Programme Area: Bioenergy

Project: Energy From Waste

Title: Appendix C: Thermal Waste Material Conversion

Abstract:

This deliverable forms part of Deliverable 2.2 in Work Package 2 and provides information on the thermal waste material conversion rig scale testing.

Context:

The Energy from Waste project was instrumental in identifying the potential near-term value of demonstrating integrated advanced thermal (gasification) systems for energy from waste at the community scale. Coupled with our analysis of the wider energy system, which identified gasification of wastes and biomass as a scenario-resilient technology, the ETI decided to commission the Waste Gasification Demonstration project. Phase 1 of the Waste Gasification project commissioned three companies to produce FEED Studies and business plans for a waste gasification with gas clean up to power plant. The ETI is taking forward one of these designs to the demonstration stage - investing in a 1.5MWe plant near Wednesbury. More information on the project is available on the ETI website. The ETI is publishing the outputs from the Energy from Waste projects as background to the Waste Gasification project. However, these reports were written in 2011 and shouldn't be interpreted as the latest view of the energy from waste sector. Readers are encouraged to review the more recent insight papers published by the ETI, available here: http://www.eti.co.uk/insights

Appendix C

Thermal Waste Material Conversion Technology Test Report
Gasification and Pyrolysis

Table of Contents

Introduction to Thermochemical Tests

The test programme for the advanced thermal waste processing technologies as defined in report 2.1 of this project was designed to provide the following information:

- The impact of changing waste mixtures on the major outputs streams – gas, tars and solid residues
- Preliminary mass balance data to inform element partitioning in the modelling work
- The chemistries of the major output streams to assist analysis of ancillary plant requirements (e.g. gas cleaning) and to identify high risk issues in the areas of engine reliability, environmental emissions and residue disposal, and
- Experience with processing real waste mixtures to identify process and operational problems

The technology assessment identified four main generic thermal process technologies based on pyrolysis and gasification which could be suitable for the processing of wastes. Of the possible variants of these technologies, it was agreed to carry out testing for the following four options:

- Fixed bed 'slow' pyrolysis
- Fixed bed, air blown up-draft gasification
- Fluidised bed, air blown gasification
- Fixed bed, air blown down-draft gasification

As indicated earlier, there were several priorities for the testing programme, which inevitably meant that compromises had to be made if a good spread of the areas requiring information were to be investigated.

The derived test plan is summarised in Table 1. Each waste material combination was proposed to be tested in each of the process configurations described above.

Table 1 Thermochemical Tests

Test Number	Sample Combination	Ratio
0 (Commissioning)	Demolition Wood	
1	Demolition Wood & High Density Plastics	50/50
2	Demolition Wood & Textiles	50/50
3	Textiles & Low Density Plastics	50/50
4	Paper and Card & Food	50/50
5	Paper and Card & High Density Plastics	50/50

To better describe their physical attributes and to aid differentiation, subsequent to Deliverable 2.1 high density plastics were re-labelled "dense plastics" and low density plastics re-labelled as "film plastics," although no changes were made to the material types which are covered by each of these classifications. The only alteration that was made when the test plan was executed was that the dense plastic element of Demolition Wood & Dense Plastics mix was substituted for film plastics to better represent a mixed construction and demolition waste stream, which would comprise mainly these energy bearing materials.

Whilst every endeavour was made to stick to this test plan, for reasons described in the appropriate section, it was at times found necessary to modify the ratio of the materials to enable a successful test to be carried out. However, for all tests a full laboratory analysis was made of the feedstock, and so comprehensive input and output data sets were compiled for all tests. Indeed, where the material ratios were required to be modified, important lessons were learned from the need for this change which could form the basis of engineering development opportunities.

Gasification/Pyrolysis Facilities

All of the thermal tests conducted at Cranfield University were based on two multi-configurable reactors. The updraft reactor comprised a vertical reactor of 150mm internal diameter which could be operated with gas injection through its base for fixed bed and fluidised bed tests. Rather than being refractory lined, this reactor was electrically trace heated to offset thermal losses through the walls. This feature also allowed the reactor to be operated in a slow pyrolysis mode without the need for the introduction of heat through the combustion of a fuel and recycled tars (as in industrial units). The same rig configuration was used for fixed bed gasification tests, but with air injection as the gasifying agent. For fluidised bed operation, the base of the rig could be changed to a conical one with central air injection and ash offtake.

The downdraft rig was operated solely as a downdraft (fixed bed) gasification rig for this project; this used a grate (as opposed to throat) to support the fuel bed. For all tests, the rig instrumentation and sampling locations were maintained for each of the rigs during all tests. Figure 1 and Figure 2 provide schematic diagrams showing locations for the updraft and downdraft rigs respectively

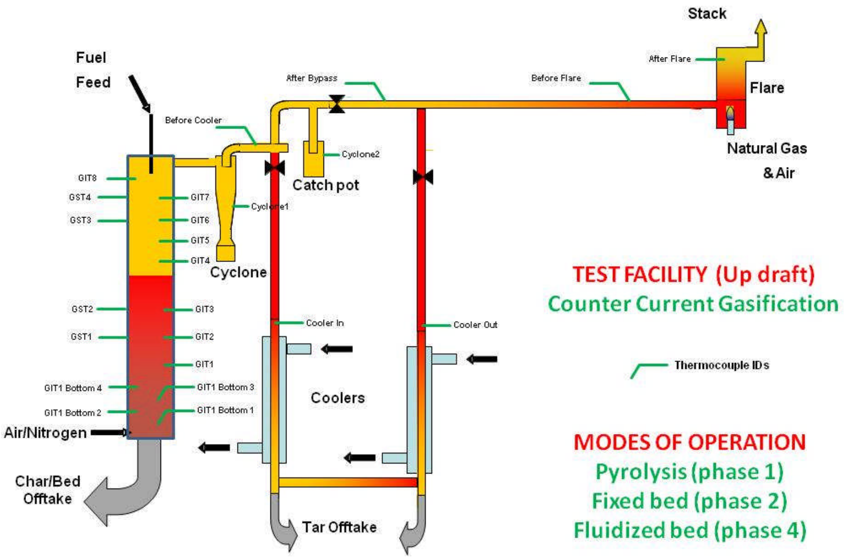

Figure 1 Schematic Diagram of Updraft Reactor for Fixed and Fluidised Bed Gasification and Fixed Bed Pyrolysis

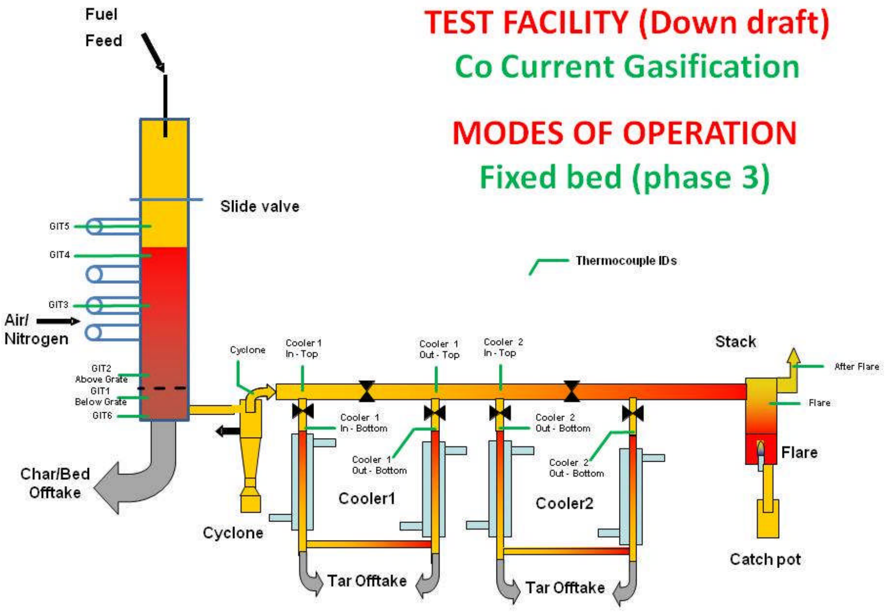

Figure 2 Schematic Diagram of Downdraft Gasifier

For the updraft rig, these are shown schematically in Figure 1 whilst for the downdraft rig these are shown schematically in Figure 2.

In general, the gasification reaction is based on the thermal degradation of the material in a reduced oxygen atmosphere, which prevents complete combustion. The gasification reaction therefore consists of two zones;

1. Combustion (lower zone)
2. Gas–solid back-mixed gasification (upper zone)

The carbon combustion reaction in the lower zone produces carbon dioxide and the heat necessary for the endothermic gasification reaction occurring above. The bi-product of the combustion reaction is ash, which is drained in the bed. The thermal reduction in the gasification zone provides the char for the lower combustion zone. All rate-controlling steam–carbon and hydrogen–carbon reactions occur in this gasification zone.

In a fixed bed gasifier, the oxygen (air) flows through the material, and thus comes into contact with the fixed bed of solid fuel particles. In a fluidised bed gasifier, the air (oxygen and nitrogen) acts to "fluidise" a bed of sand, which makes contact with the fluidised bed of waste fuels.

Pyrolysis occurs in the absence of any oxygen. In practice, the rate of the pyrolysis reaction determines the end products in terms of the relative volumes of gaseous and liquid (condensate) products, with rapid reactions ("fast pyrolysis") giving rise to higher volumes of condensate, and slower reactions, such as those examined in this project, allowing for the further thermal degradation of the liquid factions into volatile, gaseous elements.

Rig Operation

Due to the differences in rig design, different approaches were used to initiate the thermal reactions in the updraft and downdraft rigs. For the updraft rig, electrical trace heating was used to bring the reactor up to a temperature of 600-605 °C, at which temperature combustion was initiated in the fuel bed. For the fixed bed gasification test, which was batch-pre-loaded with feedstock, the trace heating was augmented with electrically heating of the incoming air flow. For the downdraft reactor, the incoming airflow was also electrically heated to a high enough temperature to initiate combustion. Industrial-scale reactors would likely initiate the combustion/gasification reactions using a different method, such as a gas burner using stored syngas.

For all project tests, when the bottom thermocouples showed 600-650°C, the gas medium (air or nitrogen depending on mode of operation) was switched on. For the fluidised bed reactor, the fuel feeding was also started at this point. In contrast, for the updraft gasification and pyrolysis tests, the 'single-batch' fuel beds were filled and sealed prior to turning on trace heating. Combustion of the fuel bed above this temperature was then used to bring the rig from the starting temperature of 600°C up to the working temperature of 800-850°C. Stable operation of the gasifier depends on maintaining the balance between combustion and gasification in the rig. Once the working (gasification) temperature range was achieved, the combustion-gasification reaction balance was maintained on the gasification side by increasing the fuel feed rate (for continuously fed FB and downdraft tests), or by replacing some of the air with nitrogen (for the updraft gasification batch tests), i.e. decreasing the air to fuel ratio. It is worth noting that the mode of operation for the slow pyrolysis tests was significantly different to that in an industrial unit as the whole process could be run using trace heating rather than needing the introduction of a hot combustion flue gas to drive the process. As a result, nitrogen was bled into the reactor to provide a flow to remove the pyrolysis products from the fuel bed. However, it is relatively straightforward to adapt the data generated from the pyrolysis by blending the gas compositions produced with a notional combustion exhaust gas to produce an approximation to that from an industrial unit.

Where possible, the gas coolers downstream of the cyclone in the hot gas path, were switched into the flow path when stable conditions were achieved. However, with the batch tests this was not possible and so the material collected represents the total for the whole period of operation.

A stable gasifier bed temperature was maintained by balancing the heat produced by the limited combustion with the energy used to heat and evaporate moisture from the fuel and energy required by endothermic gasification reactions. The balance between combustion and gasification was monitored using thermocouples in the gasifier bed and by measuring CO_2 and CO levels in the produced gas. If the balance shifted too far towards combustion, as would be the case with a fuel feed problem, the bed temperature rises and CO_2 levels increase while CO levels drop. The rise in temperature can occur rapidly and can be localised to one part of the bed, if the temperature goes high enough the bed can sinter. If the balance shifts too far towards gasification, then the temperature decreases and the CO level rises as CO_2 levels fall. These effects are shown schematically in following diagram (**Figure 3**). As most of the fuels tested in this project were representative of real heterogeneous mixed wastes, and hence with local non-uniform properties, periods of variable gas production were experienced intermittent to stable operation. Such variability in gas production and composition would also be expected if such technologies were to be applied at a commercial scale.

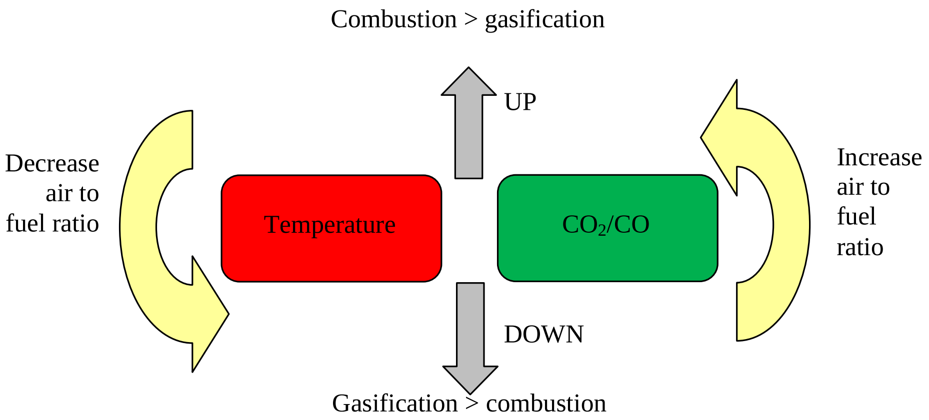

Figure 3 Schematic diagram for control of combustion and gasification

All rig operation and experimental procedures were carried out in accordance with Cranfield University's strict Safety Procedures and Standard Operating Proceedures as set out in Appendix A to this report.

Test Data Capture and Analysis

The major gases (CO, CO_2, H_2, and CH_4) were measured using thermal conductivity and infrared analyzers. The rest of the minor gases (contaminants) were measured using Draeger tubes as the ranges expected could not be known in advance of testing. Draeger tubes give a relatively crude measure of contaminant levels (within defined ranges) through a change in colour of the crystals they contain. This was not considered to be a problem in these scoping tests, as only approximate data were required from the non-optimised test conditions. It should also be recognised that the use of more accurate instrumental techniques would have been demanding in terms of efforts required, calibration and interpretation would have been more complex and so risked delaying the testing programme.

Sampling for all gas analysis was conducted at a bypass pipe between the exit of the Gasifier vessel and the flare. The sample flow diagram is shown in **Figure 4**. These gas concentration data were logged together with temperature data from each of the thermocouple by a computer. Levels of gas-bourn contaminants, notably ammonia and hydrogen sulphide (carbonyl sulphide was not measured separately) were measured directly by sampling from the fuel gas stream and also indirectly through measurement of their combustion products (mostly nitrogen oxides and sulphur oxides respectively), after the flare. Back calculation, assuming that all the ammonia and hydrogen sulphide were fully converted allowed a cross check on the levels of these important contaminants.

Intermittent analyzer calibration consisted of gases at two concentration points; zero gas flow and a span gas of known composition. Calibration drift and system bias checks were done twice during the tests.

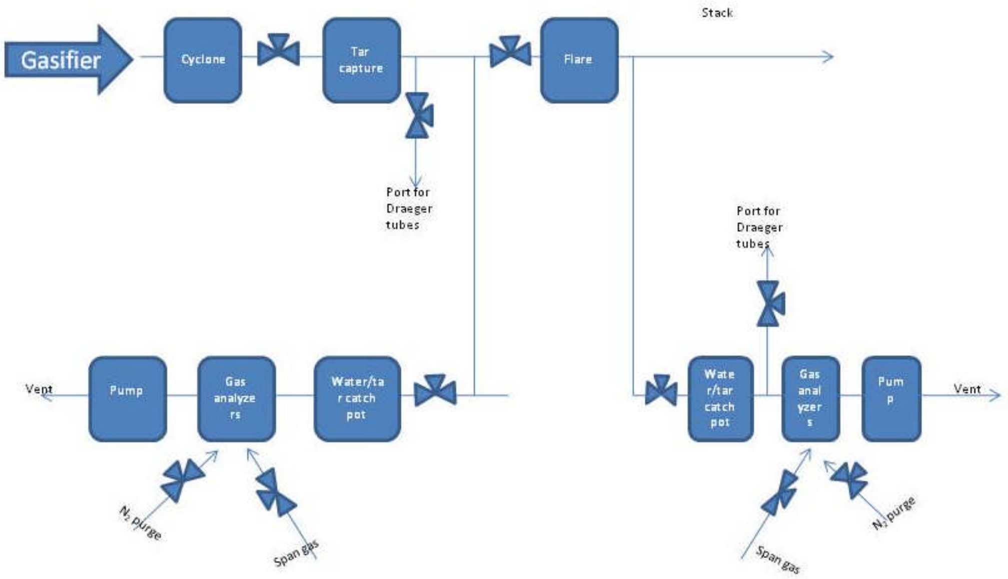

Figure 4 Sample route for both updraft and downdraft gasification

Gas samples were cooled by an ice bath and conditioned through a water bubbler to eliminate any possible interference (*i.e.* water vapour, tar and/or particulate matter) before being transported and injected into each analyzer.

The cooling apparatus and bubbler had to be constantly monitored and cleaned of tars between each tests to maintain gas sampling flow. Following each test the bubbler seemed to be coated with a black film on the surface. The explanation for the phenomena was caused by tars which were not condensed in the traps. This problem lends some uncertainty to the resulting tar concentration data, although the size of this impact would be very small and within experimental error for the tar measurements.

The solid residues from gasification (*i.e.* fly ash and bed ash) and liquid residue (*i.e.* tar) were collected after completion of each test run and recorded the weights. For both rigs the rig was allowed to cool overnight to allow easy and safe access to sample materials. Samples (Fuel, Ash (from char/bed off-take), Cyclone dust, Tar (pot 1), Tar (pot 2)) taken from each analysis point (ref Figure 1 and Figure 2) were stored in suitable containers prior to being sent to a registered third party laboratory for analysis. The ash and tar samples were sent with the mixed fuel used for each test trial.

Instrumentation and Sensitivity Ranges

The major gases (CO, CO_2, H_2, and CH_4) were measured using thermal conductivity and infrared analyzers as outlined below. The rest of the minor gases (contaminants) were measured using Draeger tubes, which are crystal filled tubes through which the gas is drawn, where a change in colour of the crystals illustrates the measured gas species concentration. Whilst a rapid and low cost measurement technique, which suited the project requirements, Draeger tube measurements are limited in accuracy due to the potential for gas contaminants (tars) to block the tube passages.

Table 2 Specification and Limitation of the Analyzers Used at Cranfield University

Analyzer	Measured Component	Measuring range Volume% (input)	Upgraded measuring range Volume % (input)	Interaction with other species
Ultramat 2	CO_2	0-22 (4-20 mA)	0-22 (4-20 mA)	-
	CO	0-16 (4-20 mA)	0-24 (4-20 mA)	-
	CH4	0-10 (4-20 mA)	0-18 (4-20 mA)	-
Ultramat 6	H_2	0-100 (4-20 mA)	0-100 (4-20 mA)	CO -0.11%
				CO2 -1.07%
				CH4 +1.59%
MGA 3000	SO_2	0-1000ppm (4-20 mA)	-	-
	CO_2	0-10 (4-20mA)	-	-
	CO	0-1000ppm (4-20 mA)	-	-
	O_2	0-25 (4-20mA)	-	-

The gas composition measurement analyser used throughout these experiments are summarised in Table 3.

The measurement of the H_2 concentration in gases is through measurement of the thermal conductivity of the gas. However, the thermal conductivity of hydrogen has a nonlinear response to interference by gas mixtures. The relevant interactions with other species measured during the tests are shown in the right hand column of Table 2. Ambiguous results can occur in certain concentration ranges; in addition to the zero offset, the gradient of the characteristics can also be influenced by the interfering gas, although this effect is negligible for most gases. Despite correction for the interfering gas, the multi-component nature of the measured gases results in the introduction of measurement errors greater than would be the case with binary gas mixtures. The resulting error, depending on the fuel and gas composition, can be up to 2% of the smallest measuring range of the respective application.

Test Conditions

The testing at Cranfield University was performed in five phases. The first four phases are based on four technologies for five different fuel mixtures on each phase. The fifth phase covered the food fuel mixed with paper and card. The waste fuels used in the programme and mixed proportion are summarized in

Table 1. Table 3 shows the tests completed for four phases which covers the fuel, date at which the tests were performed along with test number.

In the nature of any experimental work which is novel and has not been previously attempted, not every test carried out was successful at the first attempt. This was particularly the case for the thermochemical tests carried out at Cranfield University, which were the first attempted using non-biological waste materials. Issues encountered which led to unsuccessful tests include establishing the appropriate air flow rates and ignition temperatures for the materials and their mixes. A complete list of all the thermochemical tests carried out is presented in Table 3. Where tests were unsuccessful ("fail"), the test was repeated at an appropriate juncture until a successful test ("pass" – highlighted in green) was completed. The results presented below are based on these successful tests only.

Table 3 Thermochemical Rig Tests Carried Out at Cranfield University

Test	Date	Rig	Fuel	Success
1	05/02/2010	Updraft Gasification	Demolition wood	Fail
2	09/02/2010	Updraft Gasification	Demolition wood & textiles	Fail
3	12/02/2010	Updraft Gasification	Paper card & dense plastics	Pass
4	16/02/2010	Updraft Pyrolysis	Demolition wood	Pass
5	18/02/2010	Updraft Pyrolysis	Paper card & dense plastics	Pass
6	23/02/2010	Updraft Pyrolysis	Textiles & film plastics	Pass
7	26/02/2010	Updraft Pyrolysis	Demolition wood & textiles	Pass
8	04/03/2010	Updraft Pyrolysis	Demolition wood & film plastics	Pass
9	08/03/2010	Updraft Gasification	Demolition wood & film plastics	Fail
10	11/03/2010	Updraft Gasification	Demolition wood & film plastics	Fail
11	12/03/2010	Updraft Gasification	Textiles & film plastics	Fail
12A	16/03/2010	Updraft Gasification	Textiles & film plastics	Fail
13	18/03/2010	Updraft Gasification	Demolition wood & film plastics	Pass
14	24/03/2010	Updraft Gasification	Demolition wood & textiles	Pass
15	25/03/2010	Updraft Gasification	Demolition wood	Pass
12	29/03/2010	Updraft Gasification	Textiles & film plastics	Pass
D1	07/04/2010	Downdraft Gasification	Demolition wood & film plastics	Pass
D2	09/04/2010	Downdraft Gasification	Demolition wood	Pass
D3	13/04/2010	Downdraft Gasification	Demolition wood & textiles	Fail
D4	14/04/2010	Downdraft Gasification	Textiles & film plastics	Pass
D5	15/04/2010	Downdraft Gasification	Paper and card & dense plastics	Pass
D6	19/04/2010	Downdraft Gasification	Demolition Wood & Textiles*	Pass
F1	07/05/2010	Fluidised Bed Gasification	Demolition Wood	Pass
F2	10/05/2010	Fluidised Bed Gasification	Demolition Wood & film plastics	Pass
F3	11/05/2010	Fluidised Bed Gasification	Paper and Card & dense plastics	Pass
F4	12/05/2010	Fluidised Bed Gasification	Textiles & film plastics*	Pass
F5	13/05/2010	Fluidised Bed Gasification	Demolition Wood & Textiles*	Pass
FF1	20/05/2010	Fluidised Bed Gasification	Paper and Card & Food	Pass
DF1	21/05/2010	Downdraft Gasification	Paper and Card & Food	Pass
PF1	25/05/2010	Updraft Pyrolysis	Paper and Card & Food	Pass
UF1	26/05/2010	Updraft Gasification	Paper and Card & Food	Pass

*(75% / 25%)

The majority of the tests were considered stable based on the following criteria:
Temperature and gas composition data were reasonable smooth without any drifts
Time period was at least 20 mins
The sum of CO and H2 were similar or larger than the CO2 composition during the stable period
Coolers were operated during that stable period

Tests which did not fit these criteria were considered to have failed and were repeated at the earliest opportunity. However, this does not imply that the subsequent results from sample analyses and other measurements would also be considered acceptable. As the results from these analyses of the feedstocks and residues were carried out carried out post-test, there could be no guarantee of being able to obtain acceptable mass balances in all cases. Given the nature of the testing programme, this significant risk was accepted as unavoidable and no allowance was made to repeat such tests at a later date. In making this point, it is also necessary to reflect that there was limited scope for process optimisation in the test programme, and so the data from even the good mass balances should only be considered preliminary.

The ultimate and proximate analysis of the waste fuels/mixes and relevant analyses from the process samples from the tests are provided in the appendix. Of real significance to the outputs from the thermal process testing, and their value in achieving the expectations identified in the Introduction, is the unexpected variability between batches of the wastes provided for testing which make comparisons of test outputs difficult. The situation turned out as follows:

- Three batches of demolition wood were collected from different sites during the testing programme. The first batch was used for pyrolysis, the second for updraft gasification and the final batch for downdraft and fluidised bed tests.
- Two batches of textiles were collected. The first batch contained large amounts of carpet waste which was used for in the pyrolysis and updraft gasification tests. Due to handling and feeding problems with this material for the subsequent continuously-fed tests, a further batch was collected from a different site with no carpet material. The second batch of textiles was used for downdraft and fluidised bed tests.
- Only single batches of film plastics and dense plastics were collected and used in the tests. These were baled plastics which were separated by Shanks (at their Elstow Recycling Centre). These did not contain PVC which had been removed for recycling.
- One batch of paper and card was collected from Shanks, Kettering recycling site. Initially this was shredded at Cranfield and used for pyrolysis and updraft gasification tests. Further material was shredded using a facility in York for use in the downdraft and fluidised bed tests.
- One batch of food waste was collected from Linpac, Crewe. Firstly, this was separated from packaging debris and was broken down to small pieces. These smaller pieces were dried for several days at 50 °C in order to eliminate most of their moisture prior to testing.

The variations in composition between the different batches of waste can be observed in the results tables given in subsequent sections of this report and in the more detailed information provided in the appendix. Although this variability in the raw feedstock makes direct comparison of the results more difficult, it is a direct reflection of the “real-world” variability of waste streams in terms of specific material composition, and was therefore a desired element of the testing to indicate technology “robustness” in response to this variability.

As indicated earlier, the focus was on obtaining the following information:

- Chemical composition and fuel-related data on the available separated waste feedstocks

- A preliminary partitioning of the chemical components of the feedstocks in the thermal processes between the product phases, i) fuel gases (H_2, CO, etc.), ii) tars, iii) water, and iv) solid residues, from which to be able to estimate the likely blend of products arising from any identified mixture of the feedstocks, i.e. a real waste stream or a stream blended on the basis of the available feedstocks in any selected location.
- Preliminary analyses of the tars and solid residues to assist in a review of their subsequent further processing aimed at maximising energy production
- Preliminary operating experiences and other observations which could impact on future opportunities for the use of the waste feedstocks.

Because of the preliminary nature of the testing, none of the operating conditions were optimised to obtain any particular outcome in terms of the balance of the products or their compositions, nor would this have been appropriate at this stage as the waste feedstocks would not be used as tested in a real plant where the mixtures of wastes would comprise all of the components in varying proportions rather than the binary mixtures used in the tests. Such optimisation is essential before any technology demonstration should be developed to ensure that the system components are correctly sized and designed.

The results from the thermal process testing in each of the rigs are described in detail in an appendix to this summary report. In the appendix, results are presented in groups based on feedstock mixes, allowing some comparison of the technology process in the conversion of each mixture. An example set of data for the tests using demolition wood are included in this summary report by way of illustration. Processed mass balances are described in detail in the appendix, showing the destination of each of the main elements present in the feedstock material. The mass balances assume that the total mass of gas, tar, bed residue and ash plus the remaining N_2 (in the air or pure N_2 introduced into the rig to help the gasification process) is equivalent to the fuel mass consumed plus the mass of air used during the test. Each of the output streams also contains other elements which have not been measured, and so the extent of mass balance 'closure' varied between the tests as a result of these losses, errors in chemical analysis and related measurements as well as discrepancies between the chemistry of the waste mixes fed in the tests and the samples analysed (even though all sampling procedures were strictly adhered to, there is always a risk in sampling heterogeneous mixtures of materials where the particle size range is wide as the inclusion of a single large particle from one component could make the mix in the sample taken unrepresentative of the original waste mix).

The gas composition measurements shown for each of the feedstock materials are based on the species which were actively measured during the tests. These species are the reactive components of the gas, and hence the species of interest in the use of the gas to fuel an engine. The majority of the balance of the gas composition will be nitrogen, which is inert and hence the ~78% present in the air (and 100% in the pyrolysis tests where pure nitrogen was used) will not have taken part in the reactions. The remaining gas will have comprised of a range of unmeasured species.

The mass balance results are presented graphically for each feedstock and each technology rig, normalised to 100% to facilitate comparison. Data are presented in the raw form in the attached appendix. These graphs show the sum of the main measured elements of Carbon (C), Hydrogen (H), Nitrogen (N) and Oxygen (O) as they occur proportionally in the gas, cyclone ash, tar, water and the remaining bed residue in relation to their occurrence in the feedstock. A summary of key process parameters are provided later in this section of the report following the details for each waste mix.

Fuel preparation

One of the most valuable aspects of this project has been the lessons learnt in using real waste materials in the tests. For these tests to have been carried out, discarded materials were sourced from Shanks waste transfer sites and were pre-processed to a suitable physical form. This pre-processing step and the subsequent feeding to the reactors revealed important learnings which are also highly applicable to commercial energy from waste systems. These pre-processing problems and their solutions developed during this project are documented below. These issues may also form the basis for further technology engineering developments to enable more reliable and robust end to end systems to be developed, resulting in the ability to process a wider range of wastes and a lower final cost of generated energy.

The carrying out of the testing using real waste materials, as collected from waste transfer sites, has presented a unique insight into the preparation and use of these materials for energy conversion. Whilst some of these insights are limited to the experimental nature and scale of the work carried out for this project, others have commercial applicability. The most valuable insights have been gained where the use of these materials has led to challenges for which solutions are not readily available. Whilst this has led to some frustration in the testing to tight deadlines, their occurrence and solution present potential technology engineering development opportunities for the creation of more robust, reliable and waste-capable systems.

Waste Size Reduction

The preparation of the material into a suitable form for use as a fuel in the technology test rigs proved to be a challenge for some materials. Demolition wood proved to be an easy material to process into chips for use in the thermochemical rigs. This was especially so for the majority of this material, which was collected in a chipped form directly from the Shanks site. However, during the project Shanks stopped accepting and processing wood waste at their Kettering facility, and un-chipped wood was collected in the form of pallets from another source. The use of a standard chipper was used to process these pallets into chips. Similarly, Paper and Card was found to be easy to shred, and Cranfield’s grinder was found to process the material suitably. On the contrary, the processing of film plastics and textiles proved to be particularly troublesome. Based on Cranfield’s experience with other fibrous materials, it was not deemed of use to attempt to process the textiles (a random mix of cotton, denim, mixed fibre carpets, and other natural and man-made textiles (shirts, trousers, jackets etc)) using the available equipment as the materials would tangle themselves around the blades, leading to equipment failure. In absence of any other equipment, the first batch of textiles for testing was processed using scissors and Stanley knives, taking the equivalent of 6 man hours to process 5kg of material. Film plastics, such as wrapping materials, were found to be the most difficult to pre-process as it could not be processed manually, due to the tangling nature of the material, making the use of scissors or other such tools impossible. Subsequent to this initial manual preparation, it was clear that an automated shredding system was required to be found. Following an internet search and identification of potential suitable technology suppliers, contact was made with Riverside Waste Machinery, the UK distributer for Untha shredders. Riverside agreed to shred an initial batch of film plastics, dense plastics and textiles free of charge. These shredding tests proved to be highly successfully for all of the materials, and an additional demonstration was given of the machine capability to also shred wood. Further shredding of all of the materials required for the testing was carried out by Riverside at a fee, although it was felt by Cranfield that the testing could not have been completed without the use of such a shredder. Following the initial successful shredding of textiles using a screen with 25 mm holes (resulting in a nominal particle size of 25 mm), a subsequent attempt was made to shred these materials but with a screen with holes of 10 mm. Whilst the shredding of the material to this size was not found to be an issue, it was found when using the materials that they were rather “fluffy” and light for feeding and packing into the gasification reactors. The food waste was not attempted to be shredded at Riverside as this was prepared in small batches for each appropriate test to prevent decomposition of the material. However, the food waste did prove to be difficult to shred; an initial attempt was made using a garden shredder, followed by an attempt to use an industrial shredder located at the Open University in Milton Keynes. However, neither of these machines were able to suitably process the foodstuffs, and as a final resort the material was manually cut into small pieces using knives and scissors. Whilst foodstuff materials were not found to be difficult to process manually on their own, the inclusion of packaging in the raw food waste stream made presented the greatest challenge. The film nature of the majority of food packaging meant that, within the confines of the project, this packaging also had to be manually removed. However, for commercial applications a wide range of food de-packaging equipment is commercially available.

Fuel Feeding

Following the preparation of the feedstock materials into a form which was suitable as a fuel, this fuel had to be fed into the rigs. For the fixed bed updraft gasification and pyrolysis rigs, the fuel was inserted as batches into the rigs prior to the external heat supply. For the other thermochemical rigs, fuel feeding was carried out in a continuous process. These continuous feeding mechanisms were found to cause several operational difficulties in relation to some of the test materials.

When pre-processed using a screen with holes of 25mm, long strands (~200mm) of both the dense and film plastics were produced by the shredder. These were found to cause some blocking in the screw feed, due to the pitch of the screw being shorter than these strands. For this material, long strands were manually cut into shorter lengths prior to feeding. However, for commercial systems the transport distances as well as material feed rate would be considerably higher than for these tests, requiring a much larger screw. As the plastic strands would not scale in length, this blockage is not thought likely to occur in commercial scale plants.

Even when unpackaged, some issues with the feeding of food wastes into the thermochemical reactors were experienced. The main issue was that the dry and brittle food was being compressed in the screw feeder, causing it to disintegrate and block the screw. This problem was exacerbated where the dried food was mixed with other elements which were not bone dry (but less than 10% moisture content), which formed a “mush” under compression, which combined with the disintegrated material was thick and gloopy, and hence let to blockages of the feed system. This was remedied by using only the bone dry food and the fitment of a vibratory device to the screw feeder housing which prevented the settling and blockage of the small food particles.

Fuel Bridging

During the testing at Cranfield, the issue of bridging of feedstock material was experienced for both continuously fed rigs (downdraft and fluidised bed gasification). Both of these technologies are top fed, and rely on gravity to allow the metered feed to fall to the gasification zone at the base of the reactor. Bridging occurs in top fed technologies when material adheres to the side of the rig. The adhered material acts as a settling point for more material, which in turn collects yet more material. Furthermore, the arched nature of the stacked material forces stronger adhesion to the reactor sides, preventing collapse. Material continues to collect until the entire opening is blocked and no feedstock material is able to fall through to the gasification zone. Bridging is influenced by the feedstock particle size, shape (interlocking forms) and moisture content ("stickiness"). Feedstock bridging is a widely reported problem for top fed reactors at all scales.

Test Results

Demolition Wood

Initial tests were planned to carried out for each technology rig using an unmixed waste material similar to materials with which Cranfield University had previous experience of operating the rigs. To satisfy this purpose whilst using a genuinely abundant waste material, demolition wood (waste wood arising in the Construction and Demolition stream from the demolition of buildings) was selected. This comprised a mixture of wood types and previous treatments (painting, protection etc). Each of these tests was deemed to be successful when at least 30 minutes of stable output gas composition was achieved. A proximate and ultimate analysis of the feedstock used for each test is presented in **Table 4**. Due to each test being carried out on a different days, with different batches of collected waste material, each test feedstock is shown individually. The variation in feedstock, even for nominally identical materials shows the natural variability in waste materials, as further detailed in Work Package 1 of this project. The major measured gas species for each technology rig is shown in **Figure 6** whilst the concentration levels of contaminants are shown in **Figure 7**. The presence of nitrogen, coming from air as gasifying agent, reduces the concentrations of the active components in the produced gas, and dilutes the gas produced by the gasification technologies, leading to a lower calorific value for the produced gas. Pure nitrogen was used to carry out the gas from the rig, and this nitrogen was compensated for in determining the gas calorific values. For the pyrolysis test with Demolition Wood the Chloride species (HCl) was found to be difficult to measure using the Draeger tube due to a blockage in the tube.

Table 4 Proximate Analysis and Ultimate Analysis - Demolition Wood

Test Parameter	Pyrolysis	Updraft	Downdraft	Fluidised Bed
Total Moisture %	6.2	3.2	8.5	9.8
Ash %	2.4	1.6	8.5	9
Volatile Matter %	76.1	79.9	76.5	74.2
Sulphur %	0.04	0.04	0.1	0.1
Chlorine %	0.03	0.03	0.1	0.1
Gross Calorific Value kJ/kg	18935	19489	14337	14002
Net Calorific Value kJ/kg	17614	18192	13045	12749
Carbon %	46.84	48.4	43.2	40.3
Hydrogen %	5.39	5.71	5.9	5.7
Nitrogen %	0.58	0.55	0.8	0.8

Oxygen %	38.5	40.5	50.0	53.1

Figure 5 Microphotograph of the Demolition Wood

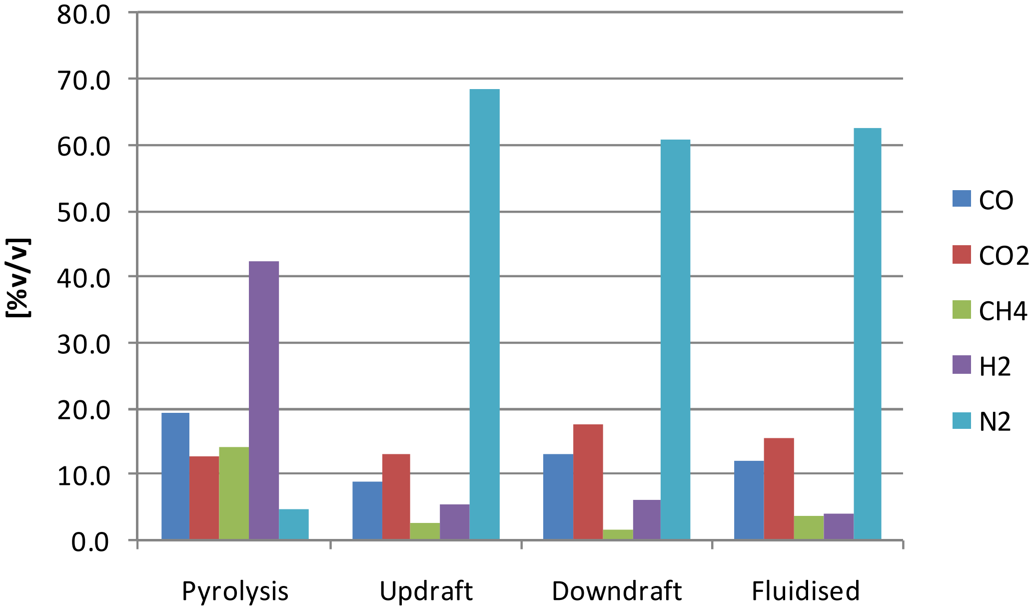

Figure 6 Major Gas Species for Demolition Wood for Thermochemical Tests

Figure 7 shows two sets of data ammonia and H_2S. The first values given, NH3 (ppm) and H_2S (ppm), come from Draeger tube measurements from samples of extracted fuel gas and are expected to be of limited accuracy, due to the nature of the Draeger tube approach.

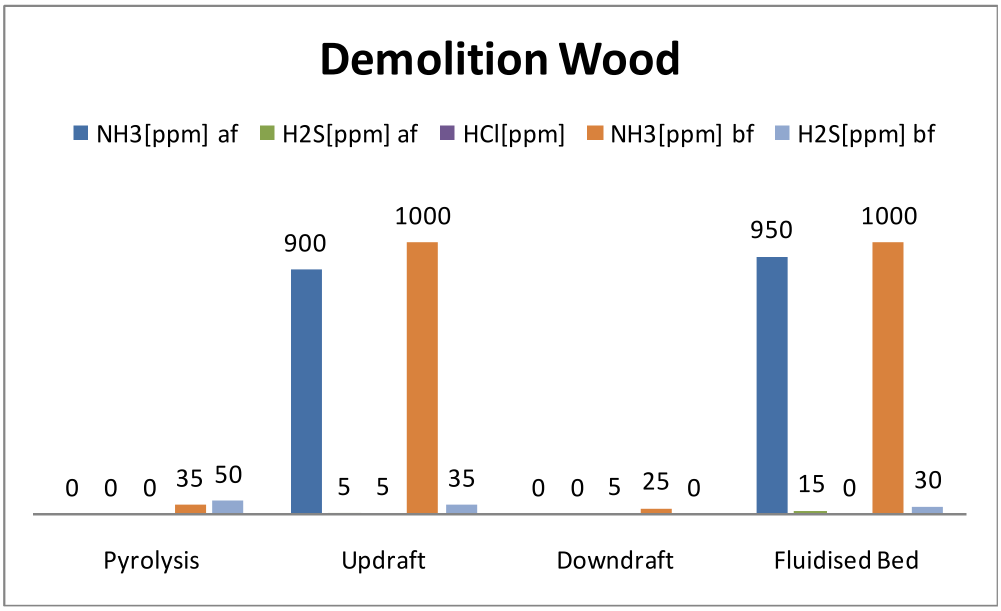

Figure 7 Minor Gas Species for Demolition Wood for Thermochemical Tests

In order to provide some confirmation of the values, NO_x and SO_x concentrations were measured after the fuel gas had been flared; the corresponding values for ammonia and H_2S which would have existed in the fuel gas to give the measures NO_x and SO_x values are reported as NH3(ppm)bf and H2S (ppm)bf respectively.

In the following tables (Table 6, 7, and 8), post analysis results of Bed Residues, Metals content in cyclone ash, and tar content are shown for Demolition Wood for each technology.

Table 5 Bed Residues Analysis for Demolition Wood for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
PAHs	mg/Kg	3.7	1	3.2	2.6
Carbon	% w/w	46.9	10.9	43.8	43.6
Na2O	%w/w	0.7	3.1	0.4	2
K2O	%w/w	1.4	3.5	3	2.4
SiO2	%w/w	0.2	0.2	0.2	0.2
Al2O3	%w/w	2.1	5.2	2.8	4.6
Fe2O3		3	6.1	2.5	3.9
Ash Fusion (Reducing) Temperature					
Initial Deformation	°C	1140	1160	1160	1170
Softening	°C	1230	1220	1250	1220
Hemisphere	°C	1240	1230	1260	1220
Flow	°C	1260	1250	1270	1220

Table 6 Cyclone Analysis – Metals for Demolition Wood for Thermochemical Tests

		Pyrolysis	Updraft gasification	Downdraft gasification	Fluidised Bed gasification
Arsenic	mg/litre	234	200	165	34
Cadmium	mg/litre	7.9	7.1	12.4	4.8
Chromium	mg/litre	2189	1213	1980	897
Cobalt	mg/litre	15	25	28	20
Copper	mg/litre	367	437	435	233
Lead	mg/litre	2234	1288	1327	915
Manganese	mg/litre	2233	1300	1658	546
Mercury	mg/litre	<0.1	0.1	<0.1	<0.1
Nickel	mg/litre	888	3428	3278	518
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	6.2	0.4	1.5	11
Zinc	mg/litre	2998	1970	2176	1437

Table 7 Tar Analysis for Demolition Wood for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
SVOC-Top 10 Compounds					
Phenol	mg/litre	1230	1216	1015	967
2-Methylphenol	mg/litre	554	1003	910	616
Naphthalene	mg/litre	443	490	456	434
Nitrobenzene	mg/litre	613	170	657	327
4-Methylphenol;	mg/litre	176	89	324	166
2-Methylnaphthalene	mg/litre	114	126	127	87
2,4-Dimethylphenol	mg/litre	99	97	135	225
Phenanthrene	mg/litre	312	115	98	138
Fluorene	mg/litre	89	115	115	115
Anthracene	mg/litre	21	32	76	68
VOC-Top 10 Compounds					
Benzene	mg/litre	125	121	68	143
Toluene	mg/litre	116	76	132	127
Ethylbenzene	mg/litre	21	45	43	54
m and p Xylene	mg/litre	34	15	22	19
o-Xylene	mg/litre	13	11	8	2.7
Styrene	mg/litre	25	21	6	5.7
Isopropylbenzene	mg/litre	3	1	0.7	1.8
Propylbenzene	mg/litre	1	<0.5	<0..5	0.7
1,2,3-Trimethylbenzene	mg/litre	2	2	0.7	<0..5
1,2,4-Trimethylbenzene	mg/litre	<0..5	0.6	2	0.8
Metals					
Arsenic	mg/litre	1	0.9	1.2	5.7
Cadmium	mg/litre	0.3	0.2	0.2	0.5
Chromium	mg/litre	0.2	0.2	0.1	12.5
Cobalt	mg/litre	<0.1	0.2	0.1	7.7
Copper	mg/litre	0.9	0.5	1.5	23
Lead	mg/litre	5.1	2.4	5	45
Manganese	mg/litre	22.1	15.1	8.6	70
Mercury	mg/litre	0.2	0.1	0.2	<0.1
Nickel	mg/litre	1	0.3	1.6	7.3
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	<0.1	<0.1	<0.1	7.1
Zinc	mg/litre	5.9	12.2	7.4	87
Calorific Value and Moisture					
Gross CV	KJ/Kg	14787	12243	14287	12911
Net CV	KJ/Kg	13750	11377	13255	12000
Moisture	% w/w	49.8	58.4	52.8	59.7

The mass balance periods shown in Table 8 indicate relatively long stable thermal decomposition duration achieved with the batch rigs compared to the other fuels. Graphically, Figure 8 shows high tar levels for this fuel in comparison to the other testes fuel mixtures. This may be due to the complex chemical structure of wood, where this complex microstructure is only slowly broken down into its constituent elements by the thermal energy. Furthermore, the time limited nature of these reactions (as metered by the gas flow rate) only allows for the partial decomposition of the material structure, resulting in the production of larger element "clumps", which report in the form of tars in the output products.

In a similar manner as for the presentation of test results for the different waste feedsctocks as set out in the subsequent sections of this report, Table 8 shows operational conditions and mass balance for Demolition Wood for each technology. This table includes an "Other" category to account for those species that it has not be possible to measure during the tests such as some light hydrocarbons, losses and deposits inside the rig etc. which account for the remaining mass balance. Figure 6 shows the proportion of the products for each technology, where the missing part of the mass balance is due to the category "Other".

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Table 8 Mass Balances for Thermochemical Tests with Demolition Wood

Pyrolysis	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	46.84						5.39						0.58						38.5						0.04			[% w/w]	540
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period [min]
																												77.4	80
	0.1405	0	0.1044	0.4108	0	0.0029	0.011	0.02	0.0251	0.0005	0	0.0195	0.0031	0	0	0.0005	0	0.005	0.0217	0.1556	0.118	0.076	0	0.1696	1E-05	0.0005	0.0001		
Updraft Gasification	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	48.4						5.71						0.55						40.5						0.04			[% w/w]	620
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												71.5	70
	0.0942	0	0.671	0.0748	0.0022	0.7164	0.008	0.018	0.0487	0.0002	0	0.1091	0.0006	0	0	0.0001	0	0.017	0.0132	0.1444	1.25	0.0492	0	0	1E-05	0.0001	0.0012		
FB Gasification	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	40.3						2						0.8						56.8						0.1			[% w/w]	730
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												97.6	30
	0.0592	0	0.885	0.0211	0.0214	0.0207	0.005	0.012	0.0704	0.0001	0	0.0552	0.0008	0	0	0	0	0.019	0.0082	0.096	1.219	0.004	0	0	3E-05	0.00003	0.0024		
Downdraft Gasification	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	43.2						1.3						0.8						54.6						0.1			[% w/w]	850
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												91.5	30
	0.1439	0	1.0945	0.0429	0.0123	0.0973	0.012	0.023	0.0728	0.0001	0	0.0825	0.0033	0	0	0.0001	0	0.022	0.0237	0.1814	1.712	0.0081	0	0	0.0001	0.0001	0.0032		

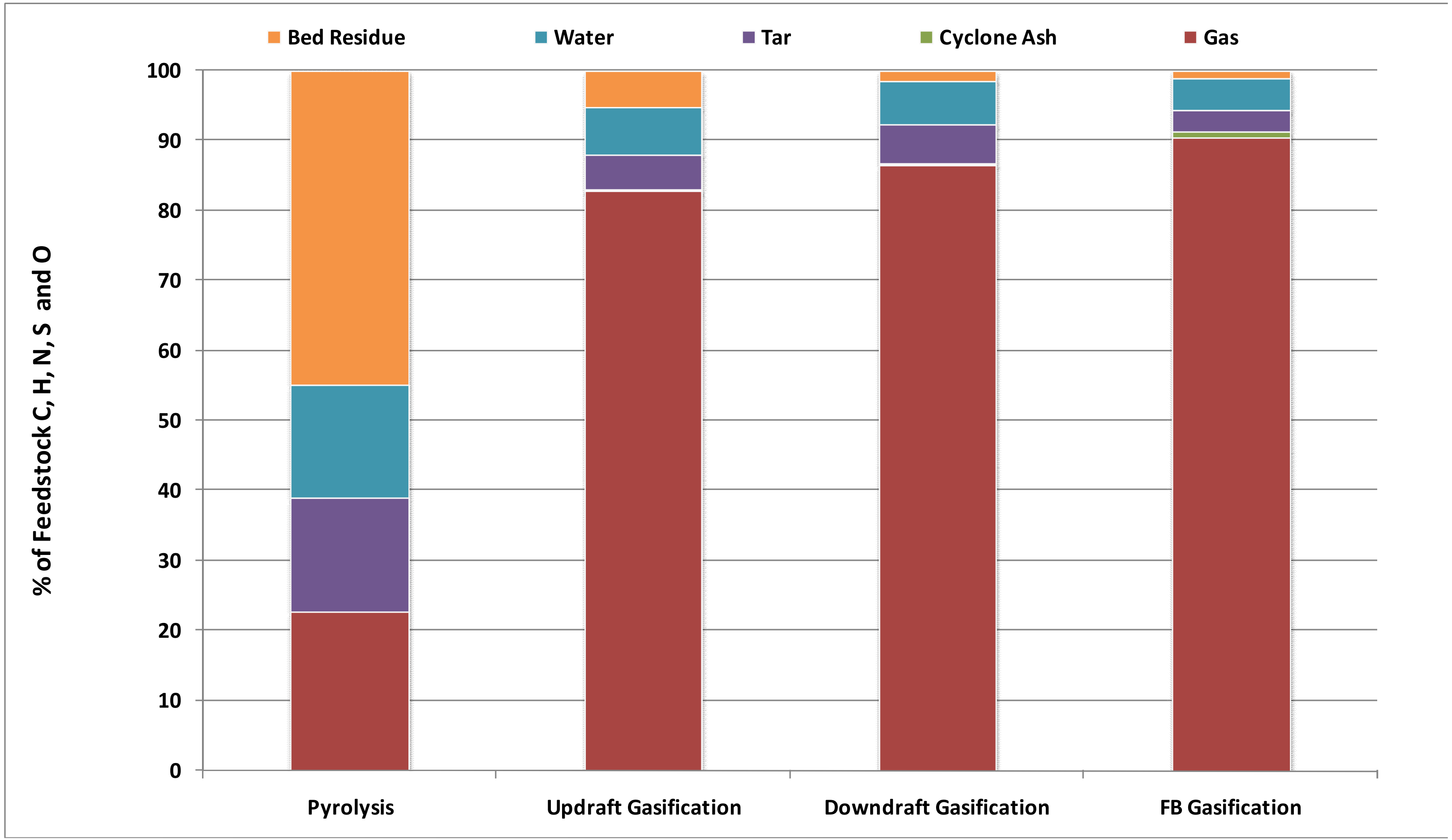

Figure 8 Proportion of Products (by weight) for Thermochemical Tests with Demolition Wood Normalised to Measured Components

Demolition Wood & Textiles

The tests using Demolition Wood and Textile mixtures were deemed to be successful when 20 minutes of stable gas composition were measured. This is a shorter duration than for the Demolition Wood only tests due to the higher reduction rate of the textiles. Issues in feeding this material were also experienced in the continuously fed rigs (downdraft and fluidised bed gasification), which was resolved by increasing the textiles proportion to 75%. This change in proportion is accounted for in the mass balance in **Table 13** due to measurement of the actual fuel composition as presented in **Table 9**, but would be expected to impact the gas composition results in **Figure 10**. Interestingly, the pyrolysis test using this material mix favoured high levels of hydrogen compared to other technologies, possibly due to the more complete breakdown of polymeric fibres present in the textiles, although the reason for this is currently unknown. As for the Demolition Wood tests, blockage was found to occur in the Draeger tubes when measuring the HCl content, and so care should be taken in interpreting these results in **Figure 11**. **Figure 12** shows a high tar loading for the outputs generated from these feedstocks, likely to be due to both the high tar loading from the wood, and a similar complex structure of some textiles contributing to only partially broken down compounds.

Table 9 Proximate Analysis and Ultimate Analysis - Demolition Wood and Textiles

Test Parameter	Pyrolysis	Updraft	Downdraft	Fluidised Bed
Total Moisture %	2.1	8.2	8	3.9
Ash %	5.5	9.3	8.1	4.1
Volatile Matter %	78.2	75.1	76.6	84.6
Sulphur %	0.37	0.1	<0.1	<0.1
Chlorine %	0.05	<0.1	0.3	0.2
Gross Calorific Value kJ/kg	21867	14220	13998	15223
DAF Calorific Value kJ/kg	23670			
Net Calorific Value kJ/kg	20511	13219	13022	14149
Carbon %	47.71	48.1	47.2	47.1
Hydrogen %	5.44	2.3	2.3	3.6
Nitrogen %	2.72	1	0.7	0.5
Oxygen %	36.2	48.5	49.5	48.6

Figure 9 Microphotograph of Textiles

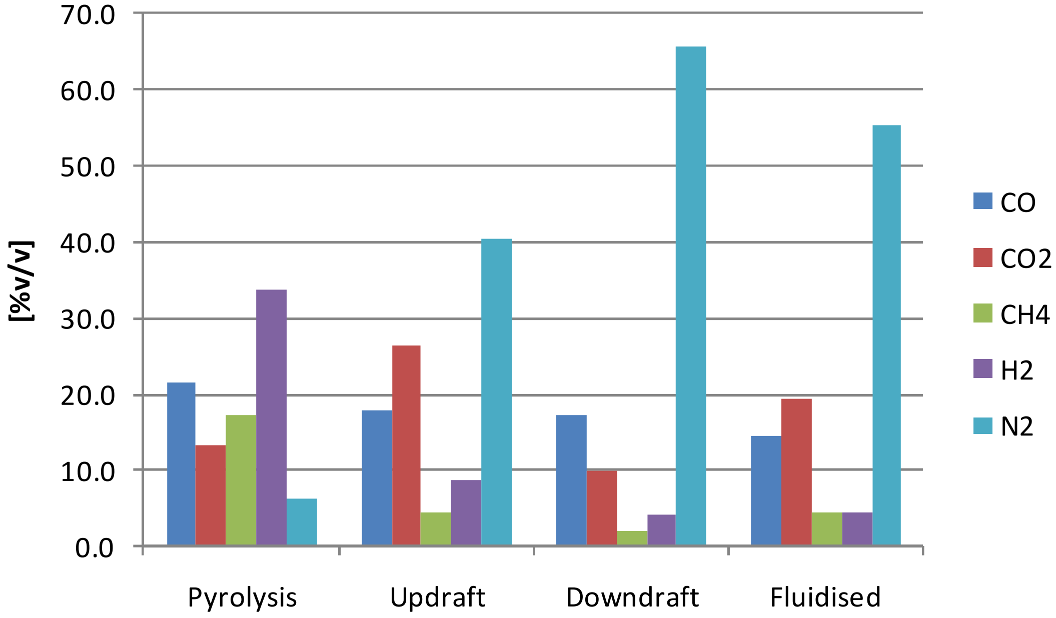

Figure 10 Major Gas Species for Demolition Wood and Textiles for Thermochemical Tests

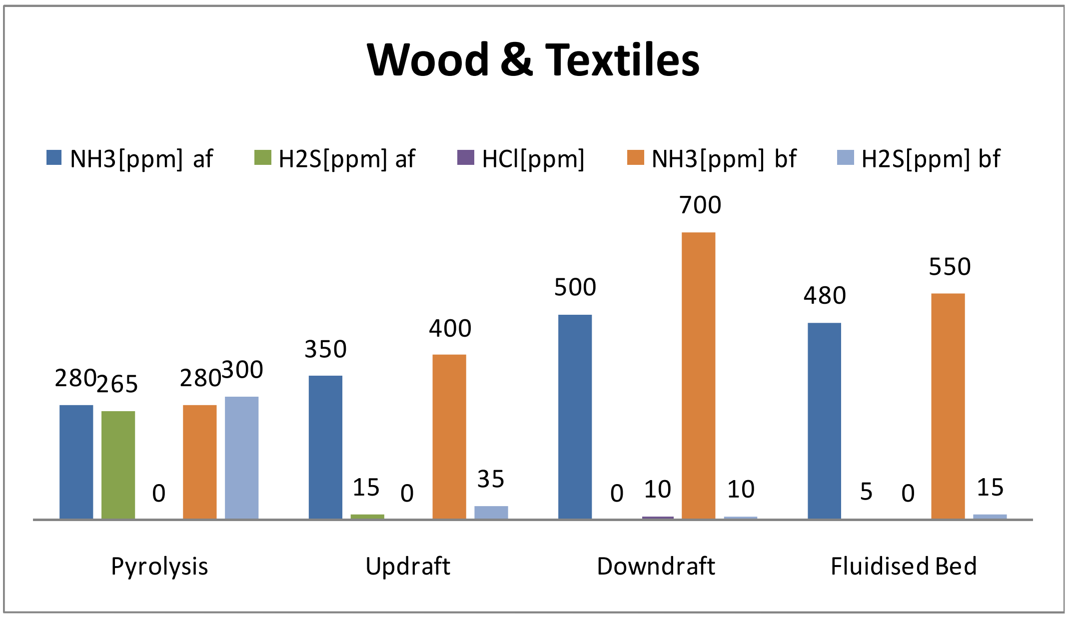

Figure 11 Minor Gas Species for Demolition Wood and Textiles for Thermochemical Tests

Table 10 Bed Residues Analysis for Wood & Textiles for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
PAHs	mg/Kg	<1.0	2.1	3.9	3.7
Carbon	% w/w	45.3	15	45.2	43.8
Na2O	%w/w	0.4	4.7	0.7	2.6
K2O	%w/w	2.5	1	1.7	2
SiO2	%w/w	<0.1	0.3	0.2	<0.1
Al2O3	%w/w	1.7	4.8	2.3	3.1
Fe2O3		2.1	5.3	2.8	4.2
Ash Fusion (Reducing) Temperature					
Initial Deformation	°C	1180	1170	1160	1170
Softening	°C	1230	1230	1250	1230
Hemisphere	°C	1240	1240	1260	1230
Flow	°C	1250	1250	1270	1240

Table 11 Cyclone Analysis – Metals for Wood & Textiles for Thermochemical Tests

		Pyrolysis	Updraft gasification	Downdraft gasification	Fluidised Bed gasification
Arsenic	mg/litre	89	164	132	54
Cadmium	mg/litre	3.1	3.6	5.9	12
Chromium	mg/litre	1567	995	1645	879
Cobalt	mg/litre	32	31	13	10
Copper	mg/litre	512	289	328	210
Lead	mg/litre	1213	1427	1333	1548
Manganese	mg/litre	2185	1217	1879	513
Mercury	mg/litre	<0.1	<0.1	<0.1	<0.1
Nickel	mg/litre	1893	2288	1990	444
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	4.2	4.7	3.9	12
Zinc	mg/litre	3378	1874	3089	2001

Table 12 Tar Analysis for Wood & Textiles for Thermochemical Tests

		Pyrolysis	Updraft gasification	Downdraft gasification	Fluidised Bed gasification
SVOC-Top 10 Compounds					
Phenol	mg/litre	1238	1723	1768	1100
2-Methylphenol	mg/litre	879	569	768	658
Naphthalene	mg/litre	354	321	569	523
Nitrobenzene	mg/litre	453	213	401	498
4-Methylphenol;	mg/litre	103	132	123	160
2-Methylnaphthalene	mg/litre	380	143	102	179
2,4-Dimethylphenol	mg/litre	113	89	120	168
Phenanthrene	mg/litre	67	103	122	90
Fluorene	mg/litre	144	87	94	99
Anthracene	mg/litre	89	56	87	127
VOC-Top 10 Compounds					
Benzene	mg/litre	114	143	91	154
Toluene	mg/litre	93	80	136	162
Ethylbenzene	mg/litre	21	22	47	49
m and p Xylene	mg/litre	26	9	12	88
o-Xylene	mg/litre	12	21	12	1.2
Styrene	mg/litre	26	11	9	4
Isopropylbenzene	mg/litre	<0.5	2	0.9	1
Propylbenzene	mg/litre	0.8	1	0.8	0.7
1,2,3-Trimethylbenzene	mg/litre	0.7	<0.5	<0.5	0.7
1,2,4-Trimethylbenzene	mg/litre	0.6	0.8	<0..5	0.8
Metals					
Arsenic	mg/litre	0.2	0.8	0.5	2.4
Cadmium	mg/litre	0.4	<0.1	<0.1	0.6
Chromium	mg/litre	0.2	0.2	0.2	9.1
Cobalt	mg/litre	0.1	0.1	0.1	2.1
Copper	mg/litre	1.1	0.8	1.1	12
Lead	mg/litre	8.2	9.1	6.1	49
Manganese	mg/litre	8.4	8.2	22.4	80
Mercury	mg/litre	0.3	<0.1	0.2	<0.1
Nickel	mg/litre	2.7	1.5	1.1	26
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	<0.1	<0.1	<0.1	8.3
Zinc	mg/litre	7.8	4.3	9.1	72
Calorific Value and Moisture					
Gross CV	KJ/Kg	15500	13887	12805	14878
Net CV	KJ/Kg	14433	12936	11910	13822
Moisture	% w/w	47.9	53.7	57.9	41.1

Table 13 Mass Balances for Thermochemical Tests with Demolition Wood and Textiles

Pyrolysis	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	47.71						5.44						2.72						36.2						0.1			[% w/w]	540
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												74.5	20
	0.0184	0	0.0084	0.0911	0.0004	0	0.0015	0.0023	0.0018	0.0004	0	0.0064	0.0003	0	0	0.0001	0	0.0058	0.0027	0.0187	0.0095	0.0155	0	0.0367	0.000001	0.0001	0.0007		
Updraft Gasification	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	48.1						2.3						1						48.5						0.1			[% w/w]	730
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												84.1	60
	0.1824	0	0.5401	0.125	0.0191	0.4056	0.015	0.0292	0.0341	0.0006	0	0	0.0015	0	0	0.0002	0	0.0247	0.0283	0.2339	1.0084	0.0859	0	0	0	0.0002	0.0024		
FB Gasification	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	47.1						3.6						0.5						48.6						0.2			[% w/w]	740
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												88.7	25
	0.0947	0	0.5796	0.0268	0.0132	0.0393	0.0077	0.0091	0.0491	0.0001	0	0	0.0016	0	0	0.0001	0	0.0063	0.0133	0.0726	0.6839	0.0058	0	0	0.00001	0.0003	0.0032		
Downdraft Gasification	**C**						**H**						**N**						**O**						**S**				T [^{0}C]
Fuel Analysis	47.2						2.3						0.7						49.5						0.1			[% w/w]	910
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												91.9	30
	0.2488	0	0.5261	0.2425	0.0155	0.02	0.0203	0.0474	0.0423	0.0011	0	0	0.0032	0	0	0.0003	0	0.0121	0.0384	0.3793	0.5335	0.0427	0	0	0.00001	0.0003	0.0019		

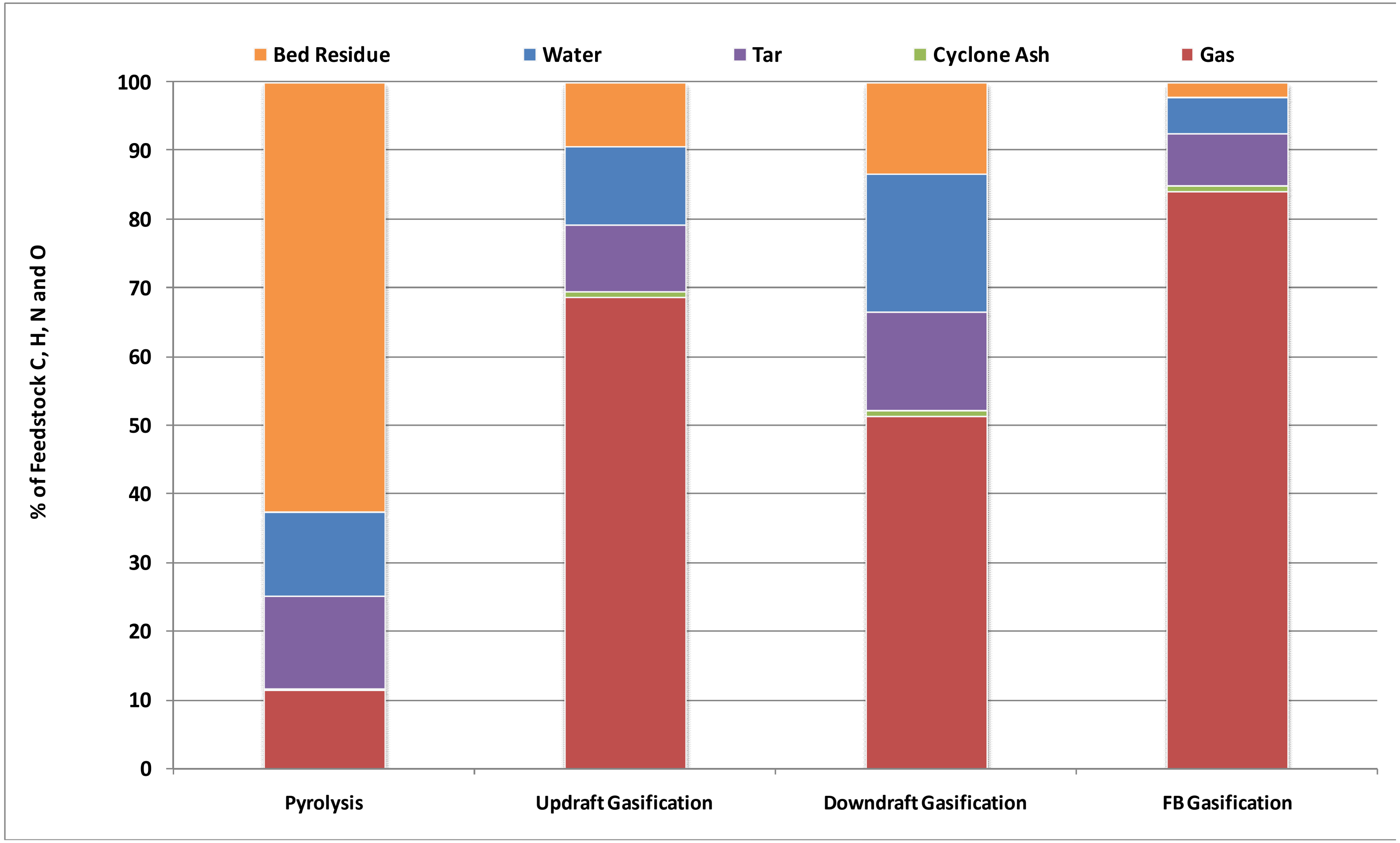

Figure 12 Proportion of Products (by weight) for Thermochemical Tests with Demolition Wood and Textiles Normalised to Measured Components

Demolition Wood & Film Plastics

Each of the tests using Demolition wood and Film Plastics were successful based on a minimum steady gas composition being measured for at least 25 minutes. These gas compositions are shown in **Figure 14** while the proximate and ultimate compsotional analysis of the feedstocks is presented in **Table 14**. In general, these tests showed high methane production levels due to the thermal break down of long chain hydrocarbons (present in the Film Plastics) into shorter chain hydrocarbons. This thermal break down also resulted in a high tar portion, comprising of multi-carbon hydrocarbon chains, as detailed in the workbooks relating to these tests. The presence of these hydrocarbons also resulted in high hydrogen content measurements, particularly for updraft gasification. It would be expected that the other technologies would also show high hydrogen outputs, perhaps more so even than updraft gasification due to the further break-down which typically occurs in fluidised bed and downdraft gasification, although this was not measured to be the case, perhaps due to the operational parameters not being optimised in terms of process temperature for this complete break down to occur. The mass balance outputs shown in **Figure 16** show a reduction in tars relative to Demolition Wood on it own, likely to be due to the large amount of feedstock, by volume, of film plastics, as the feedstock was metered by mass. The film plastics have a simple microstructure of intertwined polymers, which are long chains of carbon and hydrogen atoms. As such, these easily disintegrate into their component elements, resulting in a low contribution to the tar loading.

Table 14 Proximate Analysis and Ultimate Analysis - Demolition Wood and Film Plastics

Test Parameter	**Pyrolysis**	**Updraft**	**Downdraft**	**Fluidised Bed**
Total Moisture %	5	6.1	5.6	2
Ash %	13.2	8.6	8.2	3
Volatile Matter %	72.4	76.1	77.3	86.6
Sulphur %	0.06	<0.1	<0.1	<0.1
Chlorine %	0.02	0.2	0.3	<0.1
Gross Calorific Value kJ/kg	15602	15466	15648	28657
DAF Calorific Value kJ/kg	19070			
Net Calorific Value kJ/kg	14403	14371	15543	26659
Carbon %	56.38	44.2	49.2	66.7
Hydrogen %	7.55	4.1	3.8	4.5
Nitrogen %	0.48	1.2	1.1	0.7
Oxygen %	17.3	50.3	45.6	28.1

Figure 13 Microphotograph of Film Plastics

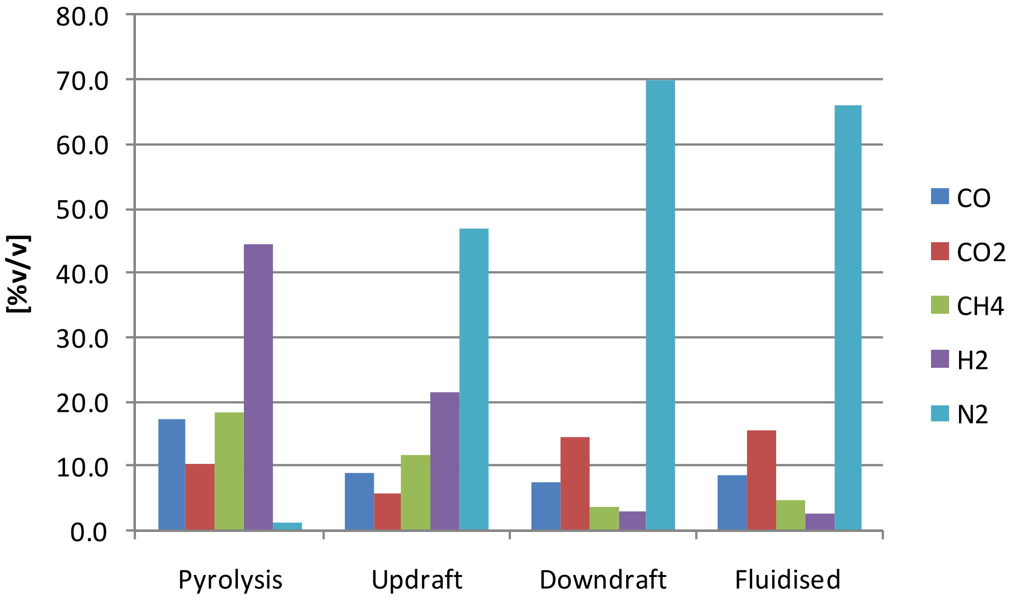

Figure 14 Major Gas Species for Demolition Wood and Film Plastics for Thermochemical Tests

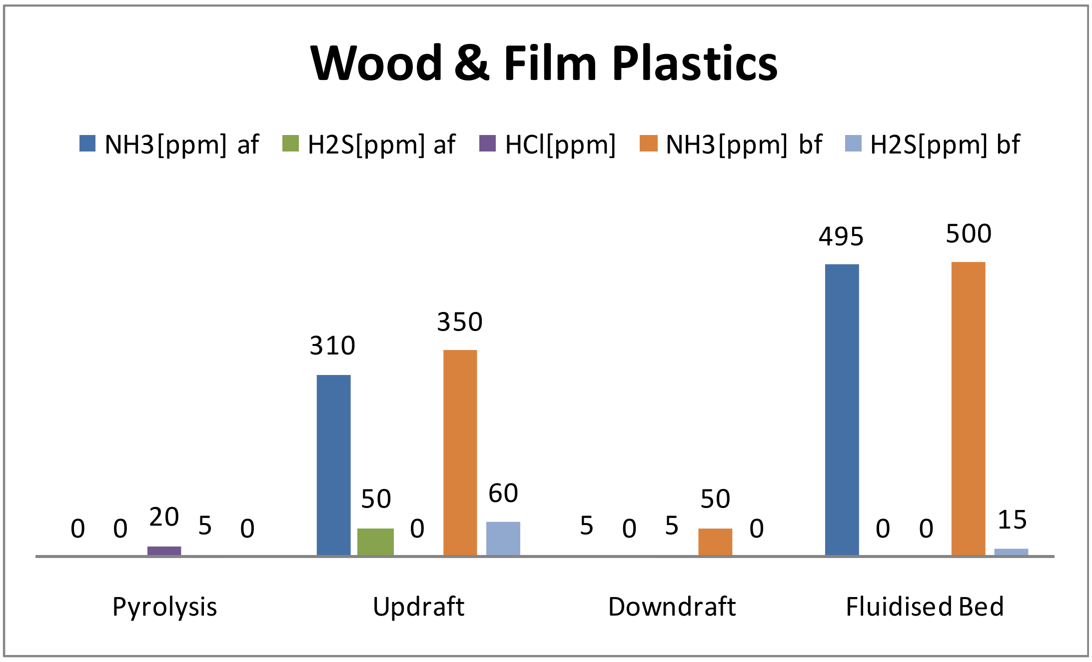

Figure 15 Minor Gas Species for Demolition Wood and Film Plastics for Thermochemical Tests

Table 15 Bed Residues Analysis for Wood & Film Plastics for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
PAHs	mg/Kg	7.2	2.5	<1.0	3
Carbon	% w/w	41.6	14.2	39.8	47.1
Na2O	%w/w	0.5	4.5	0.5	2.7
K2O	%w/w	3.3	1.6	2.6	1.6
SiO2	%w/w	0.2	0.2	<0.1	0.2
Al2O3	%w/w	2	5.6	2.5	4.1
Fe2O3		2.5	5.9	2.9	4.5
Ash Fusion (Reducing) Temperature					
Initial Deformation	°C	1170	1150	1180	1150
Softening	°C	1220	1250	1240	1230
Hemisphere	°C	1230	1260	1250	1230
Flow	°C	1250	1270	1260	1240

Table 16 Cyclone Analysis – Metals for Wood & Film Plastics for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
Arsenic	mg/litre	154	132	132	61
Cadmium	mg/litre	7.9	14.2	8.9	1.8
Chromium	mg/litre	1879	1199	1658	776
Cobalt	mg/litre	40	18	16	7.8
Copper	mg/litre	439	459	229	401
Lead	mg/litre	1377	1658	987	1327
Manganese	mg/litre	2008	1603	1879	328
Mercury	mg/litre	<0.1	<0.1	<0.1	<0.1
Nickel	mg/litre	2879	1276	3665	870
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	1.5	3	0.6	8.5
Zinc	mg/litre	2387	3003	2366	1666

Table 17 Tar Analysis for Wood & Film Plastics for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
SVOC-Top 10 Compounds					
Phenol	mg/litre	1610	912	879	1010
2-Methylphenol	mg/litre	768	401	768	687
Naphthalene	mg/litre	658	278	567	320
Nitrobenzene	mg/litre	325	567	336	657
4-Methylphenol;	mg/litre	143	218	165	101
2-Methylnaphthalene	mg/litre	128	87	231	165
2,4-Dimethylphenol	mg/litre	121	87	113	101
Phenanthrene	mg/litre	43	91	76	154
Fluorene	mg/litre	176	98	107	109
Anthracene	mg/litre	100	57	56	76
VOC-Top 10 Compounds					
Benzene	mg/litre	121	78	153	159
Toluene	mg/litre	116	127	114	88
Ethylbenzene	mg/litre	56	14	11	70
m and p Xylene	mg/litre	34	5	25	63
o-Xylene	mg/litre	6	12	6	5.8
Styrene	mg/litre	14	10	4	12
Isopropylbenzene	mg/litre	1	<0.5	<0.5	0.9
Propylbenzene	mg/litre	0.8	1	0.7	<0.5
1,2,3-Trimethylbenzene	mg/litre	2	<0..5	<0..5	1.6
1,2,4-Trimethylbenzene	mg/litre	<0..5	0.7	<0..5	<0.5
Metals					
Arsenic	mg/litre	1.3	0.4	1.3	3.1
Cadmium	mg/litre	0.2	0.2	<0.1	2.6
Chromium	mg/litre	0.2	0.2	0.3	1.9
Cobalt	mg/litre	0.2	0.1	0.3	3.7
Copper	mg/litre	1.4	0.9	1.3	16
Lead	mg/litre	6.6	4.8	7.2	30
Manganese	mg/litre	17.8	12	12.6	68
Mercury	mg/litre	<0.1	<0.1	<0.1	<0.1
Nickel	mg/litre	1.5	0.9	0.8	5.9
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	<0.1	<0.1	<0.1	2.5
Zinc	mg/litre	8.6	5	9.8	101
Calorific Value and Moisture					
Gross CV	KJ/Kg	13539	14376	12144	14287
Net CV	KJ/Kg	12576	13344	11278	13267
Moisture	% w/w	54.6	52	61.6	44.1

Table 18 Mass Balances for Thermochemical Tests with Demolition Wood and Film Plastics

Pyrolysis	C						H						N						O						S				T [^{0}C]
Fuel Analysis	56.38						7.55						0.48						17.3						0.06			[% w/w]	690
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												80.2	30
	0.0192	0	0.0286	0.082	0.0002	0.011	0.0016	0.0032	0.0058	0.0002	0	0.0082	0.0002	0	0	0.0001	0	0.0009	0.0027	0.0253	0.0138	0.0178	0	0	1.00E-07	0.0001	0		

Gasification	C						H						N						O						S				T [^{0}C]
Fuel Analysis	44.2						4.1						1.2						50.3						0.2			[% w/w]	730
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												75.0	60
	0.0538	0	0.4515	0.0271	0.0148	0	0.0044	0.0083	0.0799	0.0002	0	0	0.0015	0	0	0.0001	0	0.0109	0.0091	0.0661	0.1435	0.0193	0	0.28	2.00E-06	0.00005	0.002		

FB Gasification	C						H						N						O						S				T [^{0}C]
Fuel Analysis	66.7						4.5						0.7						28.1						0.1			[% w/w]	660
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												90.1	25
	0.088	0	0.634	0.0206	0.0341	0.2904	0.0072	0.0097	0.0596	0	0	0	0.0022	0	0	0.0001	0	0.009	0.0139	0.0779	0.7095	0.0039	0	0	0.00002	0.00002	0.0016		

Gasification	C						H						N						O						S				T [^{0}C]
Fuel Analysis	49.2						3.8						1.1						45.6						0.1			[% w/w]	920
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												89.3	25
	0.0291	0	1.1278	0.1008	0.0002	0.0047	0.0024	0.0064	0.117	0.0001	0	0	0.0004	0	0	0.0001	0	0.0277	0.0039	0.0509	0.9018	0.0219	0	0	0.00002	0.0001	0.0024		

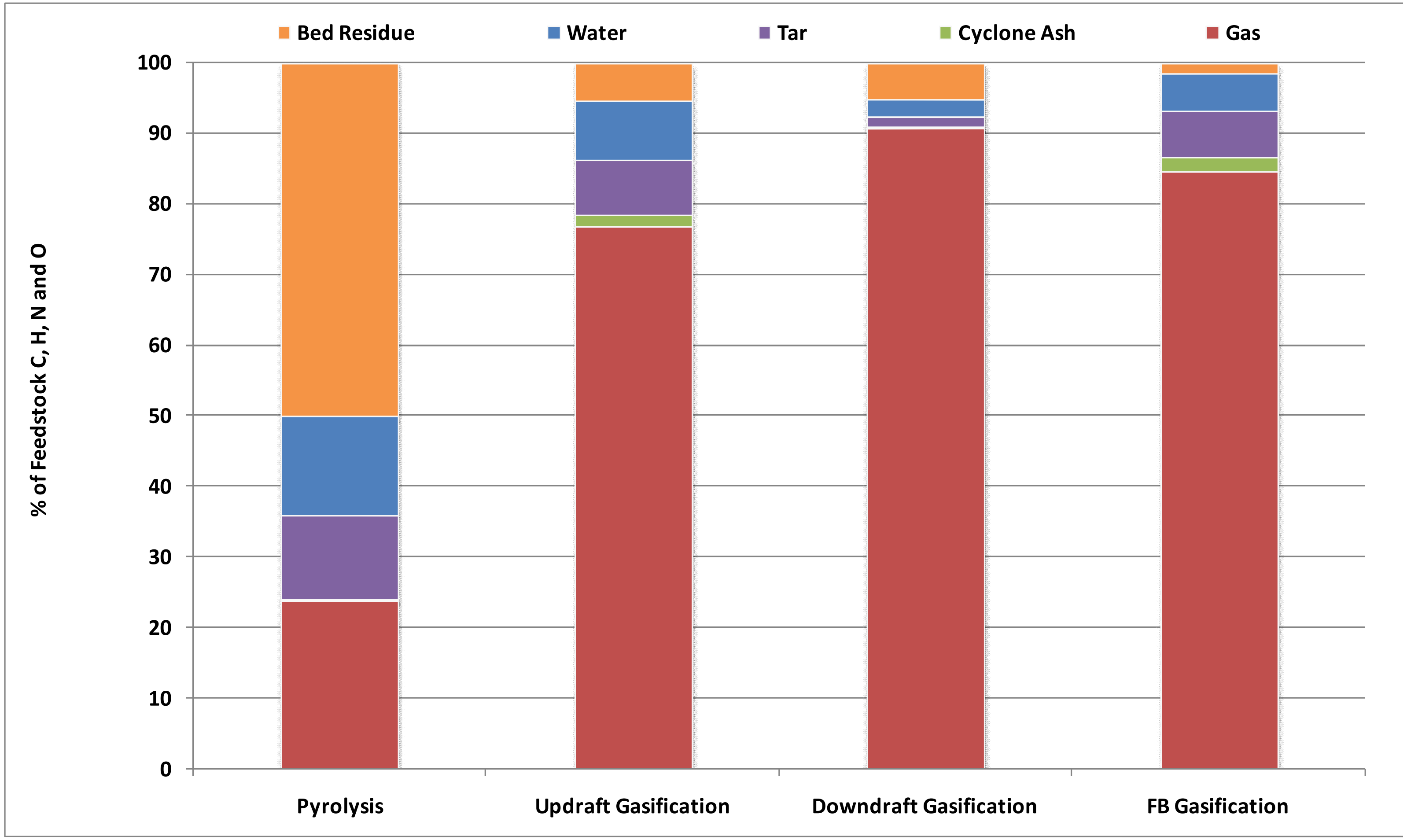

Figure 16 Proportions of Products (by weight) for Thermochemical Tests with Demolition Wood and Film Plastics Normalised to Measured Components

Textiles & Film Plastics

Tests using Textiles and Film Plastics were deemed to be successful when a stable gas composition was achieved for 20 minutes or more. The proximate and ultimate analysis of the feedstock mixtures are presented in **Table 19**. The averaged gas compositions over the stable periods are shown in **Figure 17** for each of the different technologies, whilst the concentrations of the contaminant species are shown in **Figure 18**. It should be noted that due to issues experienced in continuously feeding this mixture into the downdraft and fluidised bed gasifiers due to the tendency for polymeric textile materials to stick to sides of the rig and bridge across the top of the gasifier, for these technologies a mixture ratio of 75%/25% (Film Plastics/Textiles) was required to be used. In general for this fuel mixture, high levels of methane were produced relative to the other due to the volume of long chain hydrocarbon polymers present in this fuel mixture.

Table 19 Proximate Analysis and Ultimate Analysis - Textiles and Film Plastics

Test Parameter	**Pyrolysis**	**Updraft**	**Downdraft**	**Fluidised Bed**
Total Moisture %	5.4	6.6	6.3	2.8
Ash %	2.7	7.7	6	6.2
Volatile Matter %	78.2	76.8	78.3	83.1
Sulphur %	0.43	<0.1	<0.1	<0.1
Chlorine %	0.08	<0.1	0.1	0.1
Gross Calorific Value kJ/kg	22448	25337	24366	23980
DAF Calorific Value kJ/kg	24430			
Net Calorific Value kJ/kg	20993	23544	22624	22305
Carbon %	57.58	65.7	67.2	53.2
Hydrogen %	8.11	4.6	4.9	3.7
Nitrogen %	2.41	0.7	0.5	1.1
Oxygen %	23.4	29	27.3	41.9

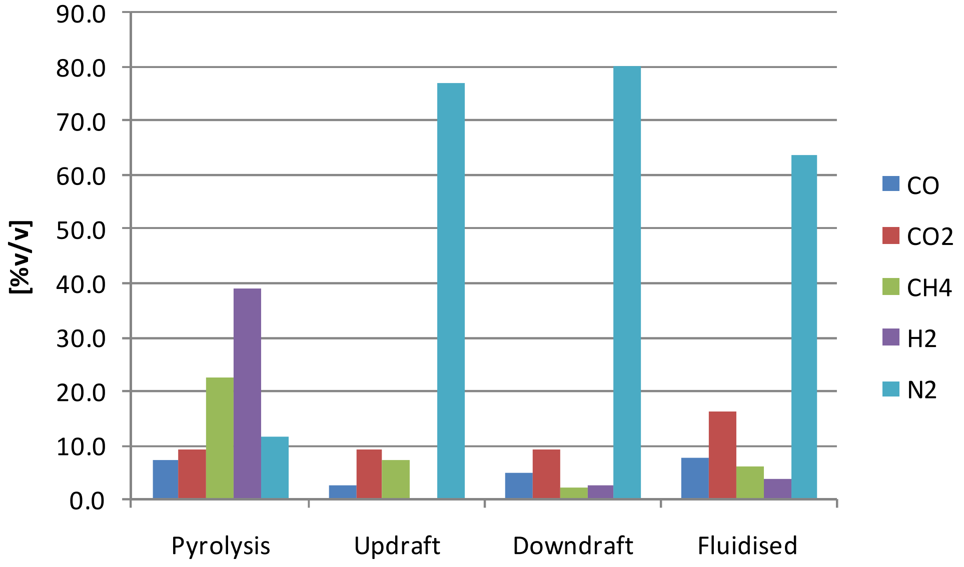

Figure 17 Major Gas Species for Textiles and Film Plastics for Thermochemical Tests

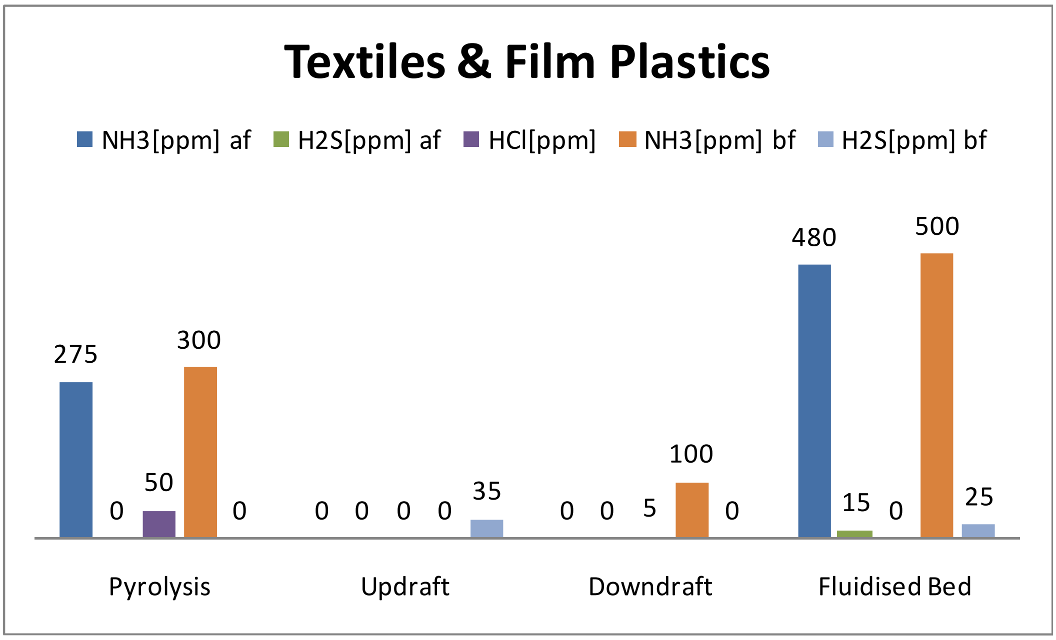

Figure 18 Minor Gas Species for Textiles and Film Plastics for Thermochemical Tests

Table 20 Bed Residues Analysis for Textiles & Film Plastics for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
PAHs	mg/Kg	3.2	3	<1.0	<1.0
Carbon	% w/w	50.1	12.5	12.7	45.9
Na2O	%w/w	0.6	4.2	4.6	1.8
K2O	%w/w	3.4	4.2	2.1	2.7
SiO2	%w/w	0.1	0.3	0.3	0.3
Al2O3	%w/w	1.6	5.5	6.1	2.8
Fe2O3		1.8	6.3	6.8	4
Ash Fusion (Reducing) Temperature					
Initial Deformation	°C	1140	1140	1140	1160
Softening	°C	1230	1240	1230	1240
Hemisphere	°C	1240	1250	1240	1240
Flow	°C	1260	1260	1250	1250

Table 21 Cyclone Analysis – Metals for Textiles & Film Plastics for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
Arsenic	mg/litre	116	179	227	96
Cadmium	mg/litre	7.4	10.8	14.6	9.2
Chromium	mg/litre	1327	1435	1325	1044
Cobalt	mg/litre	14	12	21	9.1
Copper	mg/litre	342	334	601	289
Lead	mg/litre	900	1217	1423	784
Manganese	mg/litre	1923	1767	1227	276
Mercury	mg/litre	<0.1	0.2	0.4	<0.1
Nickel	mg/litre	1328	3227	3379	616
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	9	1.2	2.5	14
Zinc	mg/litre	3426	2978	2318	1879

Table 22 Tar Analysis for Textiles & Film Plastics for Thermochemical Tests

		Pyrolysis	Updraft gasification	Downdraft gasification	Fluidised Bed gasification
SVOC-Top 10 Compounds					
Phenol	mg/litre	1536	880	999	1276
2-Methylphenol	mg/litre	1008	560	870	723
Naphthalene	mg/litre	774	342	700	662
Nitrobenzene	mg/litre	703	243	549	517
4-Methylphenol;	mg/litre	165	120	127	327
2-Methylnaphthalene	mg/litre	312	116	109	122
2,4-Dimethylphenol	mg/litre	76	132	143	45
Phenanthrene	mg/litre	121	78	105	89
Fluorene	mg/litre	132	121	125	92
Anthracene	mg/litre	67	36	45	154
VOC-Top 10 Compounds					
Benzene	mg/litre	90	67	75	99
Toluene	mg/litre	76	154	165	138
Ethylbenzene	mg/litre	43	32	56	34
m and p Xylene	mg/litre	17	10	31	12
o-Xylene	mg/litre	11	8	21	3.8
Styrene	mg/litre	11	9	13	3.2
Isopropylbenzene	mg/litre	1	3	<0.5	2.6
Propylbenzene	mg/litre	0.5	0.5		1.1
1,2,3-Trimethylbenzene	mg/litre	<0..5	1	<0.5	<0.5
1,2,4-Trimethylbenzene	mg/litre	<0..5	2	1	<0.5
Metals					
Arsenic	mg/litre	0.7	0.8	0.7	6.8
Cadmium	mg/litre	<0.1	<0.1	<0.1	1
Chromium	mg/litre	0.1	0.3	0.1	8.8
Cobalt	mg/litre	0.2	0.2	<0.1	7.9
Copper	mg/litre	1.3	1	0.6	66
Lead	mg/litre	9,5	5	6.3	38
Manganese	mg/litre	10.9	16.2	17.7	91
Mercury	mg/litre	<0.1	0.2	<0.1	<0.1
Nickel	mg/litre	1.4	1	0.4	13
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	<0.1	<0.1	<0.1	9.2
Zinc	mg/litre	12	7.4	6.6	82
Calorific Value and Moisture					
Gross CV	KJ/Kg	12510	12849	14769	13670
Net CV	KJ/Kg	11644	11924	13701	12725
Moisture	% w/w	60.5	57.9	49.9	62.4

Table 23 Mass Balances for Thermochemical Tests with Textiles and Film Plastics

Pyrolysis	C						H						N						O						S				T [^{0}C]
Fuel Analysis	57.58						8.11						2.41						23.4						0.43			[% w/w]	660
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												89.5	30
	0.0195	0	0.0887	0.0675	0.0003	0.0018	0.0016	0.0041	0.0183	0.0002	0	0.0008	0.0004	0	0	0.0001	0	0.007	0.003	0.0332	0.0261	0.0134	0	0	1.00E-06	0.0001	0.0012		
Updraft Gasification	C						H						N						O						S				T [^{0}C]
Fuel Analysis	65.7						4.6						0.7						29						0.1			[% w/w]	580
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												95.4	60
	0.0873	0	1.0057	0.122	0.0141	0.005	0.0072	0.0164	0.1315	0.0002	0	0	0.001	0	0	0.0002	0	0.0119	0.0122	0.1316	0.273	0.0862	0	0	2.00E-06	0.0002	0.0017		
FB Gasification	C						H						N						O						S				T [^{0}C]
Fuel Analysis	53.2						3.7						1.1						41.9						0.1			[% w/w]	660
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												94.5	30
	0.0269	0	0.8068	0.029	0.0262	0.0421	0.0022	0.0062	0.0857	0.0001	0	0	0.0005	0	0	0	0	0.0187	0.004	0.0494	0.8597	0.0059	0	0	2.00E-06	0.00004	0.0017		
Downdraft Gasification	C						H						N						O						S				T [^{0}C]
Fuel Analysis	67.2						4.9						0.5						27.3						0.1			[% w/w]	750
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												82.5	35
	0.0687	0	1.166	0.2025	0.0106	1.1117	0.0056	0.0125	0.1001	0.001	0	0.0674	0.0012	0	0	0.0004	0	0.0175	0.0107	0.1002	1.6554	0.1438	0	0	0.00007	0.0003	0.0034		

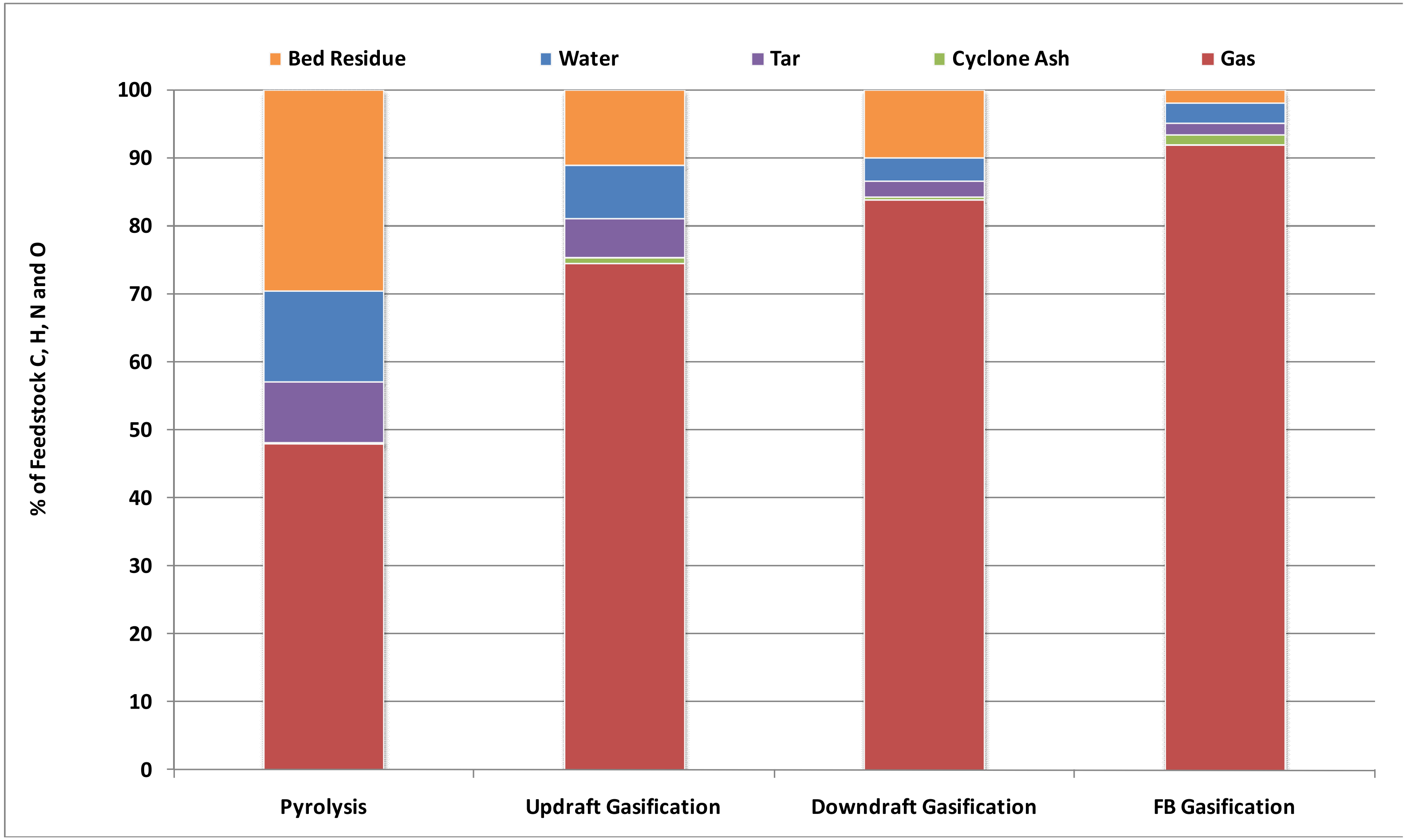

Figure 19 Proportions of Products (by weight) for Thermochemical Tests with Textiles and Film Plastics Normalised to Measured Components

Paper & Card and Dense Plastics

The tests using Paper and Card and Dense Plastics were successful based on a minimum of 25 minutes of stable output gas composition. The proximate and ultimate analysis of the feedstocks are presented in **Table 24**. These gas compositions, which show particularly high levels of CO2 production for the gasification technologies, as presented in Figure 21 whilst the contaminant levels are presented in Figure 22. Prior to carrying out these tests, it was expected that HCl levels would be high due to the presence of Chlorine in the dense plastics, but the test data appears to show low levels of HCl but high levels of H_2S, indicating that the hydrogen is preferentially combining with the sulphur, also present in the Dense Plastics, possibly resulting in Chlorine becoming a singular species, which was unmeasured for these tests.

Table 24 Proximate Analysis and Ultimate Analysis - Paper & Card and Dense Plastics

Test Parameter	**Pyrolysis**	**Updraft**	**Downdraft**	**Fluidised Bed**
Total Moisture %	5.6	4.1	2.7	1.4
Ash %	6.3	8.2	5.8	3.4
Volatile Matter %	79.9	80.8	83.5	86
Sulphur %	<0.1	0.04	<0.1	<0.1
Chlorine %	<0.1	0.06	<0.1	<0.1
Gross Calorific Value kJ/kg	26112	12155	26382	29007
DAF Calorific Value kJ/kg		13860		
Net Calorific Value kJ/kg	24290	11030	24532	26962
Carbon %	58.6	47.94	60	70.2
Hydrogen %	4.5	5.89	4.3	4.8
Nitrogen %	0.5	0.43	0.3	0.9
Oxygen %	36.4	33.4	35.4	24.1

Figure 20 Microphotograph of Paper & Card and Dense Plastics

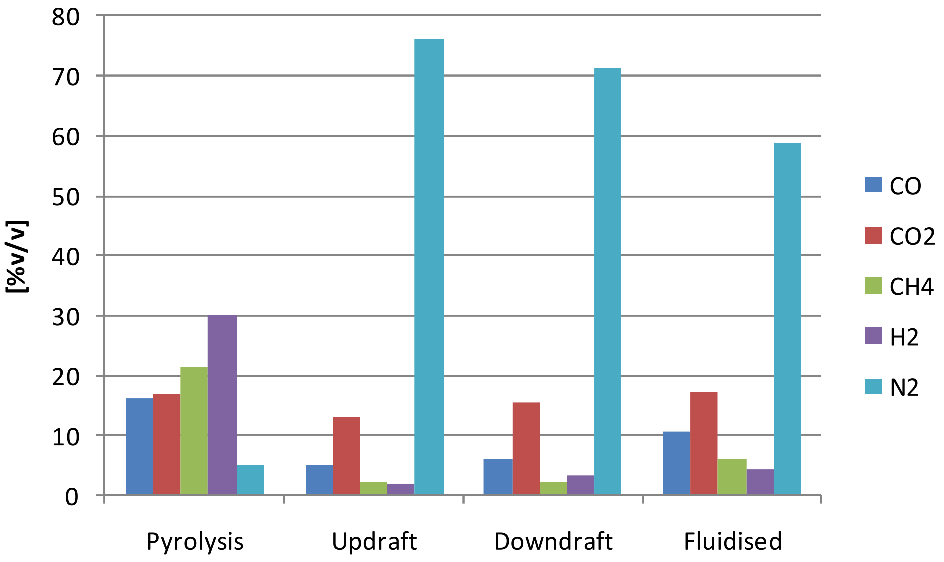

Figure 21 Major Gas Species for Paper & Card and Dense Plastics for Thermochemical Tests

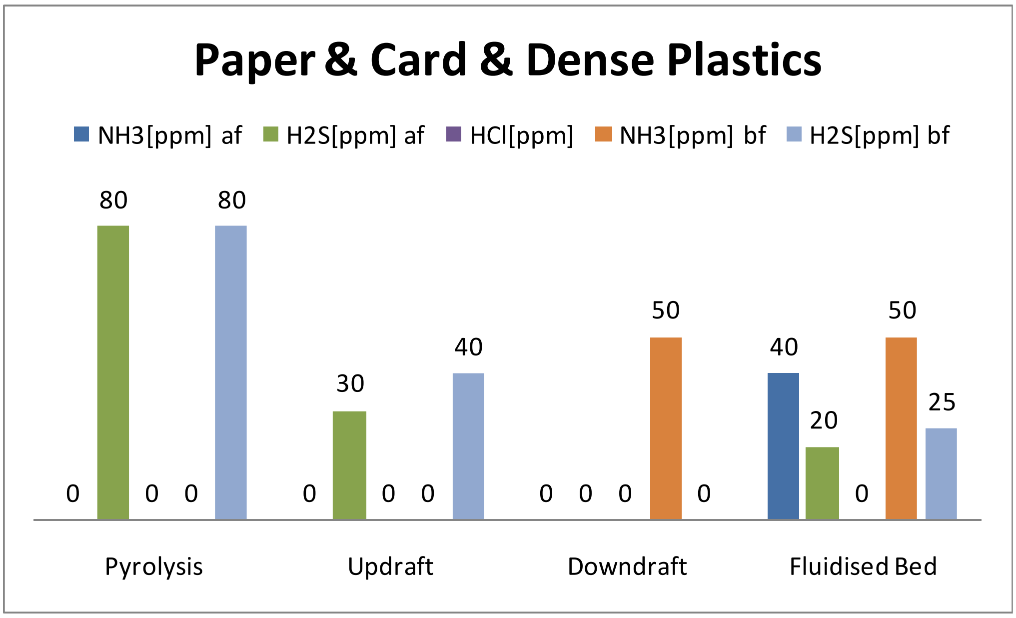

Figure 22 Minor Gas Species for **Paper & Card and Dense Plastics** for Thermochemical Tests

Table 25 Bed Residues Analysis for Paper&Card & Dense Plastics for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
PAHs	mg/Kg	6.1	4.6	<1.0	4.1
Carbon	% w/w	9.1	8.7	13.5	44.2
Na2O	%w/w	3.1	2.4	4.5	1.9
K2O	%w/w	1	2.3	2.4	2.5
SiO2	%w/w	0.2	0.1	0.5	0.1
Al2O3	%w/w	5.7	5.2	6.4	3.5
Fe2O3		6.2	5.6	7	2.8
Ash Fusion (Reducing) Temperature					
Initial Deformation	°C	1150	1170	1150	1160
Softening	°C	1220	1210	1260	1230
Hemisphere	°C	1240	1220	1270	1230
Flow	°C	1250	1230	1280	1240

Table 26 Cyclone Analysis – Metals for Paper&Card & Dense Plastics for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
Arsenic	mg/litre	104	121	99	12
Cadmium	mg/litre	10.3	3.6	10	5.9
Chromium	mg/litre	1769	1745	1522	1215
Cobalt	mg/litre	28	23	31	16
Copper	mg/litre	415	223	265	176
Lead	mg/litre	1768	1254	1768	1218
Manganese	mg/litre	1438	1216	1265	404
Mercury	mg/litre	0.3	<0.1	<0.1	<0.1
Nickel	mg/litre	1217	1528	1265	548
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	3.8	1.8	1.7	6.8
Zinc	mg/litre	4359	3428	2400	1222

Table 27 Tar Analysis for Paper&Card & Dense Plastics for Themochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
SVOC-Top 10 Compounds					
Phenol	mg/litre	870	1006	1436	895
2-Methylphenol	mg/litre	678	896	777	700
Naphthalene	mg/litre	601	564	563	518
Nitrobenzene	mg/litre	658	445	539	335
4-Methylphenol;	mg/litre	223	324	110	254
2-Methylnaphthalene	mg/litre	213	78	115	100
2,4-Dimethylphenol	mg/litre	124	231	165	78
Phenanthrene	mg/litre	89	254	132	118
Fluorene	mg/litre	106	213	87	149
Anthracene	mg/litre	45	33	87	126
VOC-Top 10 Compounds					
Benzene	mg/litre	87	101	89	103
Toluene	mg/litre	140	132	180	116
Ethylbenzene	mg/litre	17	30	32	12
m and p Xylene	mg/litre	13	22	7	58
o-Xylene	mg/litre	22	9	5	11
Styrene	mg/litre	6	12	12	5.9
Isopropylbenzene	mg/litre	0.8	1	<0.5	1.3
Propylbenzene	mg/litre	2	0.9	<0.5	1.2
1,2,3-Trimethylbenzene	mg/litre	0.9	<0.5	0.9	1.9
1,2,4-Trimethylbenzene	mg/litre	1	0.7	0.6	<0.5
Metals					
Arsenic	mg/litre	0.6	1.2	0.2	2
Cadmium	mg/litre	0.1	0.1	<0.1	1.6
Chromium	mg/litre	0.3	0.3	0.2	10.2
Cobalt	mg/litre	<0.1	0.2	0.2	5.1
Copper	mg/litre	0.7	1.2	0.7	37
Lead	mg/litre	7.2	3.5	7.3	77
Manganese	mg/litre	23.6	15.2	19.3	38
Mercury	mg/litre	<0.1	0.3	0.3	<0.1
Nickel	mg/litre	2.5	1.4	0.7	2.9
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	<0.1	<0.1	<0.1	1.6
Zinc	mg/litre	12.4	3.6	7.9	56
Calorific Value and Moisture					
Gross CV	KJ/Kg	13922	12833	12998	12657
Net CV	KJ/Kg	12921	11925	12082	11765
Moisture	% w/w	53.2	58.5	56.7	57.9

Table 28 Mass Balances for Thermochemical Tests with Paper & Card and Dense Plastics

Pyrolysis	C						H						N						O						S				T [°C]
Fuel Analysis	58.6						4.5						0.5						36.4						0.1			[% w/w] 570	
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												77.7	50
	0.0264	0	0.1702	0.0279	0	0.1185	0.0021	0.0042	0.0321	0.0001	0	0	0.0006	0	0	0	0	0.0022	0.004	0.0335	0.1319	0.0215	0	0.0223	3.00E-06	0.00005	0.0005		
Updraft Gasification	C						H						N						O						S				T [°C]
Fuel Analysis	47.94						5.89						0.43						33.4						0.04			[% w/w] 600	
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												84.5	45
	0.0303	0	0.1616	0.0184	0	0.0007	0.0025	0.0059	0.0152	0.0001	0	0.0023	0.0004	0	0	0	0	0.0014	0.0043	0.047	0.1593	0.0146	0	0	1.00E-06	0.00003	0.0001		
FB Gasification	C						H						N						O						S				T [°C]
Fuel Analysis	70.2						4.8						0.9						24.1						0.1			[% w/w] 750	
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												85.9	25
	0.0423	0	0.8767	0.0346	0.0866	0.5042	0.0034	0.0079	0.089	0.0001	0	0.0051	0.0006	0	0	0.0002	0	0.0192	0.0057	0.0633	0.9359	0.0069	0	0	0.00002	0.00004	0.0021		
Downdraft Gasification	C						H						N						O						S				T [°C]
Fuel Analysis	60						4.3						0.3						35.4						0.1			[% w/w] 875	
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												89.9	30
	0.0801	0	0.8614	0.1567	0.0092	0.455	0.0065	0.011	0.0741	0.0005	0	0.0197	0.0015	0	0	0.0003	0	0.006	0.0115	0.0882	1.0817	0.1167	0	0	0.00001	0.0003	0.0023		

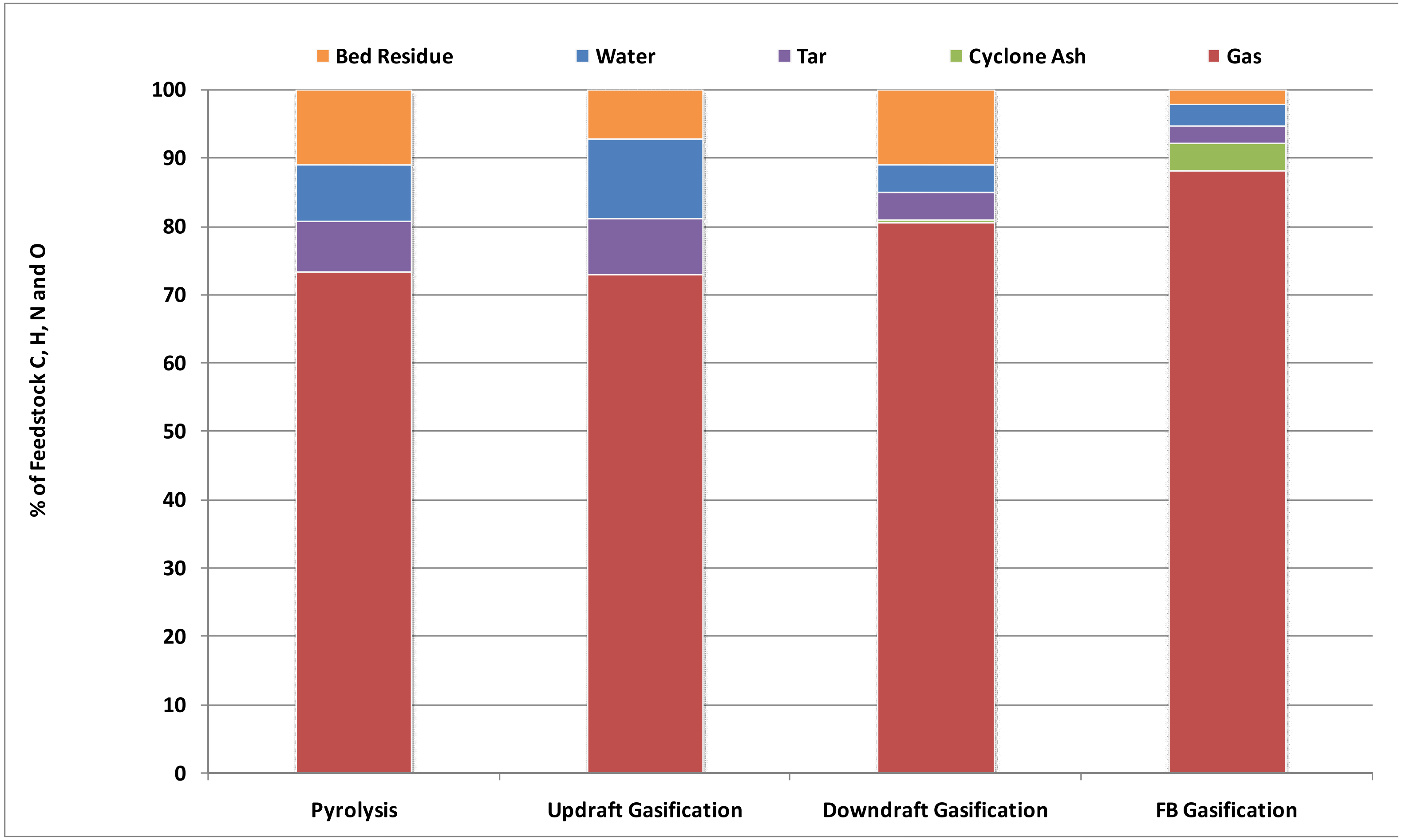

Figure 23 Proportions of Products (by weight) for Thermochemical Tests with Paper & Card and Dense Plastics Normalised to Measured Components

Food and Paper & Card

The proximate and ultimate analysis of the Food and Paper & Card mixture feedstock is shown in **Table 29**. Note that in contrast to the other thermal tests carried out, all the Food and Paper & Card tests were carried out in a single "campaign" to ensure minimal degradation of the food feedstock material, which was especially collected for these tests. As such, the same batch of material, with a single set of properties, was used for each of the tests. The graphical representation of the major and minor gases produced for each technology using the mixture of Food and Paper and Card is shown in **Figure 25** and **Figure 26** respectively. The chloride species were found to be difficult to measure due to very low levels of chlorine in the fuels. The food and paper samples also had a low ash content (~2%) and high volatile matter compared to other feedstocks tested, resulting in the reactive components of the gas (sum of CO and H_2) being greater than the inert CO_2 for majority of the technologies tested. This

Table 29 Proximate Analysis and Ultimate Analysis - Food and Paper & Card

Test Parameter	**All Rig Technologies**
Total Moisture %	9.8
Ash %	2.1
Volatile Matter %	82.5
Fixed Carbon	5.6
Total	100.0
Carbon %	53.5
Hydrogen %	3.9
Nitrogen %	2.2
Chlorine %	<0.1
Sulphur %	<0.1
Oxygen %	40.4
Gross Calorific Value kJ/kg	18776
Net Calorific Value kJ/kg	17556

Figure 24 Microphotograph of Food and Paper & Card

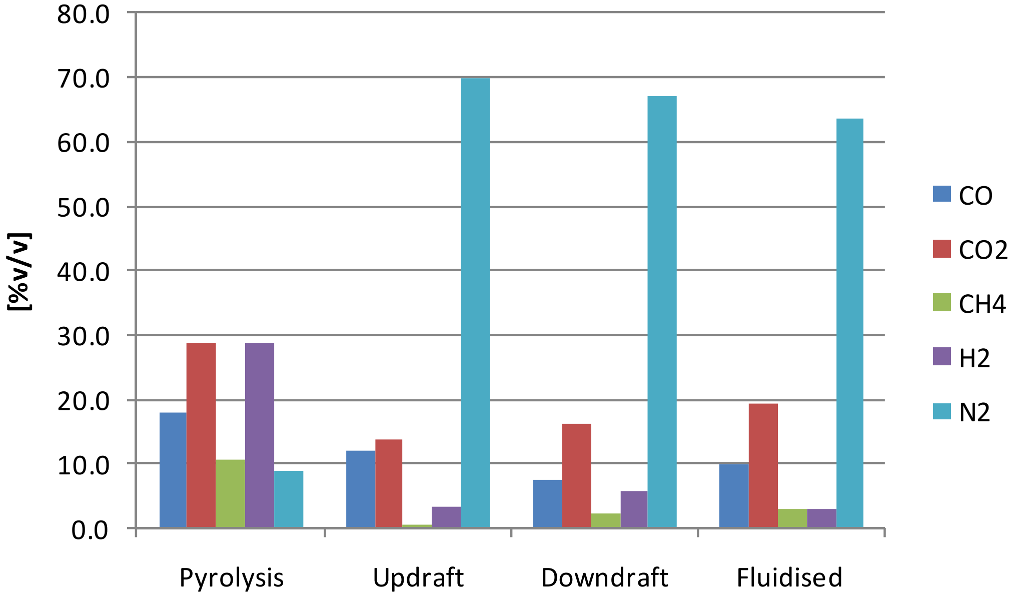

Figure 25 Major Gas Species for Food and Paper & Card for Thermochemical Tests

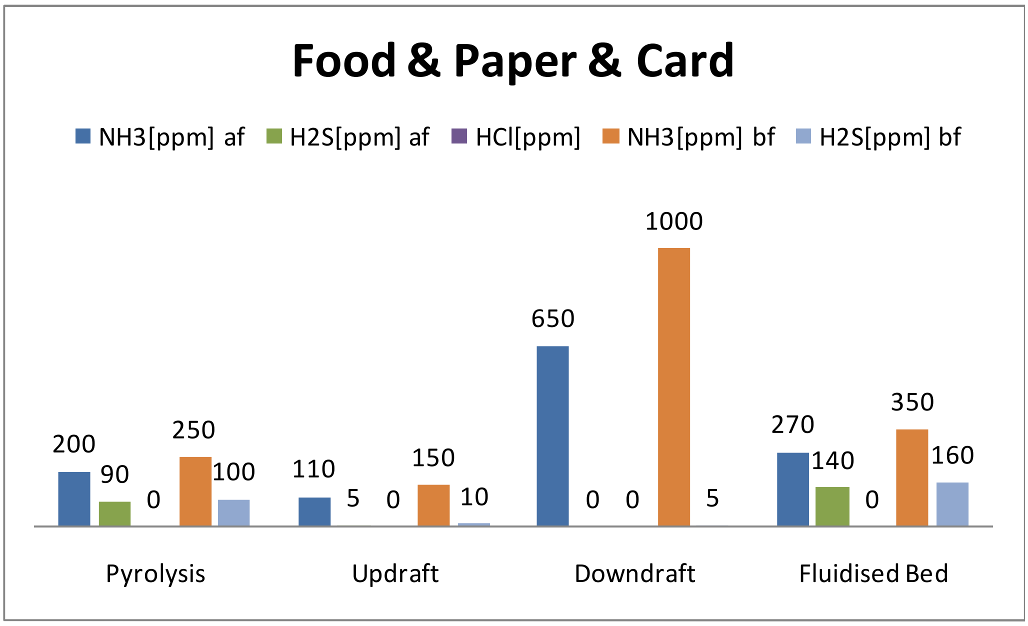

Figure 26 Minor Gas Species for Food and Paper & Card for Thermochemical Tests

Table 30 Bed Residues Analysis for Paper&Card & Food for Thermochemical Tests

		Pyrolysis		**Updraft gasification**	**Downdraft gasification**		**Fluidised Bed gasification**
		Lower Bed Residue ETI PF1	**Upper Bed Residue ETI PF1**		**Ash Pot ETI DF1**	**Bed Residue ETI DF1**	
PAHs	mg/Kg	8.3	4.7	2.9	6	2.2	<1.0
Carbon	% w/w	55.22	68.2	34.9	36.2	39.6	14.6
Na2O	%w/w	1.5	2.5	2.4	1.6	2.2	3.2
K2O	%w/w	0.5	0.6	2	1.8	2.7	2.9
SiO2	%w/w	1.6	0.6	2.7	1.3	1.8	36.9
Al2O3	%w/w	3.2	1.1	3.5	3.7	4.3	3
Fe2O3		2.4	0.6	3.1	2.9	2.7	2.1
Ash Fusion (Reducing) Temperature							
Initial Deformation	°C	1160	1170	1170	1150	1160	1190
Softening	°C	1240	1230	1240	1200	1230	1270
Hemisphere	°C	1240	1230	1240	1200-	1230	1270
Flow	°C	1260	1240	1260	1240	1250	1290

Table 31 Cyclone Analysis – Metals for Paper&Card & Food for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
Arsenic	mg/litre	43	8.4	17	91
Cadmium	mg/litre	10	2.1	12	7.7
Chromium	mg/litre	435	76	766	333
Cobalt	mg/litre	28	<0.1	18	6.6
Copper	mg/litre	176	33	116	97
Lead	mg/litre	914	78	768	365
Manganese	mg/litre	287	55	225	443
Mercury	mg/litre	<0.1	<0.1	<0.1	<0.1
Nickel	mg/litre	776	86	657	354
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	6.1	<0.1	23	13
Zinc	mg/litre	888	99	923	1327

Table 32 Tar Analysis for Paper&Card & Food for Thermochemical Tests

		Pyrolysis	**Updraft gasification**	**Downdraft gasification**	**Fluidised Bed gasification**
SVOC-Top 10 Compounds					
Phenol	mg/litre	879	339	1324	325
2-Methylphenol	mg/litre	1011	187	672	265
Naphthalene	mg/litre	810	228	562	143
Nitrobenzene	mg/litre	548	200	446	122
4-Methylphenol;	mg/litre	176	132	328	89
2-Methylnaphthalene	mg/litre	300	90	154	77
2,4-Dimethylphenol	mg/litre	287	76	254	102
Phenanthrene	mg/litre	23	69	35	57
Fluorene	mg/litre	71	19	65	12
Anthracene	mg/litre	65	12	43	13
VOC-Top 10 Compounds					
Benzene	mg/litre	154	28	225	34
Toluene	mg/litre	1658	40	209	16
Ethylbenzene	mg/litre	42	19	55	12
m and p Xylene	mg/litre	16	6.2	12	8.6
o-Xylene	mg/litre	6.1	<0.5	3.8	<0.5
Styrene	mg/litre	6.2	<0.5	3.1	<0.5
Isopropylbenzene	mg/litre	<0.5	<0.5	<0.5	<0.5
Propylbenzene	mg/litre	<0.5	<0.5	<0.5	<0.5
1,2,3-Trimethylbenzene	mg/litre	<0.5	<0.5	<0.5	<0.5
1,2,4-Trimethylbenzene	mg/litre	<0.5	<0.5	<0.5	<0.5
Metals					
Arsenic	mg/litre	0.9	19	1.3	13
Cadmium	mg/litre	2.6	19	1.2	23
Chromium	mg/litre	4.5	35	3.1	23
Cobalt	mg/litre	5.2	8.9	1.4	16
Copper	mg/litre	7.8	32	12	21
Lead	mg/litre	6.1	34	3.7	22
Manganese	mg/litre	18	29	12	22
Mercury	mg/litre	<0.1	<0.1	<0.1	<0.1
Nickel	mg/litre	2.6	9.9	1.5	12
Thallium	mg/litre	<0.1	<0.1	<0.1	<0.1
Vanadium	mg/litre	<0.1	0.7	<0.1	1.3
Zinc	mg/litre	7.8	40	12	32
Calorific Value and Moisture					
Gross CV	KJ/Kg	13111	19105	12433	18978
Net CV	KJ/Kg	12176	17755	11543	17635
Moisture	% w/w	55.9	7.6	62.1	8.9

Following both the updraft and down draft tests for Food and Paper and Card, rust and unusual deposits were observed in the coolers, as shown in **Figure 27** and **Figure 28** respectively. The rust is likely to be due to high levels of moisture I the gas, in turn coming from moisture in the feedstock (particularly foodstuffs), although the nature and source of the white deposits are currently the subject of further investigation although appear similar to those produced by the solidification of siloxanes commonly present in biogas. The source of this gas (*i.e.* food) is similar to that often digested to produce biogas, and hence it may be that certain compounds present in foodstuffs lead to the formation of this type of deposit.

Figure 27 Downdraft Gasification (Food and Paper and Card) Cooler 1 – Rust

Figure 28 Downdraft Gasification (Food and Paper and Card) Cooler 4 - White Deposits

Table 33 Mass Balances for Thermochemical Test with Food and Paper & Card

Pyrolysis	C						H						N						O						S				T [^{o}C]
Fuel Analysis	53.5						3.9						2.2						40.4						0.1			[% w/w]	700
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												73.8	75
	0.0111	0	0.3882	0.027	0	0.4076	0.001	0.0019	0.0565	0.0001	0	0.0013	0.0001	0	0	0	0	0.0341	0.0011	0.015	0.6438	0.0041	0	0	0.00001	0.0003	0.0015		
Updraft Gasification	C						H						N						O						S				T [^{o}C]
Fuel Analysis	53.5						3.9						2.2						40.4						0.1			[% w/w]	740
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												84.3	40
	0.0033	0	0.4775	0.082	0	0.2616	0.0003	0.0001	0.0272	0.0001	0	0.0324	0.0001	0	0	0.0001	0	0.0337	0.0005	0.0003	0.6926	0.0595	0	0	1.00E-06	0.00014	0.0014		
FB Gasification	C						H						N						O						S				T [^{o}C]
Fuel Analysis	53.5						3.9						2.2						40.4						0.1			[% w/w]	800
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												87.6	45
	0.031	0	0.7952	0	0	0.3509	0.0026	0.0004	0.0495	0	0	0.0333	0.0003	0	0	0.0001	0	0.0481	0.0047	0.0034	1.2837	0	0	0	0.0001	0.00000003	0.0022		
Downdraft Gasification	C						H						N						O						S				T [^{o}C]
Fuel Analysis	53.5						3.9						2.2						40.4									[% w/w]	900
Product Analysis	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Tar	Water	Gas	Bed Residue	Cyclone Ash	Other	Gas	Bed Residue	Other	Mass Balance	Stable period
																												96.1	35
	0.0388	0	0.8871	0.1469	0	0.2046	0.0032	0.0088	0.0803	0.0004	0	0.0004	0.0006	0	0.0001	0.0002	0	0.0517	0.0058	0.0704	1.1276	0.0297	0	0	5.00E-06	0.0002	0.0022		

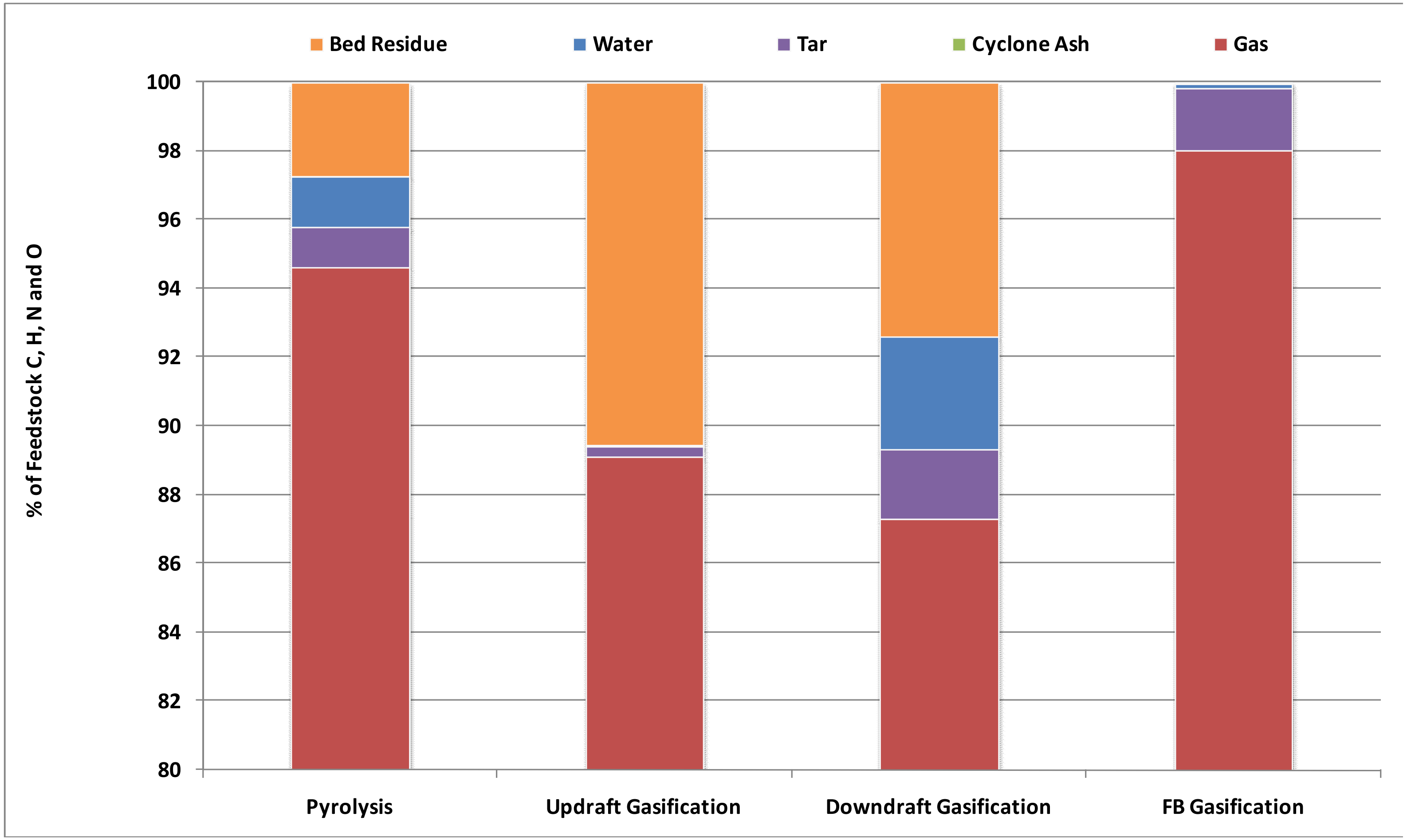

Figure 29 Proportions of Products (by weight) for Thermochemical Test with Food and Paper & Card Normalised to Measured Components

Results Analysis

The following discussion reviews the findings from all tests carried out. Other than some of the results from the demolition wood tests shown in the previous section, the additional results for demolition wood tests and the complete data sets for the other waste mixes are reported as an appendix to this report.

Most of the waste materials tested had a low ash content and were therefore suitable fuels for fixed bed gasifiers; high ash fuels can lead to problems in controlling the flow of the fuel through the reactor and disrupt steady gas production for which fuel-bed permeability is critical. In general, low levels of methane were generated for all the technologies because the water-gas shift reaction, which produces carbon dioxide and hydrogen, was dominant over the methanation reaction. The dominance of the water-gas shift reaction is usually due to a high availability of moisture. The fuel analysis (as presented earlier) show typical values of 5-10% moisture present in the feedstocks.

A more detailed assessment of the chemical compositions of the gases formed in the thermochemical tests on the basis of past experience indicates that some of the results are affected by errors. Taking into account the proportions of the products from each technology, almost all the fluidised bed gasifier results are similar for each fuel investigated. In general this finding is true for most of the other technologies, but there are some values which are suspect; e.g. the results of the updraft and downdraft with Food & Paper & Card, the pyrolysis and downdraft results with Wood & Film Plastics, and the pyrolysis results with Wood & Textiles. These discrepancies may be the result of changes in the type of fuel used in the different tests (as discussed earlier) or may be due to non-optimized operating conditions for the tests concerned. In addition, the hydrogen level in all pyrolysis results are higher than for industrial units due to the different method of heating the reactor in the current project (trace heating instead of flue gas from a supplementary combustor). Another factor, due to a batch test approach being used, the residence time in the pyrolysis bed was high creating a condition where more complete breakdown of the waste structure can occur. In some tests, especially in the updraft gasification of Wood, Paper & Card & Dense Plastics, Textiles & Film Plastics, and Food & Paper & Card, the nitrogen level in the gas appears too high leading to dilution of the gas and a consequent loss in calorific value. This may be due to the nature of these batch tests which were not fed continuously and to non-optimised operating conditions that did not allow complete break-down of the waste structure. Some of the downdraft gasification tests appear to have suffered from the same problem (Wood & Film Plastics, Paper & Card & Dense Plastics, and Textiles & Film Plastics).

Detailed assessment of the test results presented above allowed a more thorough understanding of the quality of the thermochemical tests in terms of achieving conversion of the feedstock. An analysis of the carbon conversion, mass balances and the calorific value of the gas produced is presented in **Table 34** as calculated from the equations presented in Appendix C to this report. A “gas efficiency” was also calculated to compare the conversion of the energy value of the solid feedstock to gaseous fuel on mass basis. The quality of the test is also illustrated in **Table 34** using a “traffic light” system, where green is a “good” result (the results are comparable with the data found in literature), yellow represents some deviation from an expected value, and red shows that the value obtained in testing is markedly different from a reasonable value for that result. The green flag is assigned to experimental result values similar to those found in literature, such as calorific values of the gas between 5 and 10 MJ/kg or carbon conversion values above 60% of the initial carbon. The red flag is assigned to unexpected values. For each test, an overall colour code is assigned based on the lowest rating for any of the results for that test.

Overall, at least one fully successful test was carried out with each technology, with the exception of the fixed bed rig operated in pyrolysis mode. Three successful tests were carried out using the downdraft rig and two for the updraft and fluidised bed rigs. The textiles and film plastics and food and paper & card appear to have been the most difficult to process within the test program, with no successful tests having been completed with these materials. On a positive note, however, only one test produced results which were labelled yellow and red in all aspects. Hence, all other tests have been useable for the development and validation of different aspects of the software models produced in Work Package 3 of this project, for which these tests were originally carried out. The results show that the CV of the produced gas (for successful tests) was generally in the range of 5 – 10 MJ/Kg, although that produced from Food and Paper & Card waste is slightly lower. These values are typical, although on the lower end, of those produced from gasification reactions [1]. However, all gasification gases are relatively low specific energy content to Natural Gas, which has a higher heating value of around 50 MJ/Kg (depending on exact methane concentration).

Although the tar concentration values listed in **Table 34** are indicative of likely outputs from the feedstocks in each technology, it should be bourn in mind that these values are calculated from the volume of tars measured in the cooling chambers in the gas path of the rigs over the duration of each test. As such, these measurements are affected by the operating history of the rig, as tars from previous tests may be transported to the pots. In addition, the tar collected is that which has condensed over the entire test duration, not just the steady state gasification portion of the test, and so will include that produced during prior reactions, which may include high tar production phases such as pyrolysis. Despite these limitations, a general impression of the level of tar production from each feedstock and technology can be garnered, with levels typically in the order of 10’s of thousands of mg/Nm^3 of gas. These values are also widely reported from other sources, such as the Handbook of Biomass Gasification [2] []. In determining acceptable levels of tar concentrations for downstream gas use, the condensation of tars is a cumulative process, and so any level of tars in the gas will cause degradation of the downstream equipment. The effect of tars on the gas usage is discussed later in this report. Analysing the data in detail, it can be seen that high CV values can be found in pyrolysis due to the high hydrogen content into the product gas (hydrogen level is high because the reactor was heated using trace heating rather than combustion products from burning supplementary fuel), while the CV values of the other technologies is given mainly by the CO content into the product gas. It should also be noted that the nitrogen content in pyrolysis is lower than in gasification, and this gives a substantial benefit to the CV values due to less dilution by inert nitrogen. Moreover, the gasification technologies use air to oxidise the fuel and this leads to different chemical reactions that occur between fuel and combustion air.

Table 34 Quality check in-terms of efficiency and calorific values for thermochemical tests.

		CV gas [MJ/kg]	Gas efficiency [%]	Carbon conversion [%]	Mass Balance [%]	Tars content [mg/Nm^3]
Pyrolysis	Wood	7.9	48.5	37.2	77.4	158450
	Wood & LDP	7.0	62.2	33.9	80.2	134590
	Wood & Textiles	4.4	19.2	16.4	74.5	281930
	Textiles & LDP	11.1	81.1	60.8	89.5	57610
	Paper & HDP	10.3	93.0	57.3	77.7	30930
	Paper & Food	10.3	91.3	47.9	73.8	4060
Updraft Gasification	Wood	4.6	22.0	49.1	71.5	21670
	Wood & LDP	7.6	91.1	90.8	75.0	22510
	Wood & Textiles	4.8	56.9	56.8	84.1	51910
	Textiles & LDP	3.6	8.3	88.6	95.4	49150
	Paper & HDP	2.9	18.1	91.0	84.5	52490
	Paper & Food	3.5	20.0	58.3	84.3	1510
Downdraft Gasification	Wood	4.9	51.8	89.0	97.6	22720
	Wood & LDP	3.7	27.8	91.6	89.3	5850
	Wood & Textiles	5.2	32.4	73.6	91.9	89120
	Textiles & LDP	4.4	13.2	48.2	82.5	12320
	Paper & HDP	3.6	14.8	60.3	89.9	20240
	Paper & Food	4.2	29.7	72.5	96.1	8700
Fluidised Bed Gasification	Wood	5.1	56.2	93.7	85.7	12350
	Wood & LDP	4.9	22.4	67.7	90.1	30880
	Wood & Textiles	4.6	51.1	94.7	88.7	29950
	Textiles & LDP	5.7	37.1	59.5	94.5	7340
	Paper & HDP	5.2	29.2	59.5	85.9	11440
	Paper & Food	4.4	33.4	70.2	87.6	7350

As can be seen in Table 34, all gasification technologies produce a large amount of gas compared to pyrolysis, which instead shows an increased formation of tar due to the limited cracking reaction of the fuel. Similarly, the char phase, in terms of bed residue and cyclone ash, is much lower for the gasification technologies than for pyrolysis.

Most of the red flags in Table 4 are related to the gas efficiency, in particular in the updraft and downdraft gasification tests. These results are questionable due to the presence of unburned fuel in the bed residues. Usually low values of the gas efficiency reflect low carbon conversion efficiency and a poor mass balance, as seen especially in the pyrolysis tests. The gas efficiency is an indirect measure of the tendency of the carbon to react with the oxygen and to form a syngas rich in CO, H2 and CH4. Low values of the gas efficiency will correspond to low syngas CVs.

The low values of gas efficiency in Table 34, especially in some updraft gasification tests (e.g. Textiles & LDP, Paper & Food, and Paper & HDP), reflect the low CO, H2 (and CH4) contents in the product gas. This could be due to two main factors: the process temperature and/or the equivalent ratio (ratio between the oxygen supplied in the process and the stoichiometric oxygen required for a complete combustion). In these cases, the gasification temperature was probably not sufficient to progress the gasification (i.e. the heat provided to the process was not enough to break all the chemical bonds in the waste materials and to promote and sustain all the gasification reactions). Also the equivalent ratio was probably too high or too low. In this situation, the oxygen supplied to the process promoted oxidation of the carbon in the fuel rather than the gasification reactions. Each waste fuel will have its own particular thermal conversion characteristics, and blends will have their own particular characteristics which are not necessarily a simple mixing of those of the feed materials. For example, we might expect that the mixtures of Wood & LDP and Wood & Textiles would show similar results, but we also have to consider that the results depend strongly on the parameters described above (temperature and equivalent ratio).

The post analysis of the component of the cyclone ash shows high levels of heavy metals such as lead, chromium, manganese, nickel, zinc, and copper in all the technologies and for all the fuels. These high values could come out from the high concentrations of metals in the fuels or from of erosion within the system (trace metals released from rigs materials), or from another unknown source.

Closely linked to the CV values are the gas efficiency values. Normally gas efficiency is an indicator of the quality of gas production. High CV values correspond to high gas efficiency values, while low values depend on the dilution of the product gas with nitrogen (the higher the nitrogen content, the lower will be the gas efficiency value).

Carbon conversion is also linked to the CV values, and is an indicator of how much carbon in the fuel is converted into gas or tar. Traditionally, gasification technologies give better carbon conversion values than pyrolysis, because the more severe environment in gasification is aimed at converting fuel carbon by reaction with oxygen, steam or CO2 to give CO and so these technologies have less carbon content into the ash, cyclones, and bed residue. Carbon conversion of 60% and above would be expected in the gasification of many fuels, and this has been achieved in most cases. Where this was not found, it is likely to be related to either specific characteristics of the waste mixes used or the premature completion of a test before the fuel bed had been consumed, making it difficult to estimate how much waste had actually reacted.
Table 34 highlights that after detailed review, mass balance closures are mostly good, above 80%, with many above 90%, which represents a good overall result for the testing programme given the approach adopted. The mass balance calculation procedure is detailed in Appendix B to this report. It would be normal to repeat tests several times to optimise operating conditions for stable operation and to re-evaluate analysis methods/results based on initial findings, but this was outside the scope for the thermal process testing in this project.

Although the tar concentration values listed in the previous tables are indicative of likely outputs from the feedstocks in each technology, it should be bourn in mind that these values are calculated from the volume of tars measured in the cooling chambers in the gas path of the rigs over the duration of each test. As such, these measurements are affected by the operating history of the rig, as tars from previous tests may be transported to the pots. In addition, the tar collected is that which has condensed over the entire test duration, not just the steady state gasification portion of the test, and so will include that produced during prior reactions, which may include high tar production phases such as pyrolysis. Despite these limitations, a general impression of the level of tar production from each feedstock and technology can be obtained, with levels typically in the order of 10's of thousands of mg/Nm3 of gas. These values are also widely reported from other sources, such as the Handbook of Biomass Gasification [1]. In determining acceptable levels of tar concentrations for downstream gas use, the condensation of tars is a cumulative process, and so any level of tars in the gas will cause degradation of the downstream equipment. The effect of tars on the gas usage is discussed later in this report.

Literature Comparison

The test results in Table 34 have been compared with suitable open literature data and are generally in reasonable agreement. Analysing the data in detail, it can be seen that high CV values can be found in pyrolysis due to the high hydrogen content into the product gas (hydrogen level is high because we heated the reactor using trace heating rather than combustion products from burning supplementary fuel), while the CV values of the other technologies is given mainly by the CO content into the product gas. It should also be noted that the nitrogen content in gases from pyrolysis tests are lower than those from gasification, and this gives a substantial benefit to the CV values due to less dilution by inert nitrogen. As indicated earlier, it is possible to adjust the pyrolysis results to allow for the different operation in the tests to bring them more into line with industrial scale results if needed. Moreover, the gasification technologies use air as the primary source of oxidant for the combustion and gasification reactions involved. Alternative oxidants such as steam are also often used to change the composition of the fuel gas produced. Depending on the mix of oxidants and their ratio with fuel components, the gases produced will vary in composition making difficult to make direct comparisons between tests carried out in different locations.

In order to benchmark the information gained from the thermal process testing, comparable test data were sought in the open literature. However, due to the novel nature of the materials used for the processes, very little comparative literature data was identified, especially related to the non-biomass materials. With respect to fuels used in other studies, each will have its own unique physical and chemical character, a product of the unique conditions under which it was formed. In addition, each technology will have its own gas flow and thermal transfer characteristics, and tests will have been conducted for different operating conditions. As a result, the best that can be achieved is to check whether the data from the thermal testing in this project, fall within the same data ranges from other work, where the fuels and test conditions will have been very different.

While further details of the available open literature data are given in the appendix, the following tables compare the data from the thermal testing with reputable sources where extensive data have been reviewed. For fixed bed updraft gasification, Table 35 makes the comparison with USDOE data for undisclosed types of biomass.

Table 35 Comparison of thermal testing data for fixed bed updraft gasification

	US DOE [3]	ETI EfW
CV [MJ/kg]	2.6 – 13.7	3.5 – 7
H2 [%vol.]	4.4 – 23	2 – 9.5
CO [%vol.]	11 – 39	5 – 20
CO2 [%vol.]	6 – 24	9 – 28
CH4 [%vol.]	4 – 6	2.5 – 7
N2 [%vol.]	35 – 64	37.5 – 72.5

In general, the data obtained from the thermochemical tests carried out for this work appear to be similar in magnitude to those published in the literature for updraft fixed bed gasification. However, it may be observed that the N_2 content of the gas appears high compared to the literature data. This leads to an increased gas dilution resulting in a lower concentration of the other species. This result is likely to be due to the effect of different operating conditions, gasifying agent, and fuel type (ref. Wood, Straw, MSW) used for the tests for this work.

Table 36 Comparison of thermal testing data for fluidised bed gasification

	US DOE [3]	ETI EfW
CV [MJ/kg]	4 – 16	4.5 – 7
H2 [%vol.]	4 – 43	2.5 – 5
CO [%vol.]	13 – 25	7.5 – 15
CO2 [%vol.]	12 – 40	15 – 20
CH4 [%vol.]	3 – 17	2.5 – 6.5
N2 [%vol.]	13 – 56	50 – 68

In fact, the USDOE data used a mixture of air/steam as gasifying agent which would be expected to produce a higher concentration of H_2 and CO in the gas, compared thermal tests using only air. Similarly, comparing the thermal tests with the typical gas composition from bubbling fluidised bed gasification of biomass given in [3] , a similar good correlation between the data sets may be observed in **Table 36**.

For the downdraft tests, comparison may be made to work published by the United Nations Food and Agriculture Organisation (FAO) [4] . Although this data is mature, the well developed nature of this type of gasification technology mean that such sources are still highly relevant. Comparing the current data to that of the FAO in **Table 37**, it can seen that a slightly lower H_2 and CO content of the gas measured for the current work as compared to typical biomass based gas compositions for this technology, although overall the other values correlate well, suggesting that the tests were conducted successfully.

Table 37 Comparison of thermal testing data for downdraft gasification

	FAO [4]	ETI EfW
CV [MJ/kg]		3.5 – 6.5
H2 [%vol.]	10 – 20	2.5 – 6
CO [%vol.]	15 – 30	6 – 17
CO2 [%vol.]	5 – 15	9 – 16.5
CH4 [%vol.]	2 – 4	1.5 – 4
N2 [%vol.]	45 – 60	50 – 73.5

For the pyrolysis technology tested, it was particularly difficult to find comparable data sources because there are several types of pyrolysis (slow, fast or intermediate) and their results depend essentially on the type and physical properties of the material used, the type of reactor and its operating conditions, and on how heat was exchanged with the material. To attempt to compare the data from the work with literature results, the test data has been compared with the typical gas compositions from slow pyrolysis in **Table 38**.

Table 38 Comparison of Cranfield data for slow pyrolysis

	Proceedings of 1st World Conference on Biomass [5]	ETI EfW
CV [MJ/kg]	7.8 – 11	5 – 12.5
H2 [%vol.]	2 – 5	20 – 35
CO [%vol.]	20 – 25	7.5 – 25
CO2 [%vol.]	30 – 45	9 – 30
CH4 [%vol.]	3 – 10	12 – 22.5
N2 [%vol.]	10 – 25	1.5 – 6

As can be seen from **Table 38**, values of H_2 and CH_4 were measured to be considerably higher in the present work than that presented in [5], whilst lower values of CO and CO_2 were measured. The likely explanation for this difference relates to the way in which the pyrolysis tests were conducted in the current project. Using the trace heated reactor at Cranfield meant that it was not necessary to provide a heat source from the combustion of another fuel or e.g. recycled tars, as is common in industrial pyrolysis processes. In such cases, the pyrolysis is diluted with the flue gases from the fuel burned, comprising additional CO_2 and N_2. Adjusting the results from the current work by increasing the levels of these species brings the gas compositions closer together. Another feature of an industrial style process is likely to reduce the highly reactive H_2 concentration further, as this would re-equilibrate in the mixed gas at a lower level.

The heating source is just one of several differences between available literature sources and the data generated by the current work for the slow pyrolysis gaseous products. In combination with other differences, such as reaction temperature, heating rate, type of feedstock (biomass vs. mixed wastes), reactor design and gas inert flow rate, this technology is very difficult to compare with the data of the existing literature. However, the outputs measured are of the appropriate type applicable to the input materials.

In general, the lack of comparable data highlights the novelty of the testing programme carried out, which should provide a good platform for more extensive waste fuel testing going forward in support of larger scale developments.

Discussion of Results

A comprehensive analysis of the bed residues, tars and ash as collected in the cycle for each test is presented. These data present the compositional break down of each of these components, with a particular focus on the metals content of each of them, as this is a key indicator as to the potential disposal route for each component. In general, the levels of trace metals found in the residues were high, corresponding to levels in the waste mix feedstocks. This issue will need detailed consideration moving forward to ensure that the necessary disposal routes and costs are allowed for.

The composition of the tars has been further analysed to account for the semi-volatile and volatile organic content (SVOC and VOC respectively) to indicate potential processing requirements to break up these elements. In general, high levels of tars were observed for all thermal tests conducted with (demolition) wood, with lower tars having been measured from the use of film plastic, paper and card and food. These observations may be linked to the microstructures of these materials; wood has a complex microstructure, which is only partially broken down by the time limited thermal reactions. Film plastics, by comparison, have a simple intertwined polymeric microstructure, which is easily and quickly broken down to its constituent elements by the thermal energy. Paper and Card and food also have easily accessible (thermally) microstructures, enabling their complete decomposition and hence low resulting tar levels. The microstructure of dense plastics is somewhat more complex, with binders tying the polymers together, resulting in some partially broken down elements occurring in the produced products. In terms of the metals components, the tar produced by fluidised bed gasification of all the materials can be seen to be high in chromium and cobalt, with extremely high levels of lead, zinc and manganese relative to the other gasification technologies for all tested feedstock materials. This may simply be the result of the differences in the test conditions between the different technologies. In the fluidised bed case, the exhaust gas velocity would have been higher than in the other cases and this may have ‘blown’ particulate-based trace species through the cyclone into the tar condensers. In an industrial plant designed for each technology, the cyclone gas velocities would be optimised for efficient particulate capture, whereas this was not possible in the testing carried out in this project.

The analyses also show high levels of heavy metals such as lead, chromium, manganese, nickel, zinc and copper in the cyclone ash for all the technologies and in all fuels (Appendix E). These high values need further investigation in any further development of waste gasification systems. Trace metals, such as lead and zinc, form volatile species in gasification processes and hence readily pass through particulate gas clean-up stages unless the operating temperature is below their condensation dewpoint. Marchwood Scientific, one of the third party analysis laboratories who carried out much of the chemical analysis, classified the cyclone ash as a hazardous waste under disposal regulations, making it very costly to deal with.

In addition to the measurement of CO, CO_2, CH_4, and H_2, technologically-relevant minor species such as NH_3, H_2S and HCl were measured. In most cases there was good agreement between the measured and back-calculated values of ammonia in the fuel gases. However, in some tests, the high ammonia levels are not comparable to values back-calculated from corresponding post-flare NO_x levels. While no full explanation of this can be made without further study, it is possible that this may be due to either some ammonia bypassing the flare or some of the ammonia being converted to molecular nitrogen. For the H_2S levels, there was good agreement between the measured H_2S level and that back-calculated from post-flare SO_x measurements. Where the measured H_2S values are greater than those derived from the post-flare SO_x values, measurement errors using the draeger tubes are suspected.

Ammonia and hydrogen sulphide can result in engine problems and emissions of NO_x and SO_x and so the levels to be expected in service and means of reducing these where required are critical for deployment. All these minor species were measured using draeger tubes which have limited accuracy and proved difficult to use in some cases as indicated in the appendix. While the emissions of these species are particularly important from an environmental perspective, they are also an indication of the gasification behavior of the feedstocks, as their values are strictly related to the nitrogen, sulfur and chlorine content into the fuel. In fact, the higher are the content of these elements in the fuel, the greater will be the emissions of the minor species.

Ammonia (NH_3) is the main product of nitrogen element formed during the gasification process (another one is HCN which we have not measured). This component can then react to form bonds with the tar, or can oxidize in presence of free oxygen in order to form NO_x or can react to form molecular nitrogen. H_2S is one of the main products of sulfur formed during gasification process (COS is the other one). This component can react easily with free oxygen in order to form SO_x or captured as S from the suspended particles. HCl is the only product of chlorine element formed during the gasification process (although trace metals are often transported as chlorides in the product gas, depending on HCl levels), but in presence of free chlorine it can react and form some other chlorine components such as dioxins.

The thermochemical test results indicate high level of ammonia for all fuels investigated in the fluidized bed gasifier and in the updraft gasifier, and low level in the pyrolysis and in the downdraft gasifier. With some exceptions, the picture is similar for the H_2S values, while it was often not possible to measure the HCl concentration in the fuel gas due to the blockages in the draeger tubes (there was a fouling of the draeger tubes by the particles and condensates).

Conclusions

The testing programme reviewed in this summary report was originally intended fill in gaps in available data in the public domain relevant to the technologies which could be employed at each stage of an advanced energy from waste system. However, it was found that only very limited suitable data were available on the operation of Gasification technologies using the mixed wastes, and so it was necessary to carry out a more fundamental study to determine the suitability of these technologies for use with highly variable mixed waste feedstocks.

For reliable system operation, it is essential to have an understanding of the properties of the fuel gases produced and their contaminants, as well as information other process products/residues and any operational problems which would need to be overcome. The novel test work conducted for the ETI Energy from Waste (FRP) project has provided valuable insight into the use of these technologies with mixed waste streams and empirical data to inform the development of computer-based models of advanced waste processing technologies.

The thermal testing programme met its main objective in confirming that it was possible to process mixed wastes of widely varying composition using thermal gasification/pyrolysis technologies. In addition, highly relevant waste feedstock and thermal process information were obtained to identify likely problem areas for future development and to inform the process modelling activities in the project.

Feeding and operational difficulties experienced during these tests emphasised the need for affordable pre-processing to produce a more homogenised feedstock. This emphasises the need to design any selected process as a complete system, from waste reception through to electricity/heat generation and emissions/residue control. The careful design of waste pre-processing, handling and feeding is just as important in delivering a reliable plant as the design of the main reactors or gas cleaning systems.

Fuel feeding problems were mainly influenced by the variation of the waste fuels and their properties like particle size, porosity, and moisture. In order to handle these problems several options were tried like varying particle size, improving the porosity of the materials and reducing the moisture content.

The data gathered, in conjunction with the subsequent modelling work, provide a platform from which to estimate the compositions and properties of the gases and tars generated from different processes along with the requirements for gas cleaning (e.g. removal of NH_3, H_2S and HCl) to avoid excessive emissions (of NO_x, SO_x and HCl) and downstream engine problems. In addition, data on the distribution of hazardous species and trace metals in the various residues provide a basis from which to develop/select further treatment steps prior to safe disposal or use.

Thermal tests showed a direct correlation of gas contaminants to their pre-cursor levels in the waste feedstocks. The nature of the materials in the mixed waste streams from domestic, commercial, industrial, construction and agricultural activities is such that a wide range of low volatility (tarry) and potentially corrosive elements and compounds are liable to be present in any gases derived from waste materials. For other contaminants, e.g. trace metals, information was obtained on partitioning between the various product and residue streams.

A summary of the main considerations for each of the technologies operating with mixed waste materials is presented in the following table.

Table 39 Summary of Process Technology Conclusions

Technology	General Considerations		Findings from Testing Programme	
	For	Against	For	Against
AD	Wet biodegradable wastes; right scale	Limited fuel options.	Good with food waste; possible to include paper/card	H_2S levels
Updraft Gasification	Simple technology; right scale	High tar levels; operation dependent on fuel properties	Problems with some fuels	Low/medium CV gas; high tar levels
Downdraft Gasification	Simple technology	Small scale only; operation dependent on fuel properties	Few operational problems	Low CV gas;
FB Gasification	Flexible medium scale technology	More complex equipment & operation	Fuel flexible; moderate tar levels; few operational problems	Low CV gas; high NH_3; risk of agglomeration
Slow Pyrolysis	Simple technology;	Operation dependent on fuel properties	High gas CV – high CH_4 and H_2; some operational problems	High tar levels

These considerations identify fluidised bed gasification as the most suitable technology. Downdraft gasification also demonstrated merits for smaller scale plants with waste streams of defined properties, but is restricted in scale-up due to difficulties in maintaining steady/uniform gas flows as the fuel bed cross section increases.

The operation of a reciprocating engine with clean gases of typical compositions as would be expected to be produced from of waste materials has been shown to be feasible. These tests show that a relatively high engine efficiency of 35% can be achieved without further optimisation, if the fuel system, engine hardware and operational parameters are appropriately designed. However, tars and other contaminants present in the gas from gasification processes would be expected to adversely impact engine performance, increasing engine service intervals and durations. This would thereby increase the cost of energy produced, ultimately impacting the realisation of the CO_2 emissions reductions which could be enabled.

The findings from the testing programme, in relation to the processing and gas utilisation technologies, reinforce the well-known critical nature of gas cleaning in enabling successful utilisation of the fuel gases produced in high efficiency systems. Although not a distinct area of investigation within the current project, it is expected that the key development opportunities required to enable the efficient use of waste materials would be in the area of gas cleaning, as further detailed in report 3.3 of this project.

References

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Appendix I: Safety Procedures

The experimental use of any thermal equipment can be hazardous, and gasification is intended to generate gases containing potentially toxic constituents. To minimise the risk of personal injury or damage to equipment, strict health and safety regulations were adhered to at all times. All personnel working in the area were fully briefed on the standard operating procedures for each of the rigs, and were fully inducted to the relevant safety procedures to have a complete understanding of the emergency procedures (such as fire, gas leak etc) in place at Cranfield University. All equipment was thoroughly checked for safe working condition prior to work commencing.

Potential risks included:
Fire
Explosion
Burns
Gas exposure
Electrocution in case of contact with electricity
Compressed gases and test rigs can build internal pressure
Manual handling
Moving parts

The likelihood of occurrence of these risks has been deemed to be minimal if the work is carried out in a highly competent manner, ensuring that all necessary personal protective equipment [PPE] is worn and that all procedures are adhered to. Only trained personnel were authorised to enter the vicinity whilst work is being carried out. Warning signs were present outside the test facility to prevent unauthorised entry at all times during testing. It was not possible for the facility to be locked for this purpose as the doors were required to remain open for ventilation during all testing. During testing the facility was well ventilated and all personnel were obliged to carry a carbon monoxide [CO] monitor, which would sound if CO was detected. In the event of CO being detected, work would cease immediately and personnel would evacuate the building. Similarly, CO_2, H_2S and SO_2 personal monitoring detectors were also used by all personnel operating the rigs. Staff who were trained in the use of breathing apparatus were on site to assist in the event of gas escape. Several staff who were involved in this test programme were trained as first aiders. Burns will be prevented by briefing all personnel [including visitors] prior to entry of the facility. All PPE advised by technical staff, and that specified in Cranfield's procedures was worn at all times. No personnel were allowed to work alone at any time whilst the rigs are in operation.

Personal Protection Equipment

The following Personal Protection Equipment (PPE) was required to be worn by all personnel operating the Cranfield rigs at any time:
Overalls
Lab coats
Protective disposable gloves and high temperature protection gloves
Portable CO gas monitor per person
Safety boots: High leg lace-up with toe protection
Dust mask

Safety glasses or similar [goggles etc]
Other flue gas personal monitors.

The PPE was in addition to a range of other equipment was made available prior to any test to ensure the safe and efficient operation of each test. This equipment included:
Warning notice outside rigs
Labelled pre-prepared samples
Scales
Marked gangways
Mechanical lifts
Inter-locks for compressed gases
First aid boxes
Fixed guards for moving parts such as feed system and air extraction

Visitor Welfare

Due to the consortium based nature of this project, provision was made for visitors (non Cranfield personnel) to be present during rig set-up and/or tests being carried out. Visitors were required to report to technical personnel on their arrival. No visitor was to enter the test area during testing unless fully inducted and provided with all required PPE, and all visitors had to comply with all health and safety procedures at all times and to follow the instructions of Cranfield University staff.

Standard Rig Operating Procedures

Each of the two rigs used at Cranfield University was operated to a similar test protocol as outlined below.

Throughout the test programme
Check that there is sufficient liquid nitrogen in the tanks i.e. at least one full tank
Check that there are personnel gas detectors available (minimum is one CO) and other gas detectors

1 Day before test – Overnight heat-up (Updraft Only)
Trace Heating Panel (Downstairs)
Switch power onto panel (3 indicator lights (top left) are on). Note if there is no power check the grey fuse box on the wall next to the small storeroom door.
Switch to Timer (Timer/Off/Override)
Next switch along (extraction fan) needs to be on
Set rig trace heating at different capacity to achieve the stable temperature of around 500-600 oC before the system turned into gasification mode

2 hours before test start
Trace Heating Panel (Downstairs)
Set rig trace heating for cyclone, sample line heater and filter h
For all of above set switches below to On (Off/On/Off/On)

Air/Flare Panel (Upstairs)
Turn power on and accept alarm

Push Reset button
Push switch at end of permanent pilot panel (first red light should be on)
Push second switch down then back up to light pilot (second light indicates sparking)
Third light staying on indicates that pilot has lit (Pulses)
If third light does not stay on then repeat steps 2-4

For pyrolysis, turn nitrogen on to get good indication of gasification and for fixed bed turn nitrogen and air on to get stable gasification period
Turn fluidising medium on (200 l/min mixed air and nitrogen or amount to get good indication of fluidisation from the pressure indication on the gauges bottom right of spout air rota meter)

30 minutes before start
Nitrogen needs to be turned on (liquid nitrogen tanks at end of building).
Turn the datalogger on and start saving the data

10 minutes before start
Check that the personnel gas detectors are working and positioned

Appendix II: Mass Balance Calculation Procedure

Mass balances was calculated for each of the successful thermal experimental tests by a calculation of all the masses involved in the three "phases" (tar, gas, and char) produced by the thermal processes in relation to their occurrence in the feedstock. The calculation was made using the results from the third party laboratory post-test analysis of the composition of tar and char (especially species that were contained in both phases), and the measures of the gaseous species made during testing with a gas-analyser. To provide a mass balance the molar weight of each element in the species found during the post-analysis were individually calculated, and then summed per element. The process for performing the overall mass balance calculation is shown below using a worked example of the downdraft gasification test of Demolition Wood. The first step of the calculation is illustrated for the tar phase for this test in Table 40.

Table 40 Example: Mass Balance of Tar Phase

	[g/l]	**C**	**H**	**N**	**O**	**S**	**Tot.**
Phenol	1.015	0.77744681	0.064787		0.17276596		1.015
2-Methylphenol	0.91	0.70777778	0.067407		0.13481481		0.91
Naphthalene	0.456	0.4275	0.0285				0.456
Nitrobenzene	0.657	0.38458537	0.026707	0.07478	0.17092683		0.657
4-Methylphenol	0.324	0.252	0.024		0.048		0.324
2-Methylnaphthalene	0.127	0.11805634	0.008944				0.127
2,4-Dymethylphenol	0.135	0.10622951	0.011066		0.01770492		0.135
Phenanthrene	0.098	0.09249438	0.005506				0.098
Fluorene	0.115	0.10807229	0.006928				0.115
Anthracene	0.076	0.07691566	0.004578				0.021
Benzene	0.068	0.06276923	0.005231				0.068
Toluene	0.132	0.12052174	0.011478				0.132
Ethylbenzene	0.043	0.0389434	0.004057				0.043
m-p-Xylene	0.022	0.01992453	0.002075				0.022
o-Xylene	0.008	0.00724528	0.000755				0.008
Styrene	0.006	0.00553846	0.000462				0.006
Isopropylbenzene	0.0007	0.00063	0.00007				0.0007
Propylbenzene	0.0005	0.00045	0.00005				0.0005
1,2,3-Trimethylbenzene	0.0007	0.00063	0.00007				0.0007
1,2,4-Trimethylbenzene	0.002	0.0018	0.0002				0.002
TOTAL AMOUNT	4.1959	3.30953077	0.27287	0.07478	0.54421252	0	

Similarly for the char phase (Bed Residues and Cyclone Ash), the calculation for the mass balance was made using the post analysis data, including C, H, N, O, S, Cl content as illustrated in Table 41.

Table 39 Example: Mass Balance of Char Phase

Bed Residue [kg]			0.051047945			
C	H	N	O	S	Cl	
84.1	0.1	0.1	15.8	0.1	0.1	[%wt.]
0.042931	5.1E-05	5.105E-05	0.008066	5.1E-05	5.1E-05	[kg]
Cyclone Ash [kg]			0.01808			
C	H	N	O	S	Cl	
68.0	-	-	-	-	-	[%wt.]
0.012291	0.00000	0.00000	0.00000	0.00000	0.00000	[kg]

To calculate the output gas composition, the assumption was made that the overall gas stream had the same gas compositions as the sub-stream that was analysed using the gas analysis equipment for each test.

This analysis sub-stream had a flow rate of 0.15 l/minute and it formed only a part of the total gas flow capacity. The total amount of the sub-stream was calculated for whole stable period of the test and then multiplied by a factor calculated using the theoretical production of the total gas flow stream. After that, each of the gas constituents and main contaminants were converted from their volumetric basis to their mass basis. The molar masses of each of these elements were then used to break down the measured compounds into the elemental masses, as shown in table 42.

Table 40 Example: Mass Balance of Gas Phase

CO [%v/v]	CO_2 [%v/v]	CH_4 [%v/v]	SO_2 [ppmv]	H_2 [%v/v]	NH_3 [ppmv]	NOx [ppmv]	H_2S [ppmv]	
6.7	9.0	0.9	40	3.1	25	200	0	
0.1005	0.135	0.0135	0.0000006	0.0465	3.75E-07	0.000003	0	l/min
10.6865	14.355	1.4355	0.0000638	4.9445	3.9875E-05	0.000319	0	l/min
309.9085	416.295	41.6295	0.0018502	143.3905	0.00115638	0.009251	0	l
2676.446567	3595.2267	359.5227	0.015978785	1238.35587	0.00998674	0.079894	0	l
29.02923988	38.994501	3.89945	0.000173309	13.4314393	0.00010832	0.000867	0	mol
812.8187167	1715.7581	62.3912	0.011091769	26.8628787	0.00184141	0.029463	0	g
	C [g]	H [g]	N [g]	O [g]	S [g]	Cl [g]		
CO	348.35088			464.467838			812.819	
CO_2	467.93402			1247.82404			1715.76	
CH_4	46.793402	15.5978					62.3912	
SO_2				0.00554588	0.00554588		0.01109	
H2		26.86288					26.8629	
NH_3		0.000325	0.001516453				0.00184	
NOx			0.012131623	0.01733089			0.02946	
H_2S		0			0		0	
	870.36638	43.06834	0.013648075	1712.31476	0.00554588			

The elements used for this mass balance are C, H, O, N,S and Cl. The calculations used to derive the mass balance are based on the balances of the measured elements only. The calculations were performed based on the Equations 1 to 4:

$$MB = ((M_{TAR} + M_{GAS} + M_{CHAR} + M_{AIR})/(M_{FUEL} + M_{AIR})*100 \qquad \text{eq.1}$$

$$C_{\%TAR} = (M_{C,TAR} / M_{C,FUEL})*100 \qquad O_{\%TAR} = (M_{O,TAR} /(M_{O,FUEL} + M_{O,AIR}))*100 \qquad \text{eq.2}$$

$$C_{\%GAS} = (M_{C,GAS} / M_{C,FUEL})*100 \qquad O_{\%GAS} = (M_{O,GAS} /(M_{O,FUEL} + M_{O,AIR}))*100 \qquad \text{eq.3}$$

$$C_{\%CHAR} = (M_{C,CHAR} / M_{C,FUEL})*100 \qquad O_{\%CHAR} = (M_{O,CHAR} /(M_{O,FUEL} + M_{O,AIR}))*100 \qquad \text{eq.4}$$

In relation to the accurately measured input mass, the unmeasured elements and other measurement inaccuracies would contribute to differences in total input and output mass, and hence the completeness of the mass balance. The final mass balance as broken down by the output Tars, Gas, and Char is presented in Table 43 . To give an indication, typically more than 75% of the input fuel mass can be accounted for in the mass balance using the measurement and analyses techniques employed for this project.

Table 41 Example: Final Mass Balance

Fuel Analysis	C [g]	H [g]	N [g]	O [g]	S [g]	Cl [g]	Total
	1.39093	0.18996	0.02576	1.60987	0.00322	0.00322	
Tar	0.14393	0.01187	0.00325	0.02367	0	0	0.18271
Gas	1.09447	0.07283	1.36E-05	1.71231	5.546E-06	0	2.87964
Water	0.00000	0.02268	0	0.18144	0	0	0.20412
Bed Residues	0.04293	5.105E-05	5.1E-05	0.00807	5.105E-05	5.105E-05	0.05120
Cyclone ash	0.01229	0	0	0.00000	0	0	0.01229
Tot.	1.29363	0.10743	0.00332	1.92549	5.659E-05	5.105E-05	4.10103
							Mass Balance
Diff.	0.09730	0.08254	0.02244	-0.31562	0.00316	0.00317	97.60

During the test it was not possible to measure some species such as light hydrocarbons or other species containing sulphur or chlorine or nitrogen. Furthermore, information about the content of hydrogen, nitrogen, sulphur, chlorine and oxygen into the char phase could not be economically measured in the scope of this project. It should be bourn in mind though, that a large proportion of the feedstock mass which is not accounted for in the mass balance are the dense trace metal elements. These metals would be expected to report to the tars, in which they were analysed by weight as presented in the results workbook for each test. As such, the mass balances can be used to give a preliminary indication of the main products into which the predominant chemical elements in the feedstock report.

Appendix III: Test Result Calculation Equations

The following conversion equations were used for each test to assess the test quality:

The calorific value of the produced gas was calculated using the calorific value of the major gas species included into the gas (CO = 11.95 MJ/m^3; CH4 = 33.95 MJ/m^3; H2 = 10.05 MJ/m^3):

$$LHV_{Gas} = LHV_{CO} \bullet x_{CO} + LHV_{CH_4} \bullet x_{CH_4} + LHV_{H_2} \bullet x_{H_2}$$

where LHV_i and x_i are the calorific value and mass fraction of the gas species respectively. The cold gas efficiency (η_{CGE}) was calculated by:

$$\eta_{CGE} = \frac{m_{gas} * LHV_{gas}}{m_{Fuel} * LHV_{Fuel}}$$

and the carbon conversion (η_{CC}) was calculated by:

$$\eta_{CC} = \frac{(m_{C,b} - m_{C,E})}{m_{C,b}}$$

where $m_{c,b}$ is the total mass of carbon into the biomass and $m_{c,e}$ is total mass of carbon into the ash and bed residue, plus the unmeasured carbon.