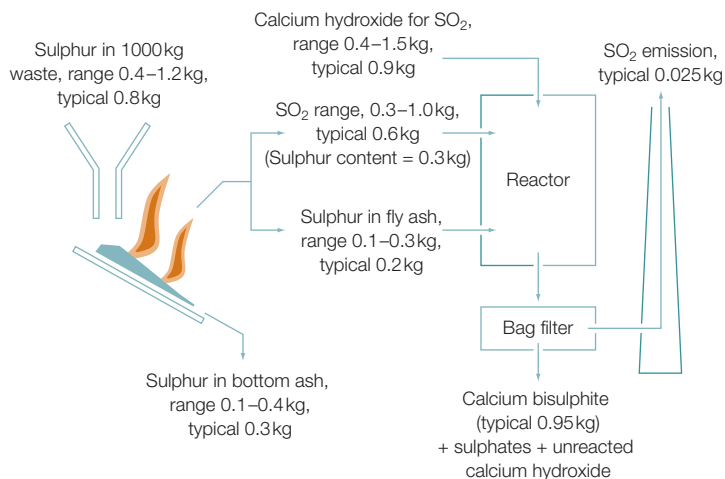Figure 14: Mass balance for chlorine with semi-wet scrubbing of the flue gas.

Figure 15: Mass balance for sulphur with semi-wet scrubbing of the flue gas.

Recycle or burn – the value of fuel and raw materials

It is desirable from an environmental point of view to recycle as much of our waste as is possible, but this can only be done if it can be made cost-effective. In considering this, the true disposal costs need to be integrated into the value of recycled materials. The value of recycled material is first diminished by the cost of collection, separation and transportation. In addition, processing recycled material is more expensive than using new material, which adds further costs. For these reasons, recycled material can have a lower value than one might expect. This may change as attitudes regarding waste disposal change and recycled materials begin to attract a premium, for example, recycled paper products.

Recycling could never be a complete option, as materials such as paper degrade as they are successively recycled and polymers can quickly become excessively contaminated with pigments, plasticisers and fillers. Where materials cannot be recycled to their original form (paper to paper, glass to glass, etc.), it is desirable, if possible, to convert them into some other valuable or environmentally friendly product.

The environmentally friendly processing option for waste that is not recycled to its original state, or to some new form, is that of energy recovery to leave an inert waste. The options for energy recovery that are applicable to most solid waste are landfill with gas recovery, incineration, gasification and pyrolysis. Options that are applicable to a portion of solid waste include anaerobic digestion and hydrolysis.

When choosing a process, the main considerations for the environment are

- minimisation of groundwater pollution
- minimisation of atmospheric pollution
- reduction of greenhouse gas emissions
- preservation of earth resources such as oil, natural gas and minerals
- return of nitrates and minerals to the soil
- minimisation of land wastage
- generation of inert non-toxic, high-density landfill residue
- high percentage recovery of iron, copper, aluminium and other valuable metals.

The public conception of waste processing is that landfill scores badly against the first consideration, whereas incineration scores badly against the second consideration. Groundwater contamination is not a significant issue for correctly sited, lined and well-managed landfill. In addition, atmospheric pollution is not a significant issue for incineration and gasification plants with state-of-the-art gas cleaning facilities.

The argument for energy recovery from waste is mainly economic. Sometimes the opportunity of recycling comes into conflict with the opportunity for energy recovery when waste has more value as a fuel than as a raw material. The relative values of differing fuels and materials with energy content are shown in Table 24.

Paper

Newsprint has 74% of the energy content of coal and should have a value as a fuel approaching 0.266 p/kWh. This is slightly more than its value to the paper mill. This argument is not true for quality paper, which can fetch up to £80/t.

MSW

Typically, MSW has an energy content of 2575 kWh/t which is 37% that of coal. The maximum value of MSW as a fuel is then calculated as 0.133 p/kWh. The actual value of MSW as a fuel usually turns out to be less than this and invariably negative rather than positive. This is because plant needed to incinerate or gasify MSW is more expensive to build and run than plant to burn coal. If this value is positive or less negative than the cost of disposal by other means (for example, -0.311 p for landfill disposal at £8/t), then conversion to a fuel or incineration is the economic option.

Plastics

Plastics – in particular polyolefins – have a very high calorific value. Mixed plastics are very difficult to recycle at any reasonable cost; hence processing to recover energy makes sense. The value of mixed plastics as a fuel is somewhat less than oil, as the chlorine content is highly undesirable.

Value is also relevant to other waste components. It will determine how much effort should be taken to extract them before processing, or to preserve them during processing. For instance, the value of aluminium is as a metal not as an oxide. If one wishes to recover both energy and aluminium from plastic/aluminium/paper laminates then incineration at 950°C would be unsuitable as the aluminium would be completely oxidised. On the other hand, a microwave pyrolysis process in the absence of air and possibly at a lower temperature can recover energy and aluminium.[42]

	Energy content	Price/value, pence/kWh	Comments
Coal	6960 kWh/t	0.359	April 2002 BP website
Natural gas	10.833 kWh/Nm^3	0.922	April 2002 BP website
Oil	11667 kWh/t	1.2	April 2002 BP website
Newspaper	5154 kWh/t	0.194	Value to paper mill (£10/t)
Quality paper	5154 kWh/t	1.552	Value to paper mill (£80/t)
Municipal solid waste	2575 kWh/t	-0.311	Disposal cost at landfill (£8/t)
Mixed plastic	9585 kWh/t	-0.311	Disposal cost at landfill (£8/t)

Table 24: Comparative values and energy content of fuel and waste.

CONCLUSIONS

In seeking a sustainable future, the first option for waste management should be recycling. The UK government target for recycling is 33% by 2015. England and Wales currently produce 29 Mt/y of MSW – mainly household waste – of which 9% is recycled, leaving 26 Mt for landfill or incineration. Household waste production is growing by 3% per year. Therefore, by 2015 the amount of household waste requiring disposal could rise to 41 Mt. Assuming that the government recycling target is met, the remainder of the household waste requiring disposal will amount to 28 Mt, an increase of 2 Mt.

It is apparent that once recycling has been maximised there could still be a growing requirement for MSW disposal facilities. If the government wants to reduce the volume of MSW for landfill there will be an increased requirement for thermal treatment-technologies.

In addition to the UK government targets on recycling and recovery, agreement has been reached with the EU to

- reduce biodegradable municipal waste sent to landfill by 25% by 2010
- reduce biodegradable municipal waste sent to landfill by 50% by 2013
- reduce biodegradable municipal waste sent to landfill by 65% by 2020.

The above targets are relative to biodegradable municipal waste send to landfill in 1995.

The following sections summarise the options covered in this report.

Composting

Composting is the aerobic digestion of organic matter. An important question that needs to be addressed is environmental performance of composting relative to thermal treatments such as mass burn incineration and gasification.

The composting of organic matter converts about 65% of the carbon content to carbon dioxide. If the remaining compost is spread on the land, a further 27% will be converted to carbon dioxide by biological action over a time span of 100 years. Mass burn incineration converts all the carbon in MSW to carbon dioxide but using energy recovery displaces fossil fuel generation. Therefore, the argument for composting cannot be won by referring to greenhouse gas emissions.

The case for composting is weakened further where waste is not continually turned over to aerate it. Without thorough aeration, significant quantities of methane will be produced (through anaerobic digestion), which affects climatic performance.

The difficulty common to both composting and anaerobic digestion of organic matter is contamination. This often makes the final material unsuitable for land spreading. Current disposal practice for most of the compost derived from household waste is landfill.

A very important part of future policy and legislation on waste management will be to limit the amount of hazardous materials – or materials that can form hazardous materials – being mixed with general waste that might be sent for incineration, gasification, composting or anaerobic digestion. Intelligent source segregation will be the key to ensuring residue from composting and anaerobic digesters does not need to be land filled.

Anaerobic digestion

Anaerobic digestion is an excellent technology for treating biodegradable organic waste. Anaerobic digestion recovers energy and therefore displaces fossil fuel generation. It can also provide nitrogen-rich humus for enhancing soils. A future attraction of anaerobic digestion is the opportunity to integrate it with gasification.

The most significant disadvantage of anaerobic digestion is that it is only effective for the putrescible part of the waste. If fragmented plastics and metal are mixed together with putrescibles, then the final sludge is unsuitable for land spreading and its fertiliser content is lost.

Landfill

Currently most MSW is sent to landfill. Using published data, it is possible to estimate that 20% of the carbon content of MSW deposited in landfill will get converted to methane and 20% will get converted to carbon dioxide.[43] The remaining 60% will become permanently – for a period longer than 100 years – fixed into the solid residue.[35]

Methane has a much greater global warming potential than carbon dioxide. Therefore, if 20% of the carbon placed in landfill is released to the atmosphere as methane and 20% as carbon dioxide the global warming effect is increased by a factor of 1.73 when compared with composting or incineration without energy recovery (Table 25). For a well-managed landfill site where gas is collected and burned in a gas engine to produce electricity at 20% efficiency, the contribution to global warming is reduced considerably. Efficient gas collection systems used with properly lined and capped landfill sites can collect up to 80 to 90% of released methane.

> ONCE **RECYCLING** HAS BEEN **MAXIMISED** THERE COULD STILL BE A GROWING REQUIREMENT FOR MSW DISPOSAL FACILITIES "

Greenhouse gas	Emission, Mt	Global warming potential	Global warming contribution	Contribution from solid waste disposal, %	Global warming contribution from waste, Mt
Carbon dioxide (fossil)	3215	1	3215	0.5	15
Methane	22	21	460	33	152
Nitrous oxide	1.02	310	325	1	3

Table 25: EU greenhouse gas emissions and global warming potential.
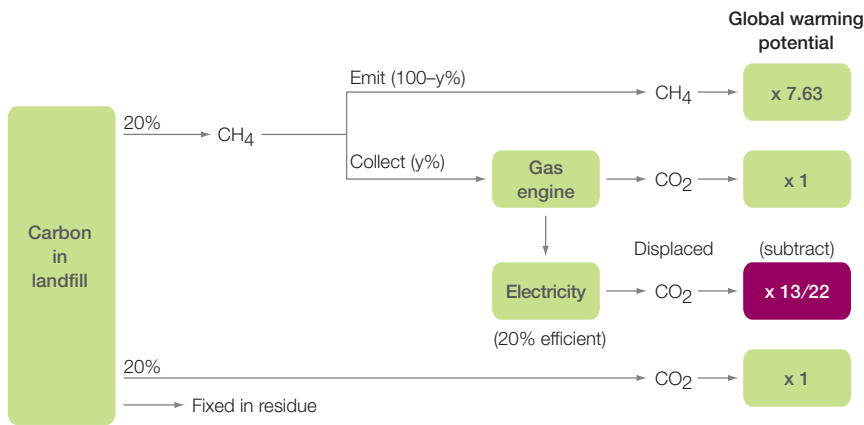
Figure 16: Carbon flow and global warming potential for a managed landfill site. The red box shows the subtracted factor $^{13}/_{22}$ for displaced generation. This is calculated on the basis that 9 moles of CO_2 are emitted for the production of 1 kWh from CH_4 being burnt in a combined cycle gas turbine (50% efficiency), and 22 moles of CO_2 are emitted for the production of 1 kWh from CH_4 burned in a gas engine (20% efficiency) at a landfill site.

Figure 16 illustrates the flow of carbon and its global warming potential at a managed landfill site. This naive analysis considering just methane and carbon dioxide emissions indicates that there is little to choose between best practice landfill and energy-efficient thermal processing of waste with respect to their potential contribution to global warming. Smith et al. give more-detailed analyses; however, this work concentrates on current practice rather than future potential.[43]

Incineration

Incineration is the most common thermal disposal technique for MSW. Incineration and other thermal waste treatments for MSW can reduce its volume by 90% and reduce its weight by 75%. Such reductions immediately lessen the demand for landfill sites.

The UK has about 60 incinerators burning MSW, chemicals, clinical waste and sewage sludge. Thirteen of these burn MSW, and two use RDF. There are no commercial facilities for the pyrolysis or gasification of MSW. The total capacity for the incineration of MSW and RDF is 2.9 Mt/y. This represents 10% of UK household waste.

The last 40 years of waste studies have produced a considerable amount of literature about individual treatment methods and thermal technologies such as incineration, gasification and pyrolysis.

However, there are few data available to enable the direct comparison of technologies

on environmental merit. There are several reasons for this:

- different studies use different waste feeds
- most gasification and pyrolysis processes have only been proven at the pilot scale
- different gas clean-up technologies are used
- new processes are developed without much comparison with the best-performing competing technologies
- operators are secretive about operating costs and parameters.

All 15 UK MSW and RDF incineration facilities, with the exception of Lerwick, Scotland, export electricity to the National Grid. The total rated capacity for electricity export is 197 MW. Plants that do not export heat for district heating schemes, etc. have efficiencies in the range 20 to 25%.

Electricity production from current waste incinerators is less than 0.5% of total demand. If all MSW was incinerated then it could provide 5% of the UK electricity demand. This would be good if the incineration of waste produced less carbon dioxide per kilowatt-hour than the combustion of gas, oil or coal, but it does not.

Initial research work on the gasification of MSW was supported on the basis that it might offer fewer emissions and reduced environmental impact in comparison with mass burn incineration. Arguments that gasification might be a cleaner technology

than mass burn incineration are now not so strong, as both technologies can meet the stringent emission regulations when the appropriate flue-gas and waste water cleaning technologies are applied.

Gasification and pyrolysis

Gasification and mass burn face the same problems. They are both required to process similar waste streams with defined amounts of heavy metals, chlorine, sulphur and nitrates. In both cases, the heavy metals can form chlorides that can pass through simple filters as a vapour. Similarly, the acid gases hydrogen chloride and sulphur dioxide are formed in comparable amounts. For gasification, fuel-bound nitrogen is more likely to form ammonia or hydrogen cyanide than oxides of nitrogen; therefore, catalytic cracking might be necessary for treating the syngas.

In both cases, there is the potential for forming dioxins by de-novo synthesis. However, the production of dioxins is relative to oxygen concentration. In gasification – where oxygen concentrations in the cooling exhaust gases are very low – the production of dioxin is also very low. Dioxin emission in exhaust gases and its concentration in the gasification residues have proved to be below detectable limits for plants in Bergau and Varnamo.

The amount of gas that must be processed is significantly different for exhaust gas clean up in gasification compared with mass burn. Mass burn incineration installations need to clean between 5.2 and 6.6 m^3 of exhaust gases per kg of waste processed. As gas cleaning actually takes place at a temperature close to 200°C, the actual volume treated will be increased by 61% to a range between 8.4 and 10.6 m^3 per kg of waste.

Gasification plants tend to utilise RDF rather than raw waste. However, for a fair comparison, the production of gases should

The production of electricity from natural gas is a very clean technology. Unfortunately UK North Sea gas is likely to run out in the next 10 to 20 years, at which point the UK is expected to become dependent on imports from Norway and Russia.[44] It is likely that the UK will continue producing a fraction of its electricity from coal. It is therefore relevant to compare electricity production from MSW with electricity production of coal.

be referenced back to the amount of raw waste received by the RDF plant. For gasification with air, the amount of syngas that must be cleaned per kilogram of raw gas is about $1.1\,m^3$. Although this amount is just 20% of that from a mass burn incinerator it will contain roughly the same total quantity of acid gases and metal chlorides, albeit in a smaller volume of gas. A reduction of cleaning load is evident in the loading of the gas with high-melting-point particulates (for example, silicates and iron oxide).

As a consequence of the reduced volume of gas having similar concentrations of silica-based particulates, but a fivefold increase in the concentration of metal chlorides and acid gases, there will be some cost savings for the gas cleaning plant. This will not be a substantial saving because most of the cost is associated with the removal of heavy metals and acid gases rather than silica-based particulates. Significant savings can, however, be made if lime can be added to the feed before pyrolysis to remove hydrogen chloride and sulphur dioxide as they are formed and eliminate the need to scrub the syngas.

The important attraction of gasification compared with mass burn incineration is the opportunity for high-efficiency electricity generation. The more electricity that can be produced from waste, the less that needs to be produced from fossil fuels, resulting in lower greenhouse gas emissions. Increased efficiency of electricity production can also reduce operating costs.

The efficiency of electricity generation from mass burn incineration is typically 20 to 27%. This is very low compared with the efficiency of generation at large coal-fired power stations ($\approx$36%) or from natural gas at combined cycle gas turbine power stations (50 to 55%). An important argument in favour of gasification is that it can achieve high efficiencies.

If the goal of gasification is to produce electricity at the highest possible efficiency, then the gas needs to be burnt in a turbine.

The technologies used to burn syngas are modified gas turbines that were originally designed to burn natural gas. Considerable efficiency gains should be achievable with turbines designed specifically to burn low-calorific-value syngas. It is invariably necessary to clean syngas following production to reduce the hydrogen chloride levels; this has to be done at a temperature below 850°C. To ensure that very little of the original energy in the fuel is lost, the gas should be cooled in a boiler to provide steam for a turbine (or perhaps hot water for a heating system).

It is of interest to work out the total equivalent carbon dioxide emissions from treating waste in the UK by either gasification or mass burn incineration.

From Table 4 it is apparent that the carbon content of MSW by weight is about 30% and this is relatively independent of the amount of waste recycled. Thermal treatments where all the carbon is converted to carbon dioxide will therefore produce 44 g of carbon dioxide for every 12 g of carbon. Consequently, 1 t of MSW will produce 1.1 t of carbon dioxide. If all the 29 Mt of household waste produced

in England and Wales was incinerated or gasified with no carbon residue then 32 Mt of carbon dioxide would be produced. This amount would represent 1% of the current EU emission.

In order to get from total emission to effective emission the displaced emissions must be subtracted. Table 26 calculates the equivalent emissions for gasification and mass burn incineration with assumed efficiencies of electricity generation where the generation displaced is natural gas CCGT.

In comparing the Proler gasification process using oxygen with the TPS gasification process using air, it is clear the calorific value of the syngas is sensitive to the concentration of methane and higher hydrocarbons.

The gas from the TPS gasifier has a higher concentration of methane and other hydrocarbons. As this may be a function of the precise nature of the waste used, then a fair comparison between the two processes starting with the same waste feed would almost certainly yield a lower calorific value for the syngas from the air gasification process. Using oxygen for gasification offers no advantage, mainly because of its cost.

The SilvaGas steam gasification process offers a clever innovation in the way in which heat is carried from the combustor to the gasifier. Most of the heat required for gasification is carried by the fluidising medium (sand) that circulates through the combustor back to the gasifier. An important parameter for the control of temperature is the rate at which sand is recycled to the gasifier.

	Efficiency of generation	Moles CO_2 per kWh electricity	Total emission, Mt	Natural gas CCGT displaced emission, Mt	Effective emission, Mt CO_2
Gasification + CCGT	45%	17.8	32	16.2	15.8
Gasification + CCGT	40%	20.0	32	14.4	17.6
Mass burn	25%	32.0	32	9.0	23.0
Mass burn	20%	40.0	32	7.2	24.8

Table 26: Effective emissions for scenarios where all UK household waste is treated thermally.

If the UK abandoned landfill for household waste and chose gasification technology to treat waste and produce electricity at 40% efficiency in preference to mass burn incineration producing electricity at 25% efficiency, then the savings in carbon dioxide emissions would be 5.2 Mt. This figure should be compared with UK man-made carbon dioxide emissions of about 560 Mt. If the cost of gasification technology is significantly higher than mass burn technology, then it probably cannot be justified against the criteria of protection against climate change.

If air gasification of waste is to have an economic benefit over mass burn incineration, it will need to handle a much greater proportion of the organic content of the raw waste than is provided through the production of high-energy RDF pellets. It would also be necessary to increase the efficiency of electricity generation from the syngas from 40 to nearer 50%.

The main advantage of pyrolysis over other gasification processes and mass burn incineration is the enhanced recovery of metals. This process eliminates all the organic-based materials frequently found with metals – paper labels, plastic labels, corks, stoppers seals and gaskets, food residues, oils and greases. Additionally, the reducing atmosphere preserves metals in an unoxidised state, and high-value metals such as aluminium are recovered readily.

A second advantage of pyrolysis is that it does not enable the formation of dioxins because of the absence of oxygen and the use of temperatures above 400°C. The process is more limited with respect to the destruction of hazardous chemicals such as polychlorinated biphenyls than higher-temperature processes. This should not really be an issue as these hazardous chemicals should not be present in the MSW stream.

However, pyrolysis is probably less energy efficient than mass burn incineration and is likely to be a very expensive technology.

Final analysis

This study has presented the major advantage of gasification and pyrolysis technologies over mass burn incineration as offering the opportunity for high-efficiency electricity generation using CCGT. If gasification has a disadvantage against mass burn incineration, it is probably cost. CCGT plant is relatively expensive and needs regular maintenance to maintain high efficiency. Where anaerobic digestion is operated alongside gasification there is an opportunity to burn the biogas with the syngas from the gasifier in the same gas turbine. This practice would give considerable cost savings. Waste heat from the gas turbine can be used to preheat organic material to sterilise it and provide a thermal treatment for the cellulose and lignin content that assists subsequent digestion.

Whichever way waste is treated, it is likely to produce greenhouse gases. If organic waste is burnt or composted it will produce carbon dioxide. If organic waste is land filled, it will be digested anaerobically and release methane. For poorly managed landfill sites, most of the methane will escape to the atmosphere.

Recycling is a good technical solution but it is only economically viable for about 20 to 30% of MSW. Where recycling is not possible, the various disposal routes must be considered. The major disposal methods applied to MSW in the UK are landfill, mass burn incineration and composting. All these methods raise economic or environmental concerns, including

- landfill is becoming expensive and unpopular
- incineration of MSW provides sterilisation, reduces volume by 75 to 90%, weight by about 70 to 75%, but has solids and gaseous emission problems
- composting mixed waste contaminated with plastics and inorganic fragments containing heavy metals makes it unsuitable for spreading on arable or parkland.

It can be seen that there are no easy solutions to MSW disposal. At present, the most likely way forward is intelligent and sustainable recycling combined with well-managed landfill or thermal incineration. In either case, co-generation of electrical power and low-grade heat recovery are essential.

In future, gasification in fluidised bed systems to produce high-energy syngas is likely to become more cost-effective.

Transport costs versus the economy of scale

Transport costs and carbon dioxide emissions associated with local collection of waste are relatively independent of final treatment, be it landfill, mass burn incineration, mechanical biological treatment, etc. The important issue is whether or not it is better to transport waste over long distances to gain economy of scale for the operation of large thermal-treatment plants.

By current standards, a large thermal-treatment plant would have a capacity of 500,000 t/y, while a small plant would have a capacity of 50,000 t/y. Handling 30 Mt of MSW in the UK by thermal treatment would require about 60 large treatment plants or 600 smaller units. Taking the land area of England, Scotland and Wales as 143,124 km^2, then the average journey to take waste to one of 60 treatment plants would be 24 km as the crow flies. By road, the average round trip is likely to be about 64 km. On the same basis, the round trip for 600 small treatment plants would be 19 km. As this is the distance appropriate to local collection vehicles, no additional transport would be required for this scenario, except for removal of ash.

The option of 60 large treatment facilities would require articulated lorries to transport waste from local collection centres. The carbon dioxide emissions for such vehicles are about 1.35 kg of carbon dioxide per 1.6 km. This means that additional carbon dioxide emissions for utilising large waste-treatment facilities would be 2.7 kg carbon dioxide per tonne of MSW. This is trivial compared with the gross emissions of 1.1 t of carbon dioxide per tonne of MSW resulting from thermal conversion of its carbon content. The additional 2.7 kg of carbon dioxide emissions would easily be recovered by the smallest of efficiency gains arising from the economy of scale. The additional cost for transportation must be offset against capital savings and operating costs for one large plant against 10 small plants.

" IF ALL MSW WAS INCINERATED THEN IT COULD PROVIDE 5% OF THE UK ELECTRICITY DEMAND "

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