



Gasification of Synthetic *CDW 1*

REPORT

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Summary

Hawaii Natural Energy Institute (HNEI) issued a request for bench-scale, fluidized bed, biomass gasification test services. ThermoChem Recovery International, Inc. (TRI) which owns and operates a Feedstock Test Reformer (FTR) was awarded a contract to perform gasification trials of HNEI feedstocks. Two trials were performed, one with clean wood and another with construction and demolition (C&D) waste. The objective of these tests was to evaluate the preliminary performance and operability of the steam reforming system for processing these feedstocks. Specific targets of investigation included operational characteristics such as agglomeration-free operation, product gas composition and yield, tars yield, fate of contaminants, preliminary estimate of carbon conversion, analysis of bed solids and filter catch solids, and stability, reliability, and safety of operation. This report provides details of the test and the results for C&D Waste, Synthetic CDW 1 supplied by HNEI.

This work comprised tasks pertaining to feeder calibration with feedstock, test facility modification, test plan development, test system preparation, test unit commissioning, testing, data and sample acquisition and analysis, data reduction and reporting.

The test was conducted successfully in the TRI Feedstock Test Reformer located at the TRI Advanced Development Center in Durham, North Carolina. Highlights:

- ➔ The feedstock gasified well with no agglomeration and no operability issues,
- ➔ The feedstock yielded a medium calorific value syngas, and
- ➔ The feedstock is an excellent candidate for conversion into biofuel/power/biochemical using the TRI steam reforming technology.

Objectives

The primary objectives and evaluation criteria for a successful TRI FTR test are as follows:

1. Determine if the HNEI feedstock can be fed at a steady rate by the feeder
2. Determine the properties of the HNEI feedstock
3. Evaluate the preliminary performance and operability of the steam reforming system for processing the HNEI feedstock
4. Check for the formation of agglomerates or degradation of the bed media
5. Determine the product gas composition, yield, and H₂ to CO molar ratio
6. Confirm that the steam reforming process, using the FTR, can produce a syngas from the HNEI feedstock with a stable gas composition
7. Quantify and speciate the volatile organic compounds (VOC) and semi-volatile organic compounds (SVOC) in the gas stream
8. Quantify the contaminants (S, Cl, and N compounds) and metals in the syngas stream
9. Determine the carbon content of the bed solids and filter catch solids
10. Perform an elemental mass balance and determine the carbon conversion
11. Evaluate the stability, reliability, operability, and safety of the process

Test Facility Description

TRI has constructed and commissioned a nominal 2.25 kg/h (~5 lb/h) feedstock to syngas steam reformer, which is ideally suited to execute project pre-feasibility steam reforming tests on a variety of feedstocks. The FTR is located at TRI's Advanced Development Center (ADC) in Durham, North Carolina and comprises the following components and subsystems:

- Solid feedstock metering and feed subsystem;
- Indirectly heated steam reformer vessel (150-mm or 6-inch nominal diameter);
- Steam generation and metering subsystem;
- Fluidization gas (other than steam such as CO₂ and O₂) metering and preheating subsystem;
- Hot gas filter;
- Product gas sampling trains for gas composition, particulates, tars, and contaminants;
- Gas chromatograph (GC) for monitoring product gas composition;
- Oxidizer; and,
- Instrumentation and controls.

Figure 1 shows the feeder system, which injects feedstock into the gasifier at a specified rate.

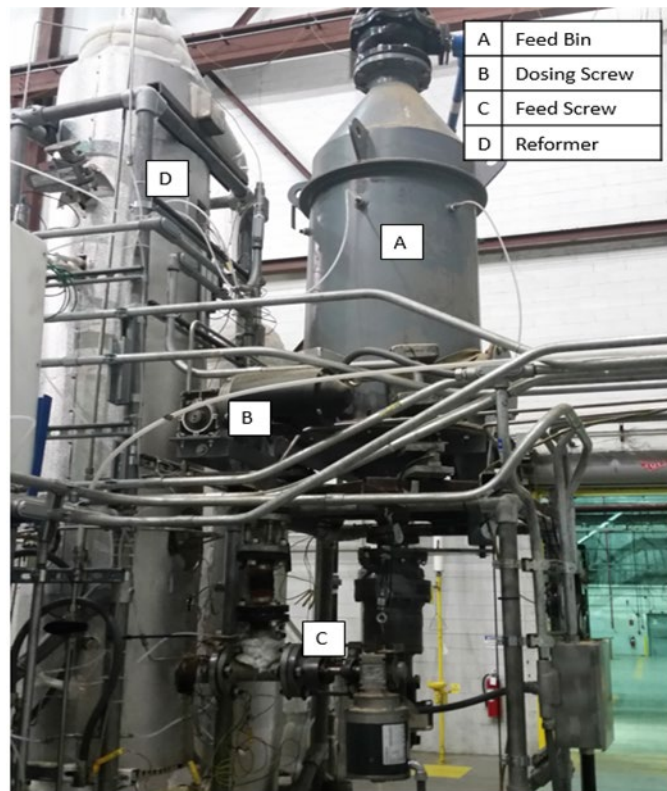


Figure 1. TRI FTR Feeder System

The reformer fluidized bed can operate at a wide range of temperatures, typically ranging from 600°C (~1100°F) to 785°C (~1450°F). The bed is fluidized with steam during normal operation and uses nitrogen or carbon dioxide for fluidization startup and instrumentation purges. Oxygen is added as necessary to simulate commercial scale operation. All fluidization and purge gases are carefully metered. While in the reformer, the feedstock is directly contacted by the fluidized bed particles and rapidly heated close to the bed temperature. It undergoes the following steps:

- Drying and Devolatilization, where water and volatiles are released in the form of steam, H₂, CO, CO₂, CH₄, and some hydrocarbons;
- Steam Reforming, where organic carbon endothermically reacts with steam to generate H₂ and CO;
- If oxygen is injected, partial oxidation where organic carbon exothermically reacts with oxygen to form mainly CO;
- Water-Gas and Hydrogenation reactions where pyrolysis products react with steam and hydrogen to reduce contaminants into water-soluble compounds that are readily captured and removed during syngas cleaning steps; and,
- Water-Gas Shift reaction, a reversible reaction where steam reacts with CO to generate H₂ and CO₂.

Fluidization gas and steam are pre-heated using gas heaters (F) before entering the reformer (D) as shown in Figure 2 below. Clamshell type heaters affixed to the outside of the reformer (D) provide indirect heat to maintain the target bed temperature and supply the endothermic heat of reaction. The temperature of the gas heaters (F), various sensors, and flow rates of all entering and exiting streams are monitored, actuated, and controlled via the control panel (E) and Distributed Control System (DCS) screens (not shown).

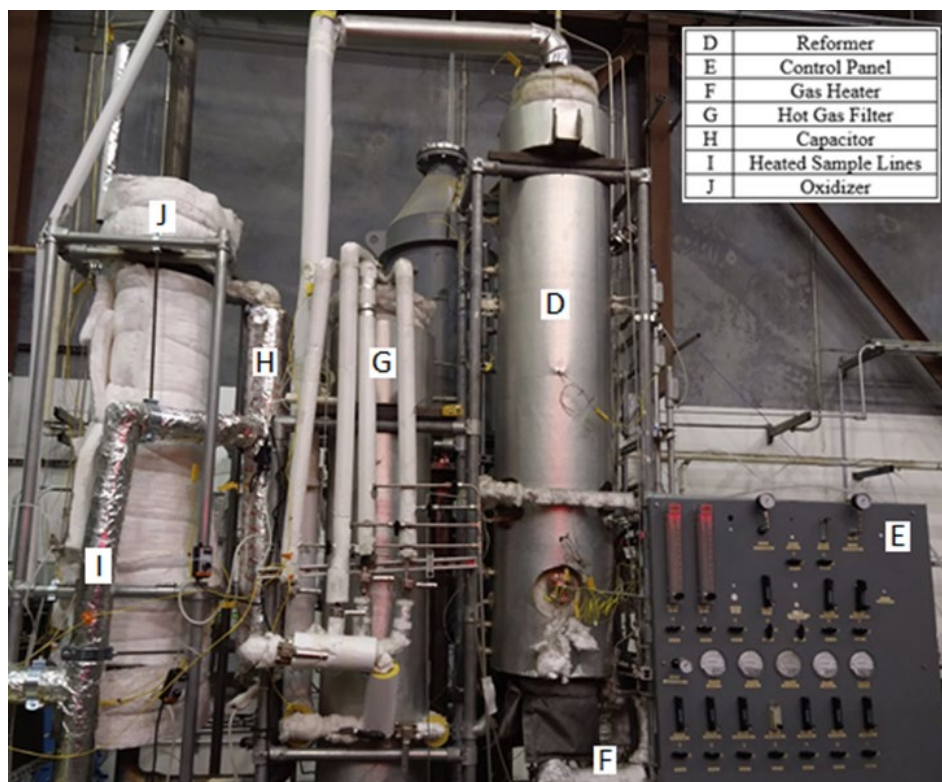


Figure 2. TRI FTR Front Side

Following the reformer (D), the product gas, comprised primarily of H_2 , CO, CO_2 , N_2 (depending on fluidization gas chosen), steam, and hydrocarbons proceeds through a hot gas filter (G) to remove particulates including carbon and ash; the hot gas filter has a pore size of 0.5 microns. From the hot gas filter (G), the product gas goes into a capacitor (H) which has five slipstreams directed from it. Three of these slipstreams are directed through heated sample lines (I) to impinger trains, the other two are directed out the back of the FTR, shown in Figure 3. The remaining product gas that is not pulled through the slipstreams goes from the capacitor to the Oxidizer (J) where it is fully oxidized, and then out through the flue vent (not shown).

As shown in Figure 3, two slipstreams are taken from the rear side of the capacitor (H). The one on the right is a cooled slipstream (L) that allows for metals sampling of the product gas. The left slipstream goes to the GC Water Impinger (M), which is part of the GC sample conditioning system (partially shown here). The GC Water Impinger (M) removes any solid particulate and some of the water that may be entrained in the product gas. After the GC Water Impinger, the product gas enters a chilled, vertical free water knockout vessel (not shown) which removes any remaining water in the product gas which might otherwise form hydrates, tight emulsions, or cause corrosion. The condensate collected in the water knockout (not shown) is stored in a set of two impingers (not shown) which sit in an ice water bath (not shown). From there, the slipstream goes to the GC (not shown). The cooling water to the Cooled Slipstream (L), the GC Water Knockout (M), and the vertical free-water knockout vessel (not shown) are provided by the Recirculating Chiller (N).

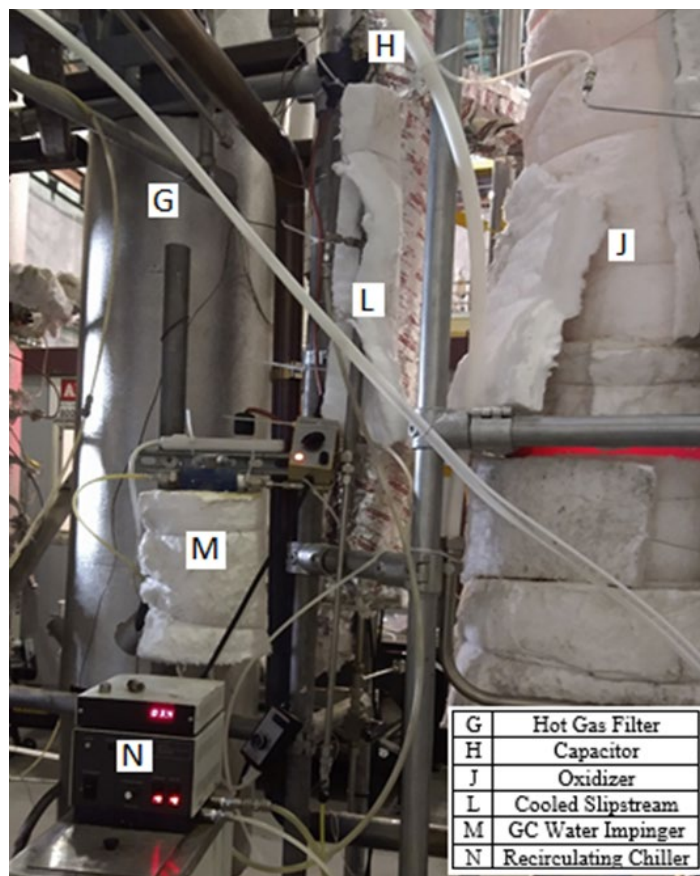


Figure 3. TRI FTR Back Side

System control is achieved through a commercial quality DCS which includes a historian data acquisition system. Temperature and feed rate sensor data are stored in the historian for recording and analysis, including the online GC data, which is collected every 6 minutes, and results are written to the historian. Thermal Desorption Tubes (TDT) and Tedlar Bag samples are taken during periods of steady state operation to measure the concentration of volatile organic compounds (VOC), semi-volatile organic compounds (SVOC), and other species in the syngas stream that cannot be quantified by the online GC.

The three slipstreams flow through Heated Sample Lines (I). Line 1 goes to a set of impingers which are used to sample condensate liquids which are condensed from the product gas. Line 2 goes to a sample point that is used for sampling TDT and Tedlar bags. Line 3 goes to a Heated Filter Box which allows for the filtration of particulate materials without cooling the gas stream, after which it goes to a set of impingers that are used to sample HCl, NH₃, and HCN gases. The metals sampling slipstream is directed through a glass tubed heat exchanger (L), then through plastic tubing, and finally through a set of glass impingers. This allows us to sample any condensate in the slipstream that forms on the tube wall without risking metal contamination from tubing material.

Each of the three impinger trains have the same arrangement for the instrument clusters and sample pumps which are used to monitor, calculate, and draw a known volume of sample gas. After the train, there is a coalescing filter, then an instrument cluster consisting of a rotameter, a thermocouple, a manometer, and a dry gas meter. After the instrument cluster, there is a “T,” with one line going to the sample pump and the other going to a needle valve and atmospheric air intake. The needle valve is used to control the suction on the impinger trains by drawing air into the sample pump. After the sample pump, the line goes to the Oxidizer.

Feedstock

The feedstock used in the FTR trial was 100% Synthetic CDW 1, ground to a particle size that is less than 6 mm (0.25 inch) in diameter. The feedstock size requirement for the reformer system is based on the projected residence time in the fluid bed and the material handling capabilities of the feeder system. For the FTR, the feedstock particle specification is 6 mm minus (1/4") i.e., the top size is nominally 6 mm (1/4") or 216 cubic mm equivalent (1/64 cubic inch). The feedstock was processed and supplied by HNEI personnel; it was double bagged, shipped, and stored in four separate containers. Shipping and storage conditions were mild, with no temperatures being hot or cold enough to affect the feedstock samples and so it is reasonable to assume that no changes to the material occurred between its creation and the testing. There was no visible contamination. Overall, the sampled feedstock was consistent, as can be seen in Figures 4 and 5.

Samples were evaluated in triplicate at the ADC using TRI's standard methods to measure average Particle Size Diameters, Moisture Content, and Bulk Density; the Sauter Mean Size and Fines Content were also calculated using these measurements. These data are provided in Table 1. The average Sauter Mean Size was 1251 microns, with a standard deviation of 176 microns. The Fines Content of the material, which is defined as the percentage of mass that falls through #20 Sieve (Mesh Size 841 microns), was 15.5%, with a standard deviation of 3.44%. This is slightly above TRI feedstock guidelines of a Fines Content below 15% by weight but is still considered acceptable for these tests. The average moisture was 9.0% with a standard deviation of 0.7%. The Bulk Density was 264.2 kg/m³ (16.5 lb/ft³), with a standard deviation of 11.5 kg/m³ (0.72 lb/ft³). Samples of the feedstock were also sent to external labs for ultimate, proximate, and ash elemental analyses and ash fusion temperature. These are provided in Tables 7, 8, and 9 and Appendix A.

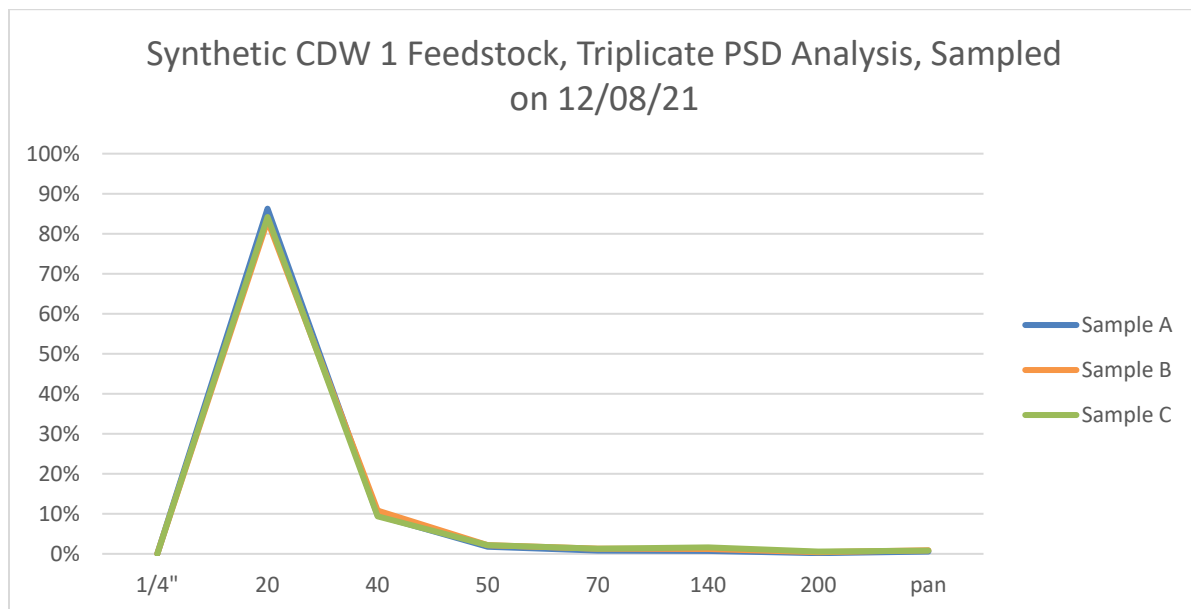


Figure 4. Synthetic CDW 1 Feedstock, Weight Percent Retained by Sieve Mesh Size

Triplicate Sample Averages for Synthetic CDW 1 Feedstock			
Screen #	Mesh Size (microns)	Mass Fraction, xi	SD
1/4"	7097	0.0%	0.0%
20	841	84.5%	1.5%
40	420	9.9%	0.8%
50	297	2.1%	0.2%
70	210	1.1%	0.3%
140	105	1.2%	0.4%
200	75	0.4%	0.2%
pan	0	0.8%	0.2%

Parameter	Value	SD
Sauter Mean Size (microns)	1251	176
Percent Fines (%)	15.5%	3.4%
Moisture (%)	9.0%	0.7%
Standing Bulk Density (kg/M3)	264.20	11.50

Table 1. Synthetic CDW 1 Feedstock, Sample Averages



Figure 5. Synthetic CDW 1 Feedstock

Test and Results

A detailed test plan was prepared. The test system was prepared and checked out. Feeder calibration tests with the Synthetic CDW 1 feedstock were performed prior to testing. The test was then performed in accordance with the test plan and all process parameters (temperatures, static and differential pressures, flow rates, etc.) were monitored and recorded. The feed subsystem clogged twice during the test, with both occurrences happening before a steady state was reached and sampling had begun. Both instances required the FTR system to be stopped and the bed to be slumped while the feed subsystem was opened and unclogged. After the feed subsystem was unclogged, the bed was fluidized and the feeder was restarted. These occurrences are not expected to have had a significant effect on the test.

The fluidized bed material consisted of 14.5 kg (32.0 lb) of engineered alumina which was weighed and loaded into the FTR before the test.

The fluidization medium was a blend of steam, at a set rate of ~2.25 kg/h (5 lb/h) and 99.9% purity Carbon Dioxide; Carbon Dioxide was used as a cofeed to ensure satisfactory fluidization quality while matching commercial system steam-to-carbon ratio (the driving force for the reactions). Carbon Dioxide was employed as purge gas in the feed hopper and in all the instrumentation ports. Due to the small size of this unit, the carbon dioxide content of the syngas was disproportionately high (60 to 70% by volume on a dry basis). But for the CO₂ dilution, the syngas composition is representative of the gasification process and therefore provides high-quality, scalable data. In a full-scale commercial system, the carbon dioxide concentration in the syngas is estimated to be 15-20% by volume.

The weigh bin was loaded with 32.8 kg of Synthetic CWD 1 feedstock prior to the test. After the test, a total of 16.5 kg of feedstock was retrieved from the weigh bin. A mass of ~0.7 kg was lost due to spillage when the feed system was unclogged. A total of 15.7 kg of feedstock was fed into the system over a total time of 5 hours and 4-minutes; this calculates to an overall average feedstock feed rate 3.2 kg/h. The average feedstock feed rate during the 2 hour and 20-minute sampling window, as measured by the change in the weights in the weigh bin, was ~2.9 kg/h. The nominal average bed temperatures were 745°C with an SD of 2.3°C during the sampling window. The measured temperature profile is shown in Figure 6. Figures 7 and 8 and Table 2 provide the feedstock's syngas composition during the sampling window. Helium was injected and used as a tie-in element for mass balance.

A major component of this successful gasification trial was confirmation of agglomeration-free operation. This was monitored via the steam reformer temperature data and physically verified after the test. Throughout the trial, temperature data were recorded every second via 5 thermocouples at 5 locations within the bed. The temperatures, especially those at locations 1 through 5 did not exhibit any significant divergence i.e., excursions remained below 14°C (25°F) after steady state was achieved thereby confirming absence of hot spots and in turn lack of bed agglomeration. An examination of the final bed at the conclusion of the trial corroborated this finding as well.

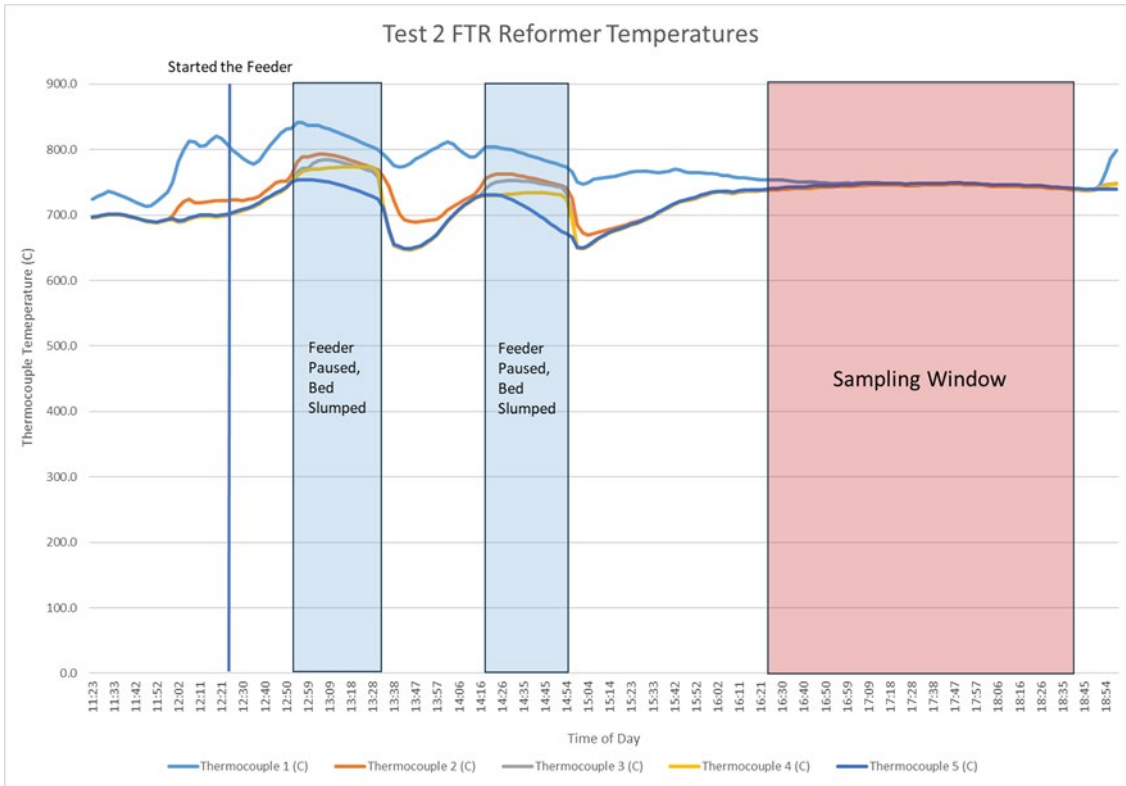


Figure 6. FTR Temperature Profile

The Impinger, TDT, and Tedlar bag sampling began after steady state was reached. This sampling period lasted for approximately 2 hours and 20 minutes, during which time temperatures and feed rates were very stable.

Synthetic CDW 1, Syngas Composition During Steady State (Volume Basis Dry)		
Compound	Average	SD
Helium	0.56%	0.03%
Hydrogen	12.49%	0.50%
Nitrogen	0.60%	0.19%
Methane	5.22%	0.11%
Carbon Monoxide	15.29%	0.44%
Carbon Dioxide	63.72%	0.78%
Ethylene	1.70%	0.24%
Ethane	0.24%	0.01%
Hydrogen Sulfide	0.15%	0.02%
Propane	0.02%	0.00%
Isobutylene	0.01%	0.01%
Butane	0.00%	0.00%

Table 2. Steady State Syngas Composition of Synthetic CDW 1 Feedstock

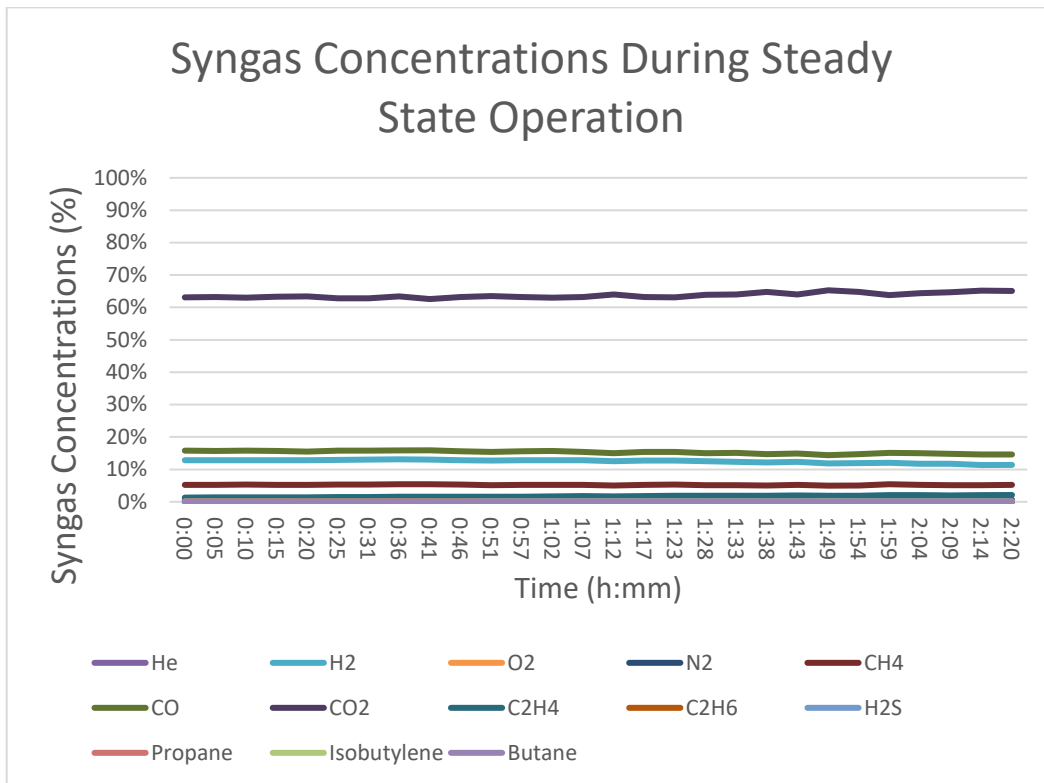


Figure 7. Syngas Concentrations During the Sampling Window

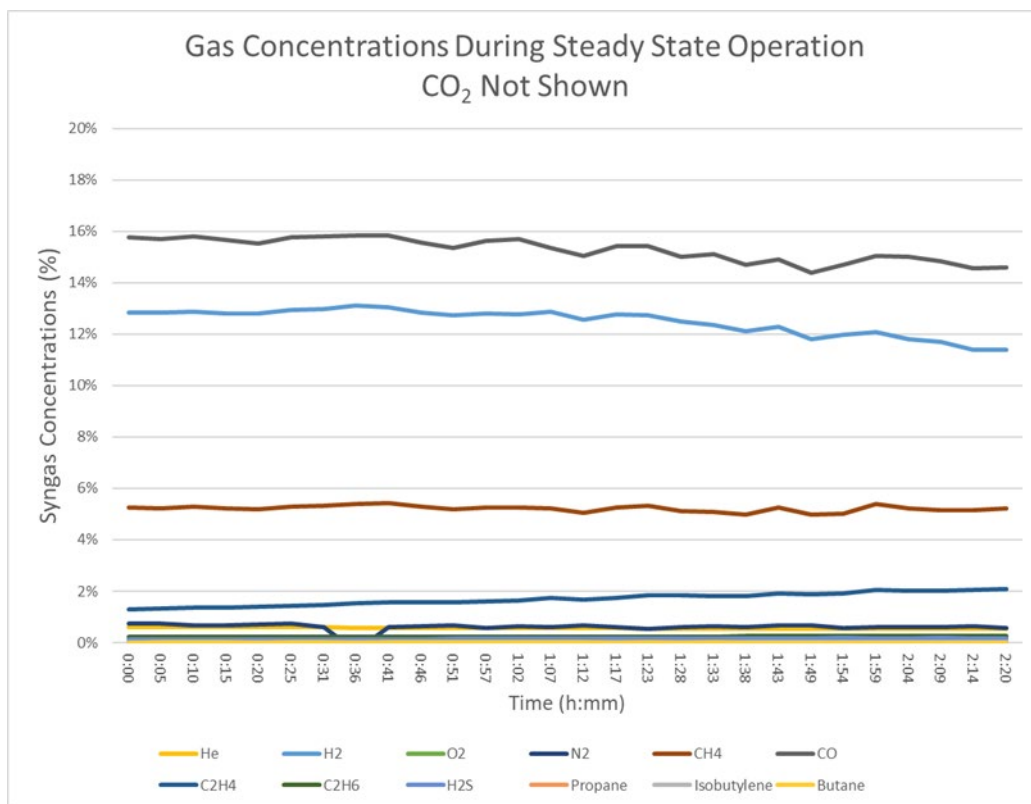


Figure 8. Syngas Concentrations (CO₂ not shown) During the Sampling Window

When the operation was steady, three sets of impinger trains were used to sample the syngas stream for Metals, Condensate, HCl, HCN, and NH₃. Table 3 below shows the sampling durations and sampled volumes of process gas, corrected to NPT, as calculated by Dry Gas Meters. Rotameters were used to provide an instantaneous flow rate measurement and to monitor the sample collection rates, the Dry Gas Meters provided the total volumetric flow for the test duration. During the test sampling period, the rotameter readings were constantly monitored and stayed steady, but were not recorded. Small leaks were found in front of the Dry Gas Meters in Trains A and C. These leaks were quantified after the test and the Dry Gas Meter volumes were corrected. These leaks are not believed to have affected any other sections of the instrument clusters and are not expected to have introduced contamination into the samples.

Impinger Train Sample Durations and Sample Volumes (NPT)			
Impinger Train	A	B	C
Analysis	HCl, HCN, NH₃	Condensate	Metals
Sample Time (HH:MM)	0:56	2:07	1:29
Dry Gas Meter Volume (L)	61.8 +/- 3%	646.1 +/- 3%	515.4 +/- 3%
Grams of Syngas Sampled	88.4 +/- 3%	933.0 +/- 3%	743.7 +/- 3%
Dry Gas Meter Accuracy: +/- 3% Permissible Error or measurement			

Table 3. Sample Durations and Calculated (NPT) Sample Volumes of the Impinger Trains

The Metals sampling was performed via an impinger train set up according to the guidelines of EPA Method 29. In lieu of the sampling probe that the method calls for, a slipstream of process gas is taken at the capacitor and passed through a water-cooled glass heat exchanger, then a Polypropylene tube (McMaster, Part Number: 5392K11), and finally into the impinger train. The particulate filter was not used because the sample point is past the main particulate filter and its catch is already analyzed for metals. The first impinger was a 1 liter, straight stemmed, glass impinger which was left empty. The second impinger was a 0.5 liter, straight stemmed, glass impinger which had 100 ml of a trapping solution consisting of 5% HNO₃ and 10% H₂O₂ in aqueous. The third impinger was a 0.5 liter, Greenburg-Smith stemmed glass impinger which had 100 ml of a trapping solution consisting of 5% HNO₃ and 10% H₂O₂ in aqueous. The fourth impinger was a 0.5 liter, straight stemmed, glass impinger which was left empty. The fifth impinger was a 0.5 liter, straight stemmed, glass impinger which had 100 ml of a trapping solution consisting of 4% KMnO₄ (W/V) and 10% H₂SO₄ (V/V) in aqueous. The sixth impinger was a 0.5 liter, straight stemmed, glass impinger which had 100 ml of a trapping solution consisting of 4% KMnO₄ (W/V) and 10% H₂SO₄ (V/V) in aqueous. The seventh impinger was a 0.5 liter, straight stemmed, glass impinger with 250 g of Drierite. Each impinger was set into an ice bath for the duration of the test. The target sample volume and flow rate were 1 cubic meter of gas NTP over 1 hour, the actual sample volume and flow rate was calculated to be 0.52 +/- 17% cubic meters of gas NPT over 1 hour and 29 minutes. The glass tube, polyline tubing, impinger glassware, and impinger solutions were collected and rinsed according to EPA Method 29 guidelines. The samples were sent to Element One Inc. (e1lab.com) for analysis according to EPA Method 29 guidelines. Samples were analyzed for mercury on a PerkinElmer FIMS-100 CVAA mercury analyzer and for metals on a PerkinElmer Nexlon 350X ICP-MS.

The HCl, HCN, and Ammonia sampling was performed via an impinger train set up as per the guidelines in EPA 26a and CARBM 426 methods. There were a few notable differences. First, the NaOH in the CARBM 426 Method was replaced with KOH due to supply chain issues, this was approved by the customer and the analytical lab and is not anticipated to have changed the underlying chemistry of the analytical procedure. Second, due to the possible presence of oxidative

materials precipitating onto the filter or tubing, any rinse used on surfaces after the heated filter is included with the HCl analysis; this may bias the HCN analysis low as any HCN which would have been collected in the rinse is not being analyzed. Third, the impinger solution concentrations and volumes were adjusted from the values in the EPA methods to capture the anticipated concentrations of their respective analytes. Fourth, the ammonia sampling was added to the lab analysis after the test and sampling was performed; this means that the analysis may have a low bias due to its method CTM-027 guidelines not being precisely followed. Fifth, in lieu of the sampling probe which the method calls for, a slipstream of process gas is taken at the capacitor and passes through a heated section of stainless-steel tubing which is kept above 260°C (500°F). Then the slipstream passes through a heated (>120°C (250°F) quartz fiber filter (2.20 µm Pore Size) with a micron rating of 2.1 to 2.2 microns, a short polyline tube and finally the impinger train. The impinger train was set up as follows. The first impinger was a 0.5-liter, shortened straight stemmed, glass impinger which had 50 ml of a trapping solution consisting of 0.1 N H₂SO₄ in aqueous. The second impinger was a 0.5-liter, Greenburg-Smith stem, glass impinger which had 150 ml of a trapping solution consisting of 0.1 N H₂SO₄ in aqueous. The third impinger was a 0.5-liter, Greenburg-Smith stem, glass impinger which had 100 ml of a trapping solution consisting of 0.1 N KOH in aqueous. The fourth impinger was a 0.5-liter, straight stemmed, glass impinger which had 100 ml of a trapping solution consisting of 0.1 N KOH in aqueous. The fifth impinger was a 0.5-liter, straight stemmed, glass impinger with 250 g of Drierite. Each impinger was set into an ice bath for the duration of the test. The target sample volume and flow rate were 60 cubic liters of gas, NTP, over one hour, the actual sample volume and flow rate were calculated to be 61.8 +/- 3% cubic liters of gas, NPT, over 56 minutes. Sampling was consistent with EPA 26a and CARBM 426 guidelines. The lines were rinsed with 114.6 g of 0.1 N H₂SO₄ solution that was included in the HCl impinger bottle (Bottle 3 in the method) for analysis. The pH of both impingers 3 and 4 (HCN/NH₃ analyses) was evaluated with indicator strips and was found to be between 8 and 9, indicating that there may have been a possible breakthrough of analytes. Sample preservation was consistent with method guidelines, approximately one g of KOH chips was added to the HCN/NH₃ sample to bring the pH back up above 12. No oxidative materials were found in the filter, sample, or rinse via Starch Iodide test strips as per CARBM 426. Samples were sent to Element One for analysis according to EPA 26a and CARBM 426 guidelines. HCl and NH₃ analyses were performed on a Metrohm 861/788 ion chromatograph system. HCN analysis was performed on Genesys 10S UV-VIS Spectrophotometer. The results are presented in Table 4.

Synthetic CDW 1, HCL, HCN, NH ₃ , and Metals Impinger Lab Results				
Analytes	Detected Mass		Concentration (per g Syngas)	
	HCL	33.6	mg	3.80E-01
HCN	964.0	ug	1.09E+01	ug/g
NH ₃	0.8	mg	9.21E-03	mg/g
Arsenic	150.8	ug	2.03E-01	ug/g
Cadmium	0.2	ug	2.22E-04	ug/g
Chromium	13.0	ug	1.74E-02	ug/g
Lead	2.1	ug	2.80E-03	ug/g
Magnesium	14.6	ug	1.96E-02	ug/g
Phosphorus	3.8	ug	5.11E-03	ug/g
Potassium	20.5	ug	2.76E-02	ug/g
Selenium	0.4	ug	5.80E-04	ug/g
Sodium	199.0	ug	2.68E-01	ug/g
Zinc	23.7	ug	3.19E-02	ug/g
Mercury	12.7	ug	1.70E-02	ug/g

Table 4. HCL, HCN, NH₃, and Metals Impinger Lab Results

The HCL, HCN and NH₃ concentrations in syngas all seem low with NH₃/HCN ratio remarkably high compared to past measurements (typical ratios of 6 to 10). It seems there is error either in sampling or analysis or both. Several metals were detected including arsenic and mercury. It is possible that part of the arsenic vaporized and was present as a compound in the syngas. It is likely that the rest of the metals were in the fine solids which slipped through the hot gas filter and carried over in the syngas stream. For many of the elements, the measured mass in the fuel input was greater than the mass recovered (HGF solids, final bed, and syngas). Conversely, for some elements (Fe, Ni, Ti, and Zn) mass recoveries were higher in the output streams than were delivered to the reactor in the fuel; it is possible that the reactor working surfaces may have contributed to this outcome. The discrepancies may also be due to sampling and analysis errors; in reality, multiple samples must be analyzed to provide reasonable closure. The latter will however increase the test cost. It may also be worth considering the addition of a trace inorganic element to the feedstock and track its closure to assess the quality of the test results.

The condensate sampling was performed via an impinger train. A slipstream of process gas was taken at the capacitor and passed in series through a heated section of stainless-steel tubing kept above 260°C (500°F), a short, uninsulated section of stainless-steel tubing, and then the impinger train. The first impinger was a 1 liter, straight stemmed, glass impinger which was initially empty. The second impinger was a 0.5 liter, straight stemmed, glass impinger which was initially empty. The third impinger was a 0.5 liter, straight stemmed, glass impinger with 250 g of Drierite. Each impinger was set into an ice bath for the duration of the test.

The prerogative of the condensate sampling was to collect as much condensate as possible over the duration of the test. A volume of 226.5 g of condensate was collected from a calculated volume of 0.65 +/- 38% cubic meters of gas, NPT, collected over 2 hours and 7 minutes. The condensate was transferred to a plastic bottle, along with 93.6 g of DI water used to rinse the impingers and stored at an ambient temperature until it could be diluted to an adequate volume of 5.5 kg and sent to ENCO Laboratories for analysis. The sample was diluted in a polypropylene vessel which was cleaned to the same standards as the impingers and put into bottles which were provided by the lab. The dilution factor was 25.1, made by initially diluting the collected 226.5 g of condensate with

93.6 grams of DI H₂O rinse and later to a mass of 5,681.6 g. A 5.5 kg sample of the type 2 DI H₂O drum was also placed in the dilution vessel and sent to the lab for analysis as a blank.

A summary table of the analytical lab results is provided in Table 5 after correcting for DI water blank. The full report is included in Appendix B. The condensate indicates the presence of organics (mainly Acenaphthylene, Phenol, and Naphthalene), suspended solids (confirms slippage of fine particulates from the hot gas filter), and nitrogen compounds. The ammonia concentration seems reasonable, but the NH₃/HCN ratio seems high. The pH is 3.0 which is quite acidic.

Synthetic CDW 1, Condensate Results				
Analyte	Results		Concentration (per g Syngas)	
Acenaphthylene	10000.00	ug/L	2553.1	ug/g
Acrylonitrile	160.00	ug/L	40.8	ug/g
Arsenic - Total	13.00	ug/L	18.4	ug/g
Phenanthrene	2200.00	ug/L	561.7	ug/g
Phenol	17000.00	ug/L	4340.2	ug/g
Phosphorus - Total	0.21	mg/L	0.1	mg/g
Sulfide	0.05	mg/L	0.0	mg/g
Zinc - Total	10.21	ug/L	2.6	ug/g
Ammonia as N	11.00	mg/L	2.8	mg/g
Benzene	1800.00	ug/L	459.5	ug/g
Cyanide (total) - Total	0.29	mg/L	0.1	mg/g
Toluene	239.18	ug/L	61.1	ug/g
Chloride	78.00	mg/L	19.9	mg/g
Chloromethane	2.80	ug/L	0.7	ug/g
Chromium - Total	12.70	ug/L	3.2	ug/g
Ethylbenzene	1.32	ug/L	0.3	ug/g
Naphthalene	29000.00	ug/L	7403.9	ug/g
Nickel - Total	8.40	ug/L	2.1	ug/g
pH	3.00	pH		
Total Kjeldahl Nitrogen	12.00	mg/L	3.1	mg/g
Total Organic Carbon	22.00	mg/L	5.6	mg/g
Biochemical Oxygen Demand	10.00	mg/L	2.6	mg/g
Chemical Oxygen Demand	45.00	mg/L	11.5	mg/g

Table 5. Condensate Summary

The initial and final solids inventory is provided in Table 6. A total of 16.3 kg of feedstock was fed into the FTR. There is an increase in bed mass due to partially devolatilized feedstock and char retention. The hot gas filter collection comprised fine char particles carried over in the syngas stream as well as some attrited bed material.

Test 2, Solids Budget			
	Feedstock	Bed	Hot Gas Filter Catch
Start (kg)	32.1	14.5	0
End (kg)	15.7	15.7	1.2

Table 6. Test 2 Solids Budget

Ultimate, proximate, and ash analyses of feedstock, final bed material and hot gas filter catch are presented in Tables 7, 8, and 9, respectively. The feedstock has a composition akin to wood but with a high ash content and has much more sulfur and chlorine in comparison to wood; there are traces of arsenic and mercury. The computed alkali number is modest (~0.105 kg/GJ) but is below the limit of 0.34 kg/GJ for operation of the reformer in dry ash rejection mode or non-slagging mode.

Alkali Number =

$$\frac{\sum((\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{Li}_2\text{O}) \text{ by weight fraction in bone dry feedstock})}{\text{HHV}}$$

The minerals data suggest that some of the ash is retained within the bed. Under steady state operating conditions, the fluidized bed ash and carbon content will achieve equilibrium and the carryover rates of carbon and ash will closely match those in the feed provided there is no accumulation in the bed that may lead to agglomeration or clinker formation. The data in this test demonstrates agglomeration-free operation. The presence of volatiles in the hot gas filter catch suggests that some of the elutriated particles did not fully devolatilize in the steam reformer due to the short residence time, some of the tars condensed onto the particles in the Hot Gas Filter, or both. There is chlorine and sulfur present in both bed material and hot gas filter catch. Either these were not yet released from the feedstock or present in inorganic form in the ash due to reaction with alkali and calcium. Hot gas filter catch has a relatively high alumina content suggesting bed material attrition and carryover. Arsenic is present in both final bed material and hot gas filter catch. However, the arsenic balance or closure is poor with arsenic outflow in Syngas, Bed, and Hot Gas Filter Catch being far smaller than the arsenic inflow from the feedstock suggesting either non-homogeneity of the feedstock in arsenic content or measurement error. Most of the other metals show similar discrepancy.

Synthetic CDW 1, Ultimate Analysis						
Parameter	Feedstock		Post-Test Bed		Hot Gas Filter Catch	
	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis
Total Moisture (%)	10.07		0.10		3.41	
Ash (%)	11.47	12.75	97.69	97.79	68.56	70.98
Carbon (%)	40.61	45.16	1.90	1.90	29.27	30.30
Hydrogen (%)	4.95	5.51	0.08	0.08	0.30	0.31
Nitrogen (%)	0.11	0.13	0.02	0.02	0.11	0.12
Oxygen (%)	32.45	36.08	0.06	0.06	-1.97	-2.03
Sulfur (%)	0.34	0.38	0.15	0.15	0.320	0.330
Chlorine (%)	0.131*	0.146*	0.016	0.016	1.888	1.955

*Value appears to be low based on the materials used in the Synthetic CDW.

Table 7. Ultimate Analysis

Synthetic CDW 1, Proximate Analysis				
Parameter	Feedstock		Hot Gas Filter Catch	
	As Received	Dry Basis	As Received	Dry Basis
Total Moisture (%)	10.07		3.41	
% Ash	11.47	12.75	68.56	70.98
% Volatile Matter	65.83	73.21	4.58	4.75
% Fixed Carbon	12.29	13.66	23.13	23.94
Higher Heating Value (GJ/Tonne)	17.07	18.98	9.58	9.92

Table 8. Proximate Analysis

Synthetic CDW 1, Ash Elemental Analysis			
Parameter	Feedstock	Post-Test Bed	Hot Gas Filter Catch
Aluminum (Al) mg/kg	8211	42650	64310
Antimony (Sb) mg/kg	< 0.22	1.35	26.11
Arsenic (As) mg/kg	221.7	31.76	605.8
Barium (Ba) mg/kg	544.6	72.4	2249
Cadmium (Cd) mg/kg	4.705	0.174	8.726
Calcium (Ca) mg/kg	12780	3407	48520
Chromium (Cr) mg/kg	216.5	66.8	1213
Cobalt (Co) mg/kg	3.71	1.72	12.45
Copper (Cu) mg/kg	124.8	33.3	452.2
Iron (Fe) mg/kg	10750	3681	15880
Lead (Pb) mg/kg	495.7	151.5	698.9
Magnesium (Mg) mg/kg	797.6	371.6	3148
Manganese (Mn) mg/kg	145.1	50.9	266.3
Mercury (Hg) mg/kg	0.091	< 0.020	< 0.020
Molybdenum (Mo) mg/kg	< 0.6	0.7	12.5
Nickel (Ni) mg/kg	22.7	117.4	3245
Phosphorus (P) mg/kg	140	< 100	453
Potassium (K) mg/kg	671.2	568.7	1832
Selenium (Se) mg/kg	0.58	< 0.50	1.5
Silicon (Si) mg/kg	10690	9227	24810
Sodium (Na) mg/kg	873.3	854.3	2698
Tellurium (Te) mg/kg	< 1.0	< 1.0	< 1.0
Thallium (Tl) mg/kg	<3.9	< 3.9	< 3.9
Tin (Sn) mg/kg	1.1	0.9	22.3
Titanium (Ti) mg/kg	1125	1617	13130
Vanadium (V) mg/kg	19.4	8.8	32.4
Zinc (Zn) mg/kg	1258	407.4	2015

Table 9. Ash Elemental Analysis

A Tedlar Bag sample was analyzed by Intertek using GC-FID (per ASTM D7833 method), GC-TCD (per ASTM D7833), GC-SCD (per ASTM D5504), and GC-NCD (per ITM 1535). These analyses are to determine the speciation and quantification of various carbon, nitrogen, and sulfur compounds present in the syngas. Potential issues with these analyses may be the decomposition of certain species due to the relatively long hold time between sampling and analysis, as well as the adhesion to the inside of the bag. The results summary is provided in Table 10. The GC-TCD and GC-FID data of syngas composition are in reasonable agreement with the online GC data indicated in Table 2 and Figures 8 and 9. The GC-NCD indicated an ammonia concentration below detection limit. The GC-SCD data suggests a high concentration of H₂S relative to COS which is in line with previous measurements which TRI has seen in past steam reforming tests. The data indicates the presence of methyl mercaptan and other sulfur species such as dimethyl sulfide.

Synthetic CDW 1, ASTM D7833, GC-TCD	
COMPONENT	MOL %
HELIUM	0.37
HYDROGEN	9.76
CARBON DIOXIDE	57.75
HYDROGEN SULFIDE	0.15
OXYGEN/ARGON	0.92
NITROGEN	3.57
CARBON MONOXIDE	20.36
Sum of Fixed Gas	93.87

Synthetic CDW 1, ASTM D7833, GC-FID	
COMPONENT	MOL %
METHANE	4.868
ETHANE	0.028
ETHYLENE	1.445
PROPANE	< 0.005

Synthetic CDW 1, ITM 1535, GC-NCD		
COMPONENT	Compound	Units
Ammonia	< 1.0	ppm Wt
Acetonitrile	< 2.5	ppm Wt
Acrylonitrile	3.4	ppm Wt
Diethyl hydroxylamine (DEHA)	< 2.5	ppm Wt

Synthetic CDW 1, ASTM D5504, GC-SCD		
COMPONENT	Compound	Units
H ₂ S	1192.4	ppm Wt
Carbonyl Sulfide	141.2	ppm Wt
Methyl Mercaptan	2.3	ppm Wt
Ethyl Mercaptan	1.9	ppm Wt
Carbon Disulfide	193.4	ppm Wt
Thiophene	114.9	ppm Wt
Unknown Sulfur as Dimethyl Sulfide	2.4	ppm Wt

Table 10. C, N, S Speciation Data Summary

Tars, or otherwise termed VOC and SVOC, present within the syngas were identified with the use of Prism Analytical Technologies, Inc.'s (PATI) wide spectrum, multi-matrix thermal desorption tube. To avoid pulling moisture into the TDT, the syngas was sampled by filling a Tedlar bag and drawing the sample into TDT. After sampling in triplicate, the sorbent tubes were sent to PATI for the quantitative identification of all VOC and SVOC compounds. The list is separated into Quantitative Results, which are the compounds that the lab has full calibration for and a high accuracy of, and Semiquantitative Results, which are the compounds that the lab does not have full calibration of and has a lower accuracy for. A summary is provided in Table 11. The complete data

is included in Appendix B. The VOC and SVOC values are comparable to those observed with TRI systems that gasify wood and other agri-waste feedstocks. It has been found that the SVOC condensable fraction generated in the TRI steam reforming environment is generally much lower than those reported in the literature for other gasifiers. The average VOC/SVOC generation rate in this test has been estimated to be 0.01 kg/kg dry biomass feed. With woody biomass feed into the PDU (4 tpd dry throughput) at Durham, North Carolina, tars generation rate in steam reforming has been observed to be quite low (<0.004 kg/kg of dry biomass feed); tests in the bench scale unit generally have indicated higher tars content in syngas due to short gas residence time and faster temperature decrease in the freeboard due to relatively high heat loss.

Synthetic CDW 1, Thermal Desorption Tube Summary Results		
Total VOCs	Sample Concentration 6.43E+06 ng/L	
Average Quantitative Results		
Compound	ng/L	PPB
1,3-Butadiene	3.00E+05	1.33E+05
Acetaldehyde	1.38E+04	7.63E+03
Ethanol	1.09E+04	5.73E+03
Acetone	4.92E+05	2.05E+05
Isopropanol	3.20E+03	1.30E+03
Carbon Disulfide	1.87E+05	5.83E+04
Acetonitrile	1.30E+04	7.60E+03
Acrylonitrile	1.30E+04	5.90E+03
Hexane (C 6)	2.30E+02	6.40E+01
Propionitrile	2.60E+02	1.14E+02
Ethyl acetate	1.26E+02	3.50E+01
Benzene	1.20E+06	3.63E+05
Toluene	2.50E+05	6.57E+04
Chlorobenzene	5.73E+02	1.22E+02
Ethylbenzene	2.23E+03	5.07E+02
m, p-Xylene	9.10E+03	2.07E+03
o-Xylene	3.45E+03	7.75E+02
Styrene	2.10E+05	4.87E+04
n-Propyl benzene	8.30E+01	1.70E+01
4-Ethyltoluene	1.33E+02	2.60E+01
1,3,5-Trimethylbenzene	2.25E+02	4.57E+01
1,2,4-Trimethylbenzene	8.63E+02	1.69E+02
p-Isopropyl toluene	6.75E+02	1.20E+02
Naphthalene	1.30E+05	2.43E+04
2-Methylnaphthalene	8.13E+03	1.40E+03
Acetonitrile	1.35E+04	8.00E+03
3-Chloropropene	3.60E+03	1.14E+03
Methacrylonitrile	8.80E+01	3.20E+01
4-Methyl-2-pentanone	1.40E+02	3.30E+01
trans 1,4-Dichloro-2-butene	1.30E+02	2.50E+01

Pentachloro ethane	2.70E+02	3.30E+01
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Synthetic CDW 1, Average Semiquantitative Results		
Compound	ng/L	PPB
Propylene	1.03E+05	5.90E+04
Carbonyl Sulfide	8.33E+03	3.37E+03
Thiophene	8.77E+04	2.50E+04
Phenyl ethyne	1.25E+05	2.93E+04
2,3-Benzofuran	9.20E+03	1.90E+03
Indene	1.70E+05	3.50E+04
1-Methylnaphthalene	7.00E+03	1.20E+03
Biphenyl	8.53E+03	1.37E+03
Acenaphthylene	5.13E+04	8.13E+03
Fluorene	1.33E+04	1.93E+03
Acetaldehyde	1.38E+04	7.63E+03
Benzothiophene	6.65E+03	1.17E+03
Dibenzofuran	5.40E+03	7.70E+02

Table 11. Summary of Thermal Desorption Tube Results

The mass balance for this test is provided in Figure 9. The overall closure and the closure of many of the major elements are considered satisfactory. It is possible that water condensate measurement was inaccurate, and this affected both hydrogen and oxygen closure. The mass fraction of char elutriated from the bed and its weight fraction of carbon retained within are shown in Figure 9. It is to be noted that most of the ash was retained within the bed. This is attributed to the lower operating velocity of the bench scale unit. The Process Demonstration Unit (PDU) and commercial scale systems generally operate at much higher fluidization velocities and therefore most of the ash is expected to carryover in the syngas to permit removal through the second stage gasifier external cyclone. The carbon conversion was good (> 93%) considering the operation comprised a single stage gasification step. The TRI PDU and commercial systems do incorporate a 2-stage gasification step to achieve high (~99%) carbon conversion.

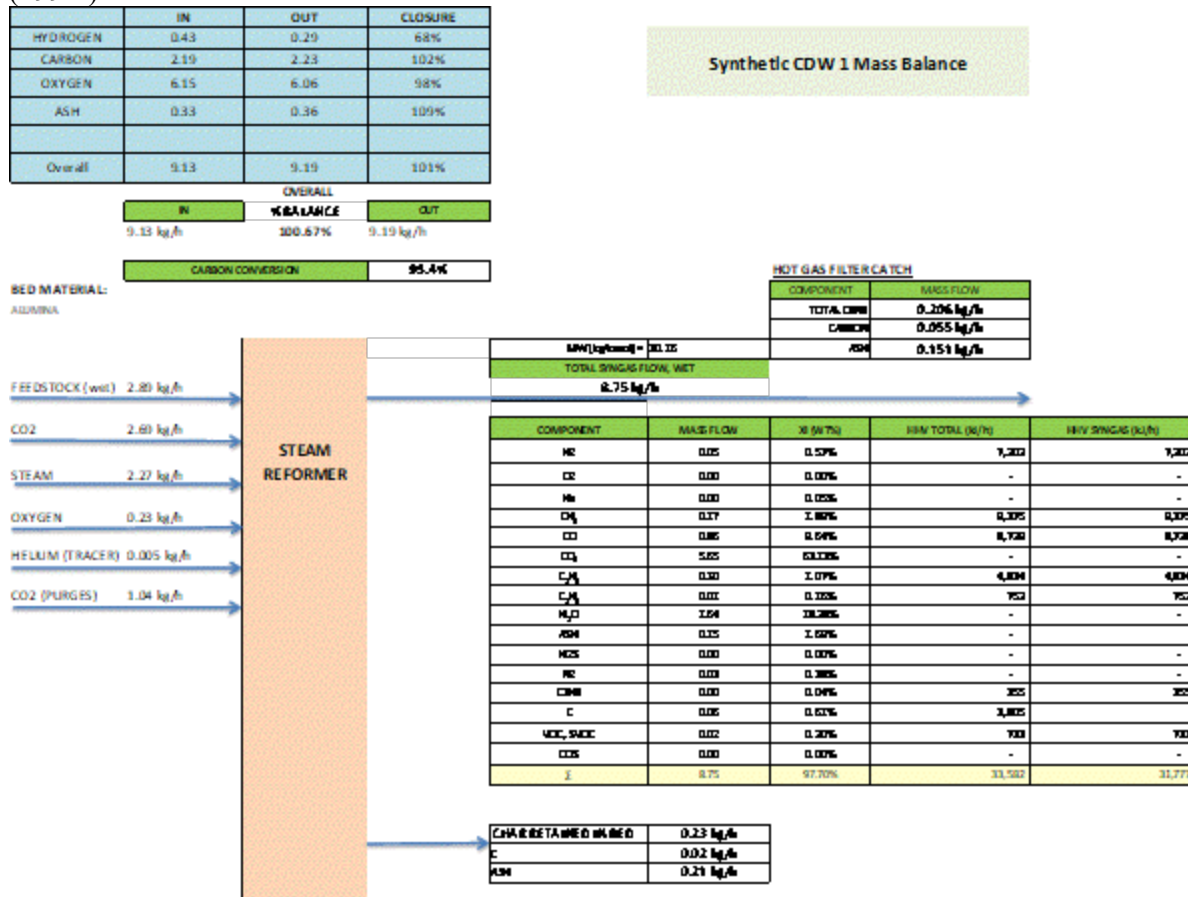


Figure 9. Synthetic CDW 1, Mass Balance

Based on an energy balance around the indirectly heated FTR, the endothermic heat of reaction for gasification was estimated to be 1,785 kJ/kg of biomass (767 Btu/lb of biomass).

Figure 10 shows the hot gas filter catch from Test 1, Test 2 hot gas filter catch appears identical and was not photographed. The hot gas filter catch which comprises fine char (carbon/ash) and carried over fine bed material. This has a significant carbon content. In the TRI 2-stage gasifier system, this stream will be routed to the 2nd stage gasifier termed Carbon Trim Cell and converted at a higher temperature partial oxidation mode and the remaining ash collected for disposal.



Figure 10. *Leucaena leucocephala* Stemwood Filter Catch Carbon & Ash

Figure 11 shows the initial and final bed material samples from Test 1, Test 2 samples appear identical and were not photographed. The initial bed is engineered alumina and the final bed has carbon and ash. The final bed appears dark and has biomass particles injected towards the end of the test undergoing drying and devolatilization; the carbon content however is less than 5% by weight.



Figure 11. *Leucaena leucocephala* Stemwood Initial and Final Bed Material Samples

Conclusions

The screening test with Synthetic CDW 1 was successful and indicated the following:

- The steam reformer demonstrated safe, stable, and reliable operation.
- There were no operational problems such as agglomeration, defluidization, channeling or heater fouling.
- The final bed had little carbon and exhibited a free-flowing characteristic.
- The carbon conversion was good (~93%) considering the operation comprised a single stage gasification step; the PDU and commercial systems incorporate a 2-stage gasification step to achieve high (~99%) carbon conversion.
- The impinger sampling and analysis for acid gases and metals was not satisfactory and will require a root cause analysis.
- Sample integrity during shipping and transportation for external laboratory analysis by GC-TCD, GC-FID, GC-SCD and GC-NCD seems to be an issue and this needs to be addressed for credible results.
- The concentration of metals such as arsenic is so low that the mass balance closure for these elements is poor. This may be due to inhomogeneity of these elements in the feedstock or analytical inaccuracy or sample inhomogeneity or all the above.

There were no surprises, and the test results support the application of the steam reformer system to generate syngas from this feedstock to produce biofuel or renewable power or biochemicals.

Recommendation

A long duration continuous test (1 to 3 week) with one or more feedstocks in the TRI integrated biorefinery PDU at Durham, North Carolina is recommended to fully characterize steam reformer performance and facilitate reliable and refined design and cost estimate of the commercial plant.

Appendix A – Feedstock Sample Data

Synthetic CDW 1, Feedstock Individual Sample Data						
Screen #	Sample A		Sample B		Sample C	
	Before Shake	After Shake	Before Shake	After Shake	Before Shake	After Shake
	tare, (g)	gross, (g)	tare, (g)	gross, (g)	tare, (g)	gross, (g)
1/4"	522.4	522.4	522.4	522.4	522.5	522.5
20	401.4	487.4	401.4	484.8	401.5	491.4
40	341.8	351.4	341.8	352.6	341.8	351.8
50	335.6	337.4	335.7	337.9	335.7	338.0
70	331.1	331.9	331.0	332.3	331.1	332.5
140	315.5	316.2	315.4	316.6	315.4	317.1
200	308.7	308.9	308.6	309.0	308.6	309.2
pan	274.6	275.2	274.5	275.4	274.6	275.5
Sum	2831.1	2930.8	2830.8	2931	2831.2	2938
Moisture	9.7%		8.4%		8.9%	
Bulk Density	251.7 kg/M3		266.7 kg/M3		274.2 kg/M3	
Sauter Mean Size	1472 microns		1172 microns		1162 microns	
% Fines	13.7%		16.8%		15.8%	

Table 12. Individual Feedstock Data, TRI Generated

Appendix B - External Lab Summaries

Synthetic CDW 1, Condensate Results							
Analyte	Results	Flag	MDL	PQL	Units	Method	Notes
Acenaphthylene	10000.00	D	3800.0	4000.0	ug/L	EPA 625.1	R-05
Acrylonitrile	160.00		3.50	10.0	ug/L	EPA 624.1	
Arsenic - Total	13.00		7.6	10.0	ug/L	EPA 200.7	
Biochemical Oxygen Demand	10.00		2	2.0	mg/L	SM 5210 B-2011	
Chemical Oxygen Demand	45.00		10.00	10.0	mg/L	SM 5220D-2011	
Chloride	78.00		1.90	5.0	mg/L	SM 4500Cl E-2011	
Chloroform	5.00		0.46	1.0	ug/L	EPA 624.1	
Chloromethane	2.80		0.5	1.0	ug/L	EPA 624.1	
Chromium - Total	12.70		1	10.0	ug/L	EPA 200.7	
Ethylbenzene	1.80		0.460	1.0	ug/L	EPA 624.1	
Naphthalene	29000.00	D	1400	4000.0	ug/L	EPA 625.1	R-05
Nickel - Total	8.40	J	2.20	10.0	ug/L	EPA 200.7	
pH	3.00		1.00	1.0	pH	SM 4S00H+B-2011	Q-01
Phenanthrene	2200.00	JD	1100.0	4000.0	ug/L	EPA 625.1	R-05
Phenol	17000.00	D	2200.0	4000.0	ug/L	EPA 625.1	R-05
Phosphorus - Total	0.76		0.0	0.1	mg/L	EPA 365.4	
Sulfide	0.05	J	0.0	0.1	mg/L	SM 450052 D-2011	
Temperature for pH (deg. C)	20.00				pH	SM 4S00H+B-2011	Q-01
Total Kjeldahl Nitrogen	12.00		0.3	0.5	mg/L	EPA 351.2	
Total Organic Carbon	22.00		0.9	1.0	mg/L	SM 5310B-2011	
Zinc - Total	20.10		4.4	10.0	ug/L	EPA 200.7	
Ammonia as N	11.00	D	0.9	2.0	mg/L	EPA 350.1	
Benzene	1800.00	D	28.0	so	ug/L	EPA 624.1	
Cyanide (total) - Total	0.29	D	0.0	0.0	mg/L	EPA 335.4	
Toluene	240.00	D	28.0	so	ug/L	EPA 624.1	

J	Reported value is between the Laboratory Method Detection Limit (MDL) and the Laboratory Method Reporting Limit (MRL), adjusted for actual sample preparation data and moisture content where applicable.
D	The sample was analyzed at dilution.
Q-01	Analysis performed outside of sample hold time
B-02	The sample dilutions set up for the analysis failed to meet the criteria of a residual dissolved Oxygen of at least 1 mg/l. Therefore, the reported result is an estimated value only.
R-05	The sample was diluted due to the presence of elevated levels of non-target analytes resulting in elevated reporting limits.
* These Synthetic CDW 1 results are from the lab report and have not been corrected for the 1:25.1 dilution factor when sampling.	

Deionized Water Drum							
Analyte	Results	Flag	MDL	PQL	Units	Method	Notes
Chloroform	5.9		0.46	1.0	ug/L	EPA 624.1	
Ethylbenzene	0.5	J	0.46	1.0	ug/L	EPA 624.1	
pH	4.6		1.0	1.0	pH	SM 4S00H+B- 2011	Q-01
Phosphorus - Total	0.57		0.025	0.1	mg/L	EPA 365.4	
Temperature for pH (deg. C)	20				pH	SM 4500H+B- 2011	Q-01
Toluene	0.85	J	0.57	1.0	ug/L	EPA 624.1	
Zinc - Total	10.3		4.40	10.0	ug/L	EPA 200.7	

Table 13. Synthetic CDW 1, Condensation Lab Summary

Synthetic CDW 1, Thermal Desorption Tube 1					
Compound	Sample Concentration			Reporting Limit	
Total VOCs	ng/L 7.30E+06			ng/L 200	
Quantitative Results					
Compound	CAS	Sample Concentration		Reporting limit	
		ng/L	ppb	ng/L	Additional Information
1,3-Butadiene	106-99-0	290000	130000	50	J*
Acetaldehyde	75-07-0	9400	5200	100	
Ethanol	64-17-5	21000	11000	500	
Acetone	67-64-1	1.2E+006	500000	250	J* K*
Isopropanol	67-63-0	3200	1300	250	
Carbon Disulfide	75-15-0	180000	58000	50	J*
Acetonitrile	75-05-08	13000	7600	100	
Acrylonitrile	107-13-1	9900	4500	50	
Hexane (C 6)	110-54-3	230	64	50	
Propionitrile	107-12-0	340	150	50	
Ethylacetate	141-78-6	160	45	50	
Benzene	71-43-2	1.2E+006	360000	50	J*K*
Toluene	108-88-3	220000	58000	50	J*K*
Chlorobenzene	108-90-7	400	86	50	
Ethylbenzene	100-41-4	2200	490	50	
m,p-Xylene	108-38-3; 106-42-3	10000	2300	100	
o-Xylene	95-47-6	4500	1000	50	
Styrene	100-42-5	160000	38000	50	J*
n-Propylbenzene	103-65-1	83	17	50	
4-Ethyltoluene	622-96-8	240	47	50	
1,3,5-Trimethylbenzene	108-67-8	460	93	50	
1,2,4-Trimethylbenzene	95-63-6	1500	290	50	
p-Isopropyltoluene	99-87-6	710	130	50	
Naphthalene	91-20-3	100000	19000	100	J*
2-Methylnaphthalene	91-57-6	6800	1200	100	
Semiquantitative Results					
Compound	CAS	ng/L	ppb	ng/L	RI
Propylene	115-07-1	85000	49000	5000	329
Carbonyl Sulfide	463-58-1	8400	3400	5000	333
C2-C4 Hydrocarbon	N/A	81000	N/A	5000	346
C3-C5 Hydrocarbon	N/A	120000	N/A	5000	405
C3-C5 Hydrocarbon	N/A	8100	N/A	5000	444
C4-C6 Hydrocarbon	N/A	43000	N/A	5000	523
Thiophene	110-02-1	88000	25000	5000	640
Phenylethyne	536-74-3	85000	20000	5000	814
C9-C11 Hydrocarbon	N/A	9500	N/A	5000	906
2,3-Benzofuran	271-89-6	10000	2100	5000	920
Indene	95-13-6	110000	23000	5000	955
C7-C9 Hydrocarbon	N/A	33000	N/A	5000	959
1-Methylnaphthalene	90-12-0	6300	1100	5000	1103
Biphenyl	92-52-4	6900	1100	5000	1132
Acenaphthylene	208-96-8	45000	7100	5000	1197
Fluorene	86-73-7	10000	1500	5000	1285

Table 14. Thermal Desorption Tube 1 Syngas VOC and SVOC Concentrations

Synthetic CDW 1, Thermal Desorption Tube 2					
Compound	Sample Concentration		Reporting Limit		
Total VOCs	ng/L 6.00E+06		ng/L 200		
Quantitative Results					
Compound	CAS	Sample Concentration		Reporting limit	
		ng/L	ppb	ng/L	Additional Information
1,3-Butadiene	106-99-0	3.70E+05	1.60E+05	50	J*
Acetaldehyde	75-07-0	17000	9400	100	
Acetone	67-64-1	230000	95000	250	J*
Carbon Disulfide	75-15-0	230000	71000	50	J*
Acetonitrile	75-05-8	14000	8400	100	
3-Chloropropene	107-05-1	4700	1500	50	
Acrylonitrile	107-13-1	16000	7200	50	
Propionitrile	107-12-0	230	99	50	
Ethylacetate	141-78-6	91	25	50	
Methacrylonitrile	126-98-7	88	32	50	
Benzene	71-43-2	1.20E+06	360000	50	J*K*
4-Methyl-2-pentanone	108-10-1	140	33	50	Methyl isobutyl ketone (MIBK) J*K*
Toluene	108-88-3	260000	67000	50	
Chlorobenzene	108-90-7	660	140	50	
Ethylbenzene	100-41-4	2200	500	50	
m,p-Xylene	108-38-3; 106-42-3	8000	1800	100	
Styrene	100-42-5	210000	49000	50	J*
trans 1,4-Dichloro-2-butene	110-57-6	130	25	50	
4-Ethyltoluene	622-96-8	92	18	50	
1,3,5-Trimethylbenzene	108-67-8	140	29	50	
Pentachloroethane	76-01-7	270	33	50	
1,2,4-Trimethylbenzene	95-63-6	650	130	50	
Naphthalene	91-20-3	130000	24000	100	J*
2-Methylnaphthalene	91-57-6	8300	1400	100	
Semiquantitative Results					
Compound	CAS	ng/L	ppb	ng/L	RI
Propylene	115-07-1	1.30E+05	74000	5000	329
Carbonyl Sulfide	463-58-1	9900	4000	5000	336
C2-C4 Hydrocarbon	N/A	120000	N/A	5000	346
Acetaldehyde	75-07-0	18000	10000	5000	396
C3-C5 Hydrocarbon	N/A	6100	N/A	5000	444
C4-C6 Hydrocarbon	N/A	63000	N/A	5000	522
Thiophene	110-02-1	99000	28000	5000	640
Phenylethyne	536-74-3	130000	31000	5000	814
C9-C11 Hydrocarbon	N/A	6600	N/A	5000	906
2,3-Benzofuran	271-89-6	8500	1700	5000	920
Indene	95-13-6	170000	35000	5000	955
C7-C9 Hydrocarbon	N/A	20000	N/A	5000	958
Benzothiophene	95-15-8	4700	840	4600	1046
1-Methylnaphthalene	90-12-0	7100	1200	5000	1103
Biphenyl	92-52-4	8700	1400	5000	1132
Acenaphthylene	208-96-8	56000	8900	5000	1197
Dibenzofuran	132-64-9	5400	770	5000	1234
Fluorene	86-73-7	16000	2300	5000	1284

Table 15. Thermal Desorption Tube 2 Syngas VOC and SVOC Concentrations

Synthetic CDW 1, Thermal Desorption Tube 3					
Compound	Sample Concentration ng/L	Reporting Limit ng/L			
Total VOCs	6.00E+06	200			
Quantitative Results					
		Sample Concentration		Reporting limit	
Compound	CAS	ng/L	ppb	ng/L	Additional Information
1,3-Butadiene	106-99-0	2.40E+05	110000	50	J*
Acetaldehyde	75-07-0	15000	8300	100	
Ethanol	64-17-5	860	450	500	
Acetone	67-64-1	45000	19000	250	J*
Carbon Disulfide	75-15-0	150000	46000	50	J*
Acetonitrile	75-05-8	13000	7600	100	
3-Chloropropene	107-05-1	2500	780	50	
Acrylonitrile	107-13-1	13000	6000	50	
Propionitrile	107-12-0	210	92	50	
Benzene	71-43-2	1.20E+06	370000	50	J*
Toluene	108-88-3	270000	72000	50	J*K*
Chlorobenzene	108-90-7	660	140	50	
Ethylbenzene	100-41-4	2300	530	50	
m,p-Xylene	108-38-3; 106-42-3	9300	2100	100	
o-Xylene	95-47-6	2400	550	50	
Styrene	100-42-5	260000	59000	50	
4-Ethyltoluene	622-96-8	67	13	50	
1,3,5-Trimethylbenzene	108-67-8	76	15	50	
1,2,4-Trimethylbenzene	95-63-6	440	88	50	
p-Isopropyltoluene	99-87-6	640	110	50	
Naphthalene	91-20-3	160000	30000	100	J*
2-Methylnaphthalene	91-57-6	9300	1600	100	
Semiquantitative Results					
Compound	CAS	ng/L	ppb	ng/L	RI
Propylene	115-07-1	94000	54000	5000	329
Carbonyl Sulfide	463-58-1	6700	2700	6700	332
C2-C4 Hydrocarbon	N/A	84000	N/A	5000	346
C3-C5 Hydrocarbon	N/A	83000	N/A	5000	405
C4-C6 Hydrocarbon	N/A	50000	N/A	5000	523
Thiophene	110-02-1	76000	22000	5000	640
Phenylethyne	536-74-3	160000	37000	5000	814
C9-C11 Hydrocarbon	N/A	7100	N/A	5000	906
2,3-Benzofuran	271-89-6	9100	1900	5000	920
Indene	95-13-6	230000	47000	5000	956
C7-C9 Hydrocarbon	N/A	9900	N/A	5000	959
Benzothiophene	95-15-8	8600	1500	5000	1047
1-Methylnaphthalene	90-12-0	7600	1300	5000	1103
Biphenyl	92-52-4	10000	1600	5000	1132
Acenaphthylene	208-96-8	53000	8400	5000	1197
Fluorene	86-73-7	14000	2000	5000	1285

Table 16. Thermal Desorption Tube 3 Syngas VOC and SVOC Concentrations

Appendix C - A list of Separate Reports

Table Of External Lab Reports	
Lab	Analysis
BEL Laboratories	Feedstock
BEL Laboratories	Ash
BEL Laboratories	Bed Material
Element One	HCN
Element One	HCL
Element One	NH3
Element One	Metals
ENCO Laboratories	Condensate
Enthalpy	TD Tube (3 Reports)
Intertek	GC-SCD
Intertek	GC-NCD
Intertek	GC-FID/TCD

Table 17. A List of External Lab Reports