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Coal / Biomass Gasification Test on Transport Gasifier at National Carbon Capture Center Power Systems Development Facility

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Disclaimer

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List of Abbreviations/Acronyms

Btu	British thermal unit
CCAD	Continuous Coarse Ash Depressurization
CCAT	Connecticut Center for Advanced Technology
CFAD	Continuous Fine Ash Depressurization
CGE	Cold Gas Efficiency
COD	chemical oxygen demand
DHL	DHL Analytical Inc.
DLA	Defense Logistics Agency Energy
DOE	U.S. Department of Energy
F-T	Fischer-Tropsch
hr	hour
KBR	Kellogg Brown & Root
LHV	Lower Heating Value
lb	pound
LOI	loss on ignition
NBE	New Biomass Energy
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
PCD	Particulate Control Device
PDAC	Pressure Decoupled Advanced Coal
ppmv	parts per million by volume
ppmw	parts per million by weight
PRB	Powder River Basin
PSD	particle size distribution
PSDF	Power Systems Development Facility
psia	pounds per square inch absolute
psig	pounds per square inch gauge
RCRA	Resource Conservation and Recovery Act
Southern Company	Southern Company Services, Inc.
SCF	standard cubic feet
SCU	Syngas Cleanup Unit
TCLP	Toxicity Characteristic Leachate Procedure
TOC	total organic carbon
TRIG™	Transport Reactor Integrated Gasification
WGS	Water-Gas Shift
µm	micron, micrometer, 10^{-6} meter

Executive Summary

The Connecticut Center for Advanced Technology, Inc. (CCAT) with partners ARCADIS U.S., Inc. (ARCADIS), and technical expert Arie Geertsema (the Project Team) coordinated gasification testing of selected coal / biomass mixtures on the Transport Reactor Integrated Gasifier (TRIG™)at the National Carbon Capture Center (NCCC) in Wilsonville, Alabama. Testing was conducted from September 7 to 17, 2012 in support of a Department of Defense goal of being able to procure liquid fuels produced from secure domestic coal resources. The goal of the CCAT demonstration test at NCCC was to provide data on the gasification component of the coal/biomass to liquid fuel process in support of the production of liquid fuels for military applications utilizing a flexible source of feedstocks.

The tests NCCC conducted for CCAT were similar to tests conducted on a smaller transport reactor at the Energy and Environmental Research Center (EERC) from February to April 2012. The TRIG™ at NCCC is approximately 10 times larger than the one at EERC (fuel feed rate approximately 4,000 vs 400 lb/hr). One objective was to test the ability to feed coal and biomass from separate feeders at the target feed ratios and rates at the larger scale unit. Testing different types of biomass supports the objective of having flexibility in feedstock supply. Another objective was to collect enough data from steady state operations under similar test conditions to assess scale up considerations and whether operating at a larger scale results in better conversion, higher efficiency, and a syngas composition more suitable for producing liquid fuels than at the smaller scale. Direct comparison with the results obtained from EERC will be presented in a separate report.

To fulfill the test objectives, inputs and outputs to the gasifier and gasifier operational parameters were monitored by NCCC throughout the test. Feedstock composition, fuel, oxygen, nitrogen, air, steam and product gas flow rates, temperature, pressure, and pressure differential at several locations in the gasifier; product gas composition; and thermal oxidizer flue gas emissions were monitored continuously. The product gas and product gas condensate were analyzed for trace species; coarse and fine ash were collected once per test condition during steady state conditions for laboratory analysis.

Major results include:

- The test plan called for oxygen-blown gasification of 100% PRB coal and of mixtures of coal with 10%, 20%, and 30% by weight of raw and torrefied pine wood pellets. Actual coal / biomass blends tested contained approximately 12%, 20%, and 28% raw pine and 16%, 17%, 19%, 20%, and 29% torrefied pine.
- The H_2:CO molar ratio of the product gas ranged from 1.34 to 1.70 and was fairly consistent with the various biomass feed fractions. However, relationships between multiple independent operating variables, e.g. steam and oxygen to fuel ratios, are confounded within the matrix making it difficult to ascribe effects to particular variables.
- A mass balance was performed around the TRIG™ and supporting equipment to determine if the majority of all flows are represented by the measurements performed. Carbon conversion ranged from 97.6 to 98.7 percent for all oxygen-blown tests.

- An energy balance was performed around the gasifier using the flows developed from the mass balance, heating value of components, and sensible heat of inputs and outputs. On this basis, energy balance closure ranged from 91 to 103%.
- Conversion of feedstocks to product gas was quantified by Cold Gas Efficiency (CGE). The CGE ranged from 59.6% to 69.7% for oxygen-blown tests. The CGE appears to be slightly lower for the raw biomass tests averaging 61.2% compared to torrefied biomass tests averaging 66.8%, and 67.8% for the coal only case. These results may be attributed to the lower heating value and energy density of raw biomass compared to that of torrefied biomass and coal; however there is no apparent trend with biomass feed percentage for either feedstock.
- Product gas from feedstock containing torrefied biomass had significantly fewer tars than gas from raw biomass blends. Tar levels increased with higher percentage of biomass for both raw and torrefied feedstock blends. The greatest amount of tars was observed in the 28% raw biomass and 100% coal cases.
- Results of leaching and pH analyses of both the coarse and fine ash indicate the ash would not be considered hazardous waste for disposal purposes. If the material has suitable characteristics for alternative use, it could be considered a by-product and not a waste.

NCCC completed the CCAT test with 219 hours of nearly continuous operation in oxygen-blown mode. The CCAT demonstration test conducted on the TRIG™ at NCCC fulfilled all major test objectives. Gasification of PRB coal alone and with varying amounts of both raw and torrefied pine in oxygen-blown conditions was successfully achieved. Very few discernable differences in the operating conditions or quality of the product gas were observed between the test cases performed on the TRIG™ at NCCC. Parametric studies on multiple independent operating variables, e.g. steam and oxygen to fuel ratios, are needed to evaluate the effects of biomass type and feed percentage on gasifier outputs relative to their potential use for liquid fuel production.

1 Introduction

The Connecticut Center for Advanced Technology, Inc. (CCAT) was authorized by Defense Logistics Agency Energy (DLA) to coordinate gasification testing of selected coal/biomass mixtures at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. The PSDF is a state-of-the-art test center sponsored by the U.S. Department of Energy (DOE) with the purpose of advancing clean coal technologies. The PSDF now hosts the National Carbon Capture Center (NCCC) to address the nation's need for commercially viable carbon dioxide (CO_2) capture options for fossil-fuel based power plants. The facility is operated by the Southern Company Services, Inc. (a division of the Southern Company). The NCCC includes multiple, adaptable test skids that allow technology development of CO_2 capture concepts using fossil-derived syngas and flue gas in industrial settings. Because of the ability to operate under a wide range of flow rates and process conditions, research at the NCCC can effectively evaluate technologies at various levels of maturity and accelerate their development path to commercialization.

This work was done in support of a Department of Defense goal of being able to procure liquid fuels produced from secure domestic resources. The goal of the CCAT demonstration test at NCCC was to provide data on the gasification component of the coal/biomass to liquid fuel process in support of the production of liquid fuels for military applications utilizing a flexible source of feedstocks. For the purpose of this report, "product gas" refers to the particulate-free bulk raw gas produced in the gasifier, while "syngas" refers to particulate-free product gas cleaned sufficiently for Fischer-Tropsch (F-T) processes (i.e. removal of sulfur, CO_2 and other contaminants) . The carbon monoxide (CO) and hydrogen (H_2) components of the syngas are the building blocks for the synthesis of liquid fuels by F-T technology.

The Southern Company and DOE maintain all necessary permits and thus no additional permitting was required for CCAT. On February 9, 2012, DLA submitted DLA Form 1664, Record of Determination Environmental Evaluation, which determined that the proposed test at the PSDF in Wilsonville, Alabama is a categorically excluded action and that further environmental review under National Environmental Policy Act was not necessary.

The CCAT Project Team consists of staff from CCAT, ARCADIS, and an internationally recognized expert on gasification technology, Arie Geertsema. Activities carried out for the CCAT testing effort were performed on the Transport Reactor Integrated Gasification™ (TRIG™). The CCAT test was included as part of an air-blown test NCCC conducted for DOE beginning in June 2012 (Southern Company Services, Inc. 2012) with a combined duration of 722 hours. This report presents the demonstration test objectives, methodology, results, and conclusions for the 219-hour oxygen-blown gasification test of selected coal/biomass mixtures. Although NCCC conducted the test and generated the raw data, the CCAT Project Team reduced the data, prepared tables and figures, and wrote this report. In-depth discussion of results and conclusions will be presented in the overall project summary report prepared by CCAT for the DLA. The CCAT test at NCCC is a scaled up version of the coal/biomass gasification test performed at the Energy and Environmental Research Center (EERC) from February to April 2012. The Transport Reactors at both sites are based on a KBR (formerly Kellogg Brown & Root) design; the reactor at NCCC is larger and incorporates more recent design modifications. One of the objectives of this work is to compare the carbon conversion, gasifier efficiency, and syngas composition from the larger system at NCCC with those obtained from tests on similar feedstock mixtures at EERC. This comparison will be presented as part of a separate report to the DLA.

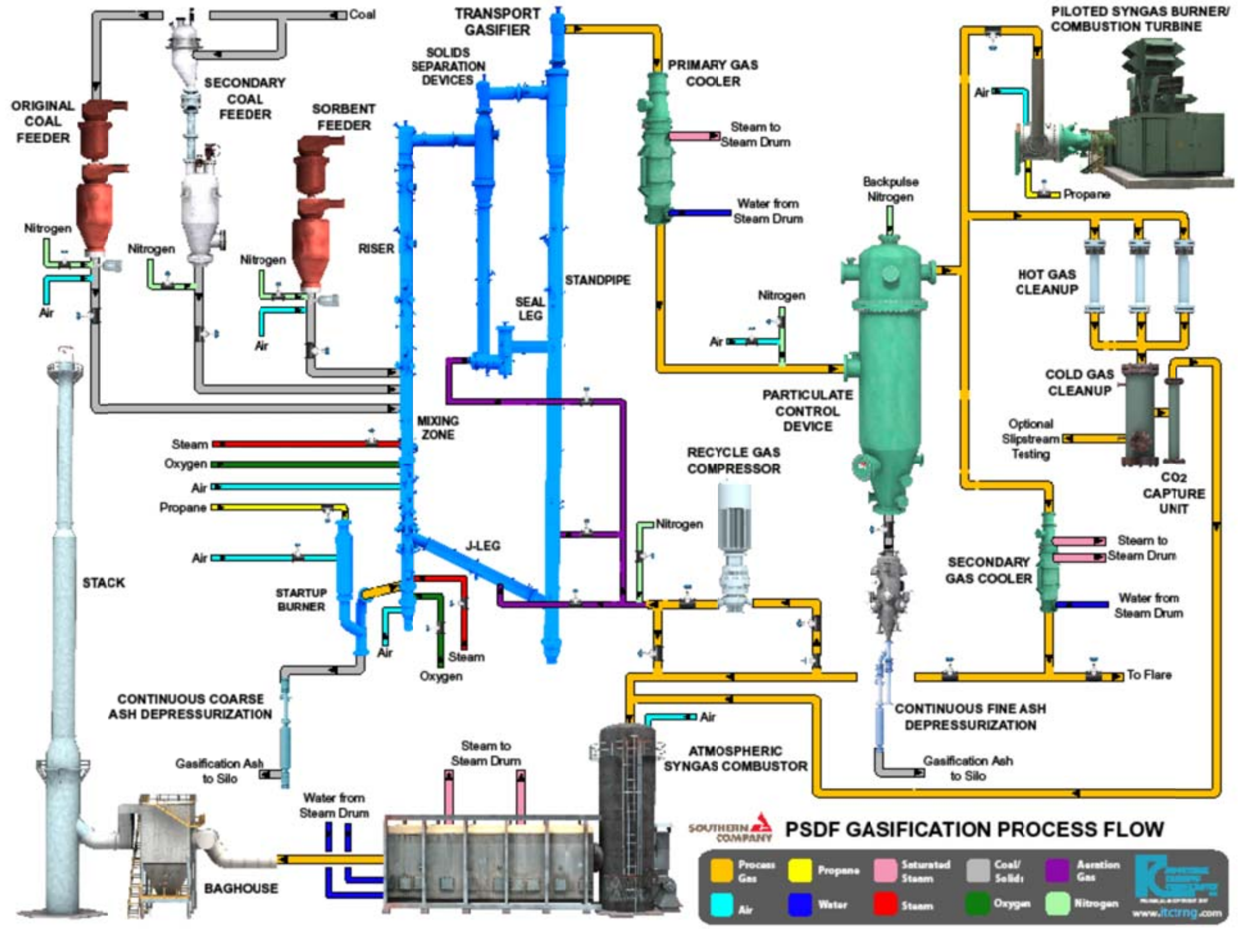
2 Transport Gasifier

2.1 Historical Background

The PSDF began commissioning its advanced coal-fired power generation technologies in 1996. Originally, the PSDF was constructed to demonstrate two independent processes: the KBR Transport Reactor process featuring a hot gas particulate control device (PCD) and the Foster Wheeler Advanced Pressurized Fluidized Bed Combustion process. Testing of the Foster Wheeler process was terminated in 2000, and subsequent testing at the PSDF was based solely on the TRIG™ process. The TRIG™ Process is comprised of several components including the Transport Gasifier, coal feed, ash removal, syngas cooling, and particulate filtration systems. The TRIG™ can operate in combustion mode or as a gasifier in either air-blown or oxygen-blown gasification mode. Between 1996 and 1999, the Transport Reactor successfully operated as a fluid bed coal combustor for about 5,000 hours. These operational hours were accumulated during nine test campaigns during which five different fuels (three bituminous coals, one subbituminous coal, and petroleum coke) and four *in situ* sulfur sorbents (three limestones and one dolomite) were evaluated.

The system was transitioned to gasification operation in late 1999. Four gasification commissioning tests, totaling 1,000 hours, were completed by early 2001. By 2009, 25 gasification test campaigns were completed, each nominally 250 to 1,500 hours in duration, for a total of about 12,000 hours of coal gasification operation. During this period, the gasifier operated for about 2,000 hours in oxygen-blown mode with the balance in air-blown mode. The fuels for the gasifier included several types of bituminous, subbituminous, and lignite coals. In addition, the PSDF has developed coal and biomass feed systems and continuous ash removal systems, while improving the performance of existing technologies, such as hot gas filtration and hot gas cooling (Southern Company Services, Inc. 2009). Source: (NCCC, 2012)
Figure 2-1 shows the various components associated with the Transport Gasifier at the PSDF.

In 2009, a new cooperative agreement between the DOE and PSDF established "The National Carbon Capture Center at the Power Systems Development Facility." Since then, the facility has completed about 8,700 hours of gasification operation to support development and testing of advanced carbon capture, hydrogen separation, and other gas cleanup technologies, while expanding the knowledge of operation of the KBR gasification system. These efforts support integration of all components into a reliable gasification process that can be scaled up to commercial applications. The new 582 MW Mississippi Power Company Integrated Gasification Combined Cycle power plant currently under construction in Kemper County, Mississippi will be the first full-scale, commercial implementation of the TRIG™ technology.

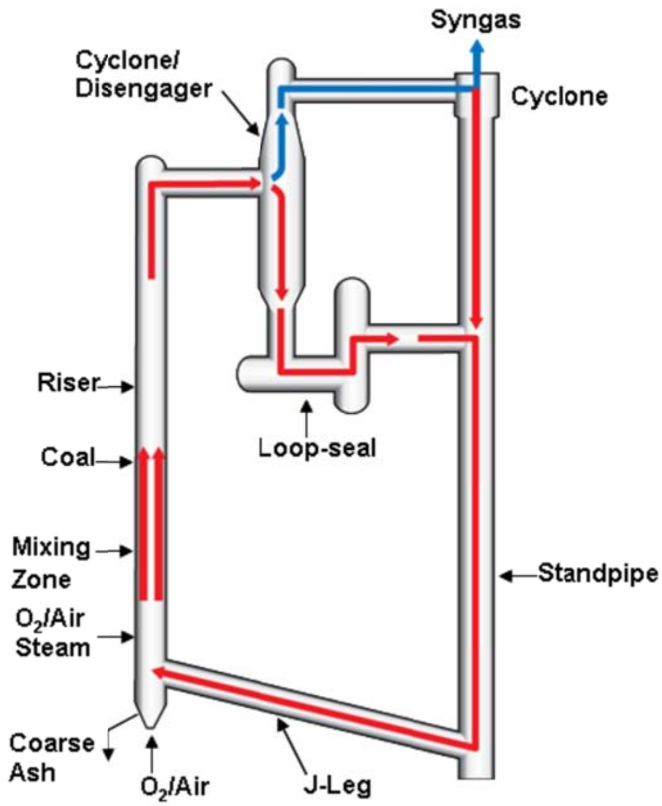


Source: (NCCC, 2012)

Figure 2-1: NCCC / PSDF Process Flow Diagram

2.2 TRIG™ Gasifier Description at NCCC

The Transport Gasifier at NCCC is a pressurized, advanced circulating fluidized bed reactor. Except for the differences described in Section 2.3 below, the TRIG™ at NCCC is essentially a larger scale (50 tons/day) demonstration unit of the pilot scale (5 tons/day) system that has been operating at EERC since 1993. The TRIG™ operates at high pressure, approximately 160 psig. The mechanical design and operation of the gasifier are based on KBR's fluidized catalytic cracking technology. The TRIG™ has no internals, expansion joints, valves, or other moving parts. The gasifier consists of a mixing zone, riser, solids separation units (primary and secondary cyclones), seal leg, standpipe, and J-leg (KBR 2008). Figure 2-2 shows the configuration of the KBR Transport Gasifier.



Source: (KBR 2008)

Figure 2-2: Schematic of the KBR Transport Gasifier (TRIG™)

The Transport Gasifier operates best using low-sodium coals and is generally operated at moderate temperatures (1,500°F to 1,950°F), i.e., at least 200°F below the ash fusion temperature, to avoid particle sintering and slagging of most coals. The gasifier is designed to operate using air (air-blown mode), pure oxygen (oxygen-blown mode), or enriched air/oxygen mixtures as oxidant. For commercial operation, air-blown mode is generally used for power generation, while oxygen-blown and enriched air-blown modes are used to optimize the production of syngas for synthesis of liquid fuels or chemicals. Feedstocks (coal, biomass) enter the gasifier in the upper mixing zone where the atmosphere is reducing (oxygen-free). Air or oxygen is fed with steam into the mixing zone at different elevations and orientations to evenly distribute heat generated from the partial combustion of the circulating solids. Partial oxidation reactions between the char (unreacted carbon) in the solids returning from the J-Leg and the injected oxidant completely consume oxygen in the lower mixing zone of the gasifier. The endothermic gasification reactions occur primarily in the riser above the feed injection point (gasification zone) by utilizing the heat generated from char combustion in the lower mixing zone. The circulating solids in the system transfer heat generated from the mixing zone to the gasification zone.

The Transport Gasifier operates at higher superficial gas velocities, riser densities and solids circulation rates than most conventional circulating fluidized bed reactors. These features are said to enhance product gas production, mixing, and high heat and mass transfer rates. Within the riser, the gas superficial velocities are appropriately maintained such that sufficient residence time is available to maximize both carbon conversion and tar cracking (KBR 2008). As fresh feed devolatilizes and chemical reactions occur to generate product gas, the gas and solids move up the riser and enter the solids separation units (cyclones). The primary separation unit removes the majority of the particles (unreacted feed and coarse ash) in the gas-solids mixture by gravity and/or centrifugal forces. The gas and the remaining finer solids then pass to a secondary separation unit that captures most of the fine particulates not collected in the first stage of separation. The product gas then leaves the unit and flows through a gas cooler for high-grade heat recovery followed by a PCD. A portion of the particulate-free product gas is compressed and recycled to three locations in the gasifier. Recycled product gas is used for aeration in the J-leg, standpipe, and seal leg. The product gas can either be combusted or on a slip-stream research scale, further conditioned and processed to produce chemicals or fuels. Processing product gas into liquid fuels was not an objective of this CCAT test; therefore, product gas was combusted in the atmospheric syngas combustor.

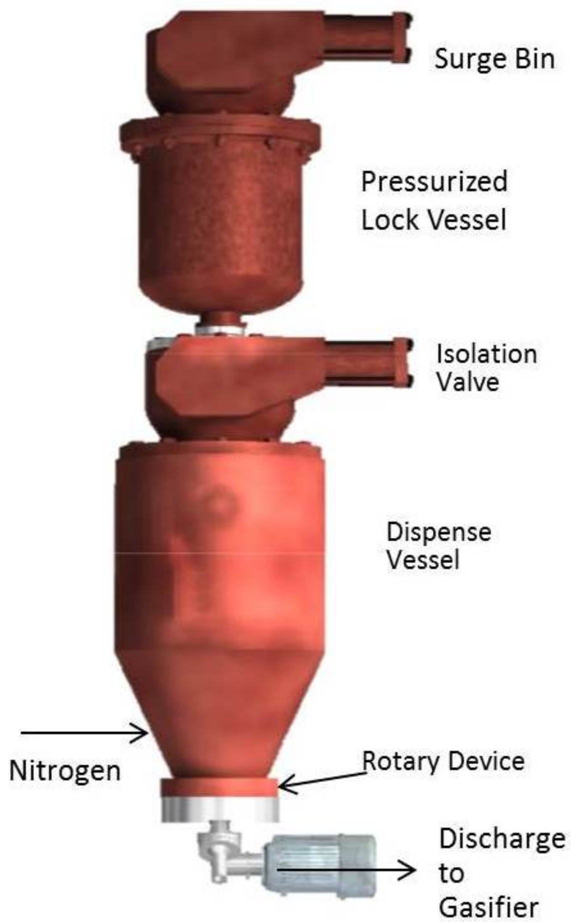
The continuous dry ash handling system eliminates the technical difficulties associated with slag handling and removal faced by comparable slagging gasifiers (KBR 2008). Solid particles collected by the separation units are returned to the seal leg and standpipe and circulated back to the mixing zone of the riser from the J-Leg. Gas flow is controlled by the level of solids in the standpipe. The level of solids in the standpipe is controlled to be at least as high as the seal leg to prevent backflow of gas. Coarse ash is removed from the bottom of the riser, below the startup burner, through the continuous coarse ash depressurization (CCAD) system, which cools and depressurizes the solids. Fine ash is not recirculated, but is removed from the PCD through the continuous fine ash depressurization (CFAD) system.

NCCC installed a new oxygen flow meter and cleaned the supply system for the CCAT test. All of the oxygen lines were cleaned and tested prior to the test. Oxygen for the gasifier (purity greater than 99.5% by volume) was delivered to the NCCC site as liquid and stored in a holding tank. The liquid oxygen was vaporized using ambient vaporizers prior to being fed to the gasifier. The oxygen tank was refilled daily by an outside vendor (Linde) for the duration of the test. Oxygen was fed to both the upper and lower mixing zones of the gasifier.

2.2.1 Feed Systems

As described in Section 4.2, coal and biomass for this test were prepared in two parallel mill trains and stored in separate feed silos. NCCC utilized two feed systems for conveying the coal and biomass to the Transport Gasifier separately. Both feeders utilize lock hopper designs to pressurize the material to gasifier operating pressure, but differ in the feed delivery systems as described below. The feed rate is determined by loss of weight calculations on the feeder load cells.

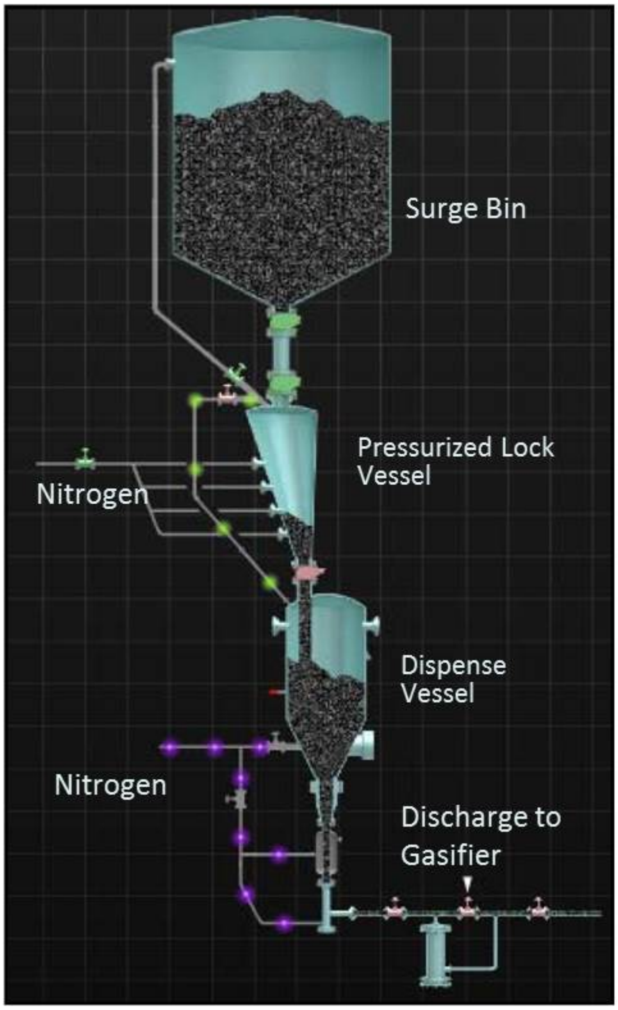
<u>Biomass Feed System</u> (shown as Original Coal Feeder on Source: (NCCC, 2012)
Figure 2-1). Milled biomass is transferred from the pulverized feed silo to the surge bin, which always operates at atmospheric pressure. The system also has two pressure vessels, with the feed pressurized in the upper lock vessel and then gravity fed into a dispense vessel, which is always pressurized. The material is fed out of the dispense vessel by a mechanical rotary device, which is driven by a variable speed electric motor, and into the discharge line where it is conveyed by air or nitrogen into the gasifier. A schematic of the system is shown on Figure 2-3.



Adapted from: (Southern Company Services, Inc. 2009)

Figure 2-3: Biomass Feeder

<u>Coal Feed System.</u> Coal is fed to the gasifier via the Pressure Decoupled Advanced Coal (PDAC) feeder system (shown as Secondary Coal Feeder on Source: (NCCC, 2012)
Figure 2-1). The proprietary design was first tested at the PSDF in 2007. Pulverized coal is transferred from the silo to the surge bin, which also operates at atmospheric pressure. As shown on Adapted from:
Figure 2-4, the PDAC system is a lock hopper-based feeder, but differs from the biomass feeder in that it has no moving parts and uses conveying gas (nitrogen) flow to control the solids feed rate. The gasifier pressure feedback controller permits automatic adjustments to feeder pressure and nitrogen flow as gasifier pressure changes. (Gasifier operating pressure is reduced for oxygen-blown operation due to the supply pressure capabilities of the oxygen supply system.)



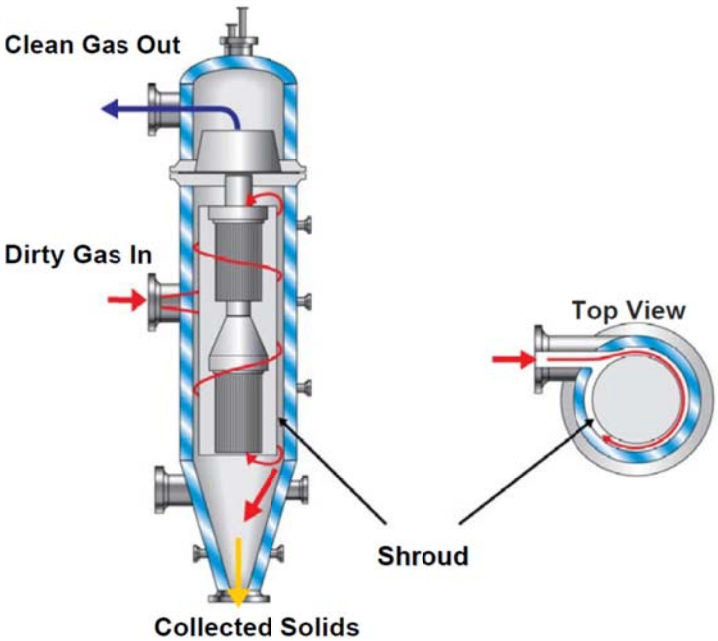
Adapted from: (Southern Company Services, Inc. 2009)

Figure 2-4: Coal Feeder (PDAC)

2.2.2 Particulate Control Device

The PCD was designed by Siemens (previously Westinghouse) to remove greater than 99.999% of fine ash particles from the cooled product gas. The PCD consists of up to 91 filter elements on two plenums arranged within a shroud, as shown on Source:
Figure 2-5 and Source:
Figure 2-6. Most of the filter elements used during the CCAT test consisted of Pall PSS sintered powder element made of iron aluminide material and Pall Dynalloy sintered fiber elements constructed of an HR-160 alloy. Metal filter elements were found to be less brittle than ceramic ones at the 750 – 800°F product gas operating temperature (Southern Company Services, Inc. 2009). A high pressure nitrogen backpulse system cleans the elements every five minutes. A failsafe device is located on each element to prevent solids leakage in the event of filter element failure. In addition, *in situ* gas sampling and online particulate monitors are used to evaluate PCD performance and detect filter element failure.

Detection of higher levels of particulates in product gas at the outlet of the PCD resulted in a system shutdown midway through the DOE test in July 2012. Filter element failure was originally suspected, but after a thorough inspection of the PCD, NCCC determined the root cause was a crack in the tubesheet expansion joint weld. All filter elements were removed and replaced with spare elements from NCCC's onsite inventory, the tubesheet weld was repaired, and the PCD was reassembled and tested before gasifier operation resumed. The whole operation took about four weeks to complete.



Source: (KBR 2008)

Figure 2-5: Particulate Control Device

Source: *(NCCC 2012)*

Figure 2-6: PCD Filter Elements

2.2.3 Product Gas Combustor

A 1,500 pound per hour (lb/hr) slipstream of product gas exiting the PCD passes through the Syngas Cleanup Unit (SCU) for testing of product gas conditioning technologies. All product gas from the PCD and SCU is burned in the atmospheric syngas combustor and the exiting hot gas stream flows through a waste heat boiler, generating steam and cooling the gas before it enters the stack to the atmosphere.

2.3 Comparison with EERC Gasifier

One of the objectives of testing at NCCC's large-scale demonstration Transport Gasifier was to compare results with those obtained from the smaller TRIG™ unit at EERC. This will help assess scale up considerations and whether operating at a larger scale results in better conversion, higher efficiency, and a syngas composition more suitable for producing liquid fuels than at the smaller scale.. Although both units were designed by KBR, there are a few differences between the original TRIG™ unit built at EERC and the more recently built one at NCCC. It is important to identify and understand the operational differences between the two systems. These differences are presented at an overview level and no proprietary information is given.

Significant differences exist in the feed systems used during CCAT's tests at the EERC and NCCC TRIG™ units. At EERC, fuels were pre-blended to the desired mixtures. A drag chain elevator was then used to raise the feed into the top of two parallel continuously diverging feed lock hoppers. From the lock hoppers the feed was dropped into the feed delivery hopper, which also serves as a mixing drum. The feed was then conveyed laterally by an auger. At the end of the auger the feed was blown into the gasifier. As described above, the NCCC feed system actually consists of two separate feed systems for the coal and biomass. The fuels were stored separately in storage silos and fed to the independent feed systems. The biomass feeder is a conventional lock hopper system that utilizes a rotating disk and pneumatic conveying to control the solids feed rate. The coal feed system is a proprietary design of the Southern Company that combines some of the successful concepts developed at the facility such as continuous ash depressurization systems with traditional designs for flow rate control. Like the biomass feeder, this feeder is a lock hopper-based system, but differs in that it uses conveying gas flow to control the solids feed rate. Flow from each feeder was metered to obtain the desired mixture of coal and biomass. The two feeds entered the gasifier approximately 12 inches apart.

A second difference between the two systems is the order in which the gas flows through the standpipe and dipleg. For the EERC TRIG™, the disengager (cyclone) separates larger particulates from the gas coming from the riser. These particles fall into the standpipe. The gas then passes through the primary cyclone where finer particles are removed. These solids fall into the dipleg. The dipleg solids (finer solids) are returned to the standpipe (coarser solids) through the loop seal (about mid-way down the standpipe). The combination of solids is returned to the riser via an "L valve" configuration. The Transport Gasifier at NCCC was originally constructed with a similar configuration. However, in 2006, the configuration of the NCCC Transport Gasifier was changed so that coarse ash from the riser is separated from the gas stream in the primary cyclone (99% coarse solids removal) and the ash falls directly into a seal leg, which differs in design from the loop seal and is considered proprietary. Finer solids are removed from the syngas by the secondary cyclone. These solids fall into the standpipe. The seal leg returns the coarser ash from the primary cyclone to the standpipe. From the standpipe, the combined solids are returned to the riser via a "J-leg" valve configuration. NCCC has found slightly greater carbon conversion to syngas and about 20% increase in the heating value of syngas produced since they changed the seal leg configuration to the current arrangement (Northington 2012).

One other significant difference between the two gasifiers is in the use of nitrogen. EERC uses nitrogen to fluidize the bed material in the standpipe and move solids through the L-valve. The NCCC TRIG™ unit offsets a large fraction of nitrogen by using recycled syngas to fluidize the standpipe and to provide transport gas through the seal leg and J-leg. However, nitrogen is still used throughout the system, but at a lower fraction (compared to total syngas output) than in the TRIG™ at EERC. Aside from constituting an operating expense, the more nitrogen used, the greater the dilution and the lower the unit volume heating value of the product gas. This increases the volume of syngas to be processed by F-T catalysis.

3 Test Objectives

The goal of the project demonstration testing is to provide data on the gasification element of the coal/biomass to liquid fuel process in support of the production of liquid fuels for military applications utilizing a wide variety of feedstocks. Specific objectives of this testing are:

- Demonstrate that desired coal/biomass mixtures are achieved with separate feeding of coal and biomass.
- Demonstrate that the TRIG™ gasifier can gasify the selected coal/biomass mixtures while continuously producing syngas under the desired operating conditions.
- Determine the level of carbon conversion and the amount of carbon in the solids removed from the gasifier for each test condition, if possible.
- Show that the ash produced from the oxygen fed coal/biomass mixtures can circulate in the TRIG™ gasifier successfully without forming deposits or having the bed material agglomerate.
- Determine if and to what extent tars are produced with the coal/biomass mixtures in the TRIG™ gasifier.
- Determine performance of hot gas particulate removal system for each test condition.
- Monitor gasifier operating conditions as outlined in test plan, including solids recirculation rate, syngas recirculation rate, and coal/biomass mixtures that will produce syngas suitable for F-T liquid and high carbon conversions. The intention of monitoring these parameters is to compare them against EERC conditions.
- Generate system data in support of DOE NETL modeling and for use in validation of the models.
- Collect test results for comparison with those obtained from the EERC tests. . This comparison, which will be presented as part of a separate report, will assess whether operating at a larger scale results in better conversion, higher efficiency, and a syngas composition more suitable for producing liquid fuels.

4 Methodology

The test plan implemented by NCCC on behalf of CCAT was prepared by ARCADIS after numerous discussions with the Project Team, NCCC, and NETL. In addition, EERC provided guidance based on previous CCAT testing done on the transport gasifier at EERC. NCCC performed grindability and other tests on samples of raw and torrefied biomass pellets to determine if the material was suitable for use in their system before finalizing the test plan. The outcome of these preliminary feedstock tests was acceptable to NCCC (mean particle size diameter 1100 µm raw; 800 µm torrefied; 350 µm coal). When suitability was confirmed, CCAT arranged for the purchase of all biomass feedstocks and equipment needed for desired operation of the oxygen system at NCCC. The final test plan, dated June 19, 2012, is included in Attachment 1. The timing of the CCAT test depended on the schedule of the DOE test.

4.1 Test Scenarios

The test plan called for testing seven scenarios of coal and woody biomass mixtures in oxygen-blown mode at an assumed oxygen to fuel feed ratio of one pound oxygen per one pound of feed. As shown in Table 4-1, the tests include 100% coal and coal with three different concentrations of raw and torrefied wood pellets, increasing from 10% to 20% to 30% by weight. Unlike at EERC, a portion of syngas produced would be recycled to the gasifier for use as fluidizing gas as mentioned previously. Target gasifier operating conditions were: maximum mixing zone temperature of 977°C (1,790°F), exit temperature of 920°C (1,690°F), exit pressure of 160 pounds per square inch gauge (psig); and riser velocity of 24 feet per second. Actual conditions were adjusted as necessary to maintain stable operations and recorded continuously.

Several operating parameters are used to define steady state gasifier operation. For steady state to be achieved, all parameters must be within an acceptable range of deviation for a minimum of 4 hours. The acceptable deviations for these parameters are shown in

.

For example, if the average Syngas Heating Value during a 5-hour steady state period was 95.0 British thermal units per standard cubic feet (Btu/SCF) and the largest deviation during the period was 5.0 Btu/SCF, the percent deviation during the period would be 5.3% (5.0 /95.0 * 100). Therefore, the steady state period for this parameter is acceptable.

Table 4-1 Test Plan Scenarios

Test #	Run Time (hr)	Test Conditions/ State	State	Comments	Biomass (wt %)	Total Feed Rate (lb/hr)	Coal Feed Rate (lb/hr)	Biomass Feed Rate (lb/hr)
1 & 2	28	Coal Only / O_2-blown	Steady State	1 feed hopper, coal	0	3,000	3,000	0
3	24	Coal + 10% torrefied / O_2-blown	Steady State	2 feed hoppers	10	3,000	2,700	300
4	24	Coal + 20% torrefied / O_2-blown	Steady State	2 feed hoppers	20	3,000	2,400	600
5	24	Coal + 30% torrefied / O_2-blown	Steady State	2 feed hoppers	30	3,000	2,100	900
6	2	Transition to raw biomass	Transiti on	"Empty" hopper and load raw biomass.	0	3,000	3,000	0
6	24	Coal + 10% raw /O_2-blown	Transiti on	Remove all torrefied biomass from system.	10	3,000	2,700	300
7	24	Coal + 10% raw / O_2-blown	Steady State	2 feed hoppers	10	3,000	2,700	300
8	24	Coal + 20% raw / O_2-blown	Steady State	2 feed hoppers	20	3,000	2,400	600
9	24	Coal + 30% raw / O_2-blown	Steady State	2 feed hoppers	30	3,000	2,100	900

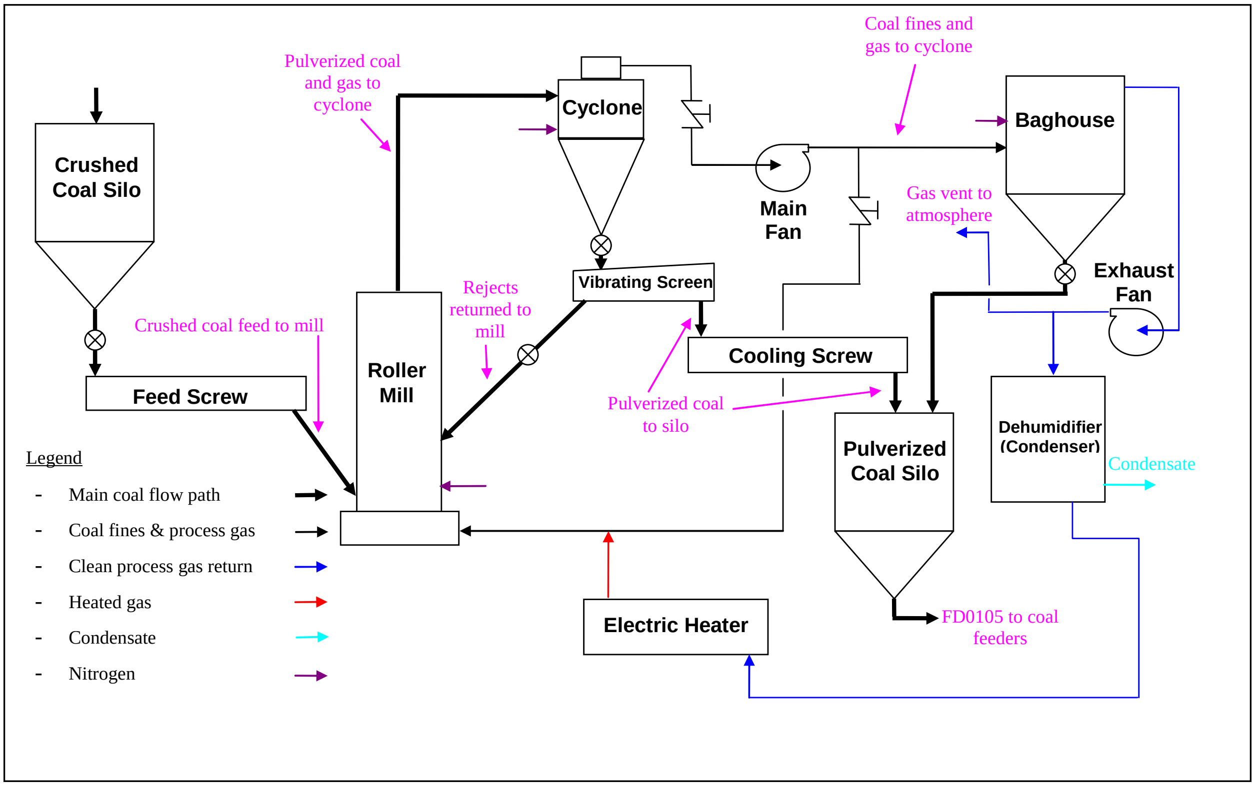
Table 4-2 Steady State Operating Parameters and Acceptable Ranges

Operating Parameter	Duration	Acceptable Deviation Criteria
Product Gas Heating Value (LHV- dry basis)	> 4 hours	Deviation from average during period < 10%
Gasifier Product Gas Flow Rate	> 4 hours	Deviation from average during period < 10%
Gasifier Air Flow Rate	> 4 hours	Deviation from average during period < 10%
Gasifier Oxygen Flow Rate	> 4 hours	Deviation from average during period < 10%
Gasifier Nitrogen Flow Rate	> 4 hours	Deviation from average during period < 10%
Gasifier Steam Flow Rate	> 4 hours	Deviation from average during period < 10%
Gasifier Standpipe Level	> 4 hours	Deviation from average during period < 10%
Gasifier Outlet Pressure	> 4 hours	Deviation from average during period < 2%
Gasifier Upper Mixing Zone Temp.	> 4 hours	Deviation from average during period < 3%
Gasifier Exit Temp.	> 4 hours	Deviation from average during period < 3%

4.2 Feedstock Preparation and Feeding

Source:

Figure 4-1 shows the process flow diagram for the feed preparation system at NCCC. Coal and biomass were processed separately. Material was fed by a feed screw from the silo to the Williams Patent Crusher fluid bed roller mill, a pulverizer, where it was mechanically ground and contacted with heated process gas (mainly nitrogen) from an electric heater. By design, the pulverizer functions as a flash dryer with the heated process gas also functioning to convey the pulverized material from the mill to the cyclone. This results in a very short residence time (approximately 1 to 3 seconds), during which only surface or “free” moisture is evaporated. The cyclone separates the process gas and fines from the pulverized feedstock. Fines are separated from the process gas in a baghouse; the gas is returned to the mill after passing through a dehumidifier and heater. The feed exiting the cyclone was screened and oversize material returned to the pulverizer for further milling. The remaining product continued through a cooling screw, and was stored in a silo ready for use as gasifier feedstock. Nitrogen gas was added to the dense phase conveyors to increase the flowability of pulverized biomass to the biomass feeder. Instrumentation and control logic were optimized for each feedstock to improve system control, reliability, and troubleshooting. Representative samples of each feedstock were analyzed for ultimate and proximate analysis by the Alabama Power Laboratory (Southern Company) that is located in Calera, Alabama.



Source: *(NCCC 2012)*

Figure 4-1: Fuel Processing Equipment Setup for Gasifier Testing

4.2.1 Coal

NCCC acquired the coal for this test from Southern Company Plant J.H. Miller. The coal was a Powder River Basin (PRB) sub-bituminous coal from Arch Coal's Black Thunder mine. The coal was processed in the mill system to achieve the desired moisture content (18%) and particle size distribution. Approximately 450 tons of coal were used for the CCAT test.

4.2.2 Raw Woody Biomass

NCCC performed grindability tests on samples of raw and torrefied wood pellets received from New Biomass Energy (NBE), Quitman, Mississippi in March and April 2012. As noted above, the tests showed that the material would be suitable for the NCCC feed system. The raw pellets were made from thinnings from southern pine plantations, including bark and needles, which were chipped offsite. Moisture content of the chips delivered to NBE was about 55%. The chips were dried and pelletized using a proprietary process. NBE measured the heating value of each batch of pellets produced with a Parr 6400 calorimeter. CCAT purchased approximately 40 tons of raw wood pellets from NBE. The pellets were delivered in bulk to NCCC on June 26 and 27, 2012 and stored under cover until milled for the test. A small portion of the pellets were darker in color and had slightly higher Btu content than the other material. NBE stated that these pellets were likely coated with dust from torrefied wood processed on the same equipment (Peterson 2012). The Project Team, in consultation with NCCC, determined that the effect of the darker material on the whole batch of raw pellets would be insignificant for the test and the material

was accepted (Northington 2012). A picture of a sample of the as received raw pellets is shown on Source: Adapted from
Figure 4-2.

Source: Adapted from (Southern Company Services, Inc. 2012)

Figure 4-2: As Received and As Fed Raw Southern Pine Pellets from NBE

4.2.3 Torrefied Woody Biomass

Torrefaction is the process of heating the wood under controlled temperatures in an oxygen-free environment to drive off volatile compounds and moisture. This results in a substantial increase in the heating value per unit mass and a decrease in the fibrous nature of woody biomass. The off gas can be burned to provide heat to the reactors, increasing thermal efficiency of the torrefaction process. Development of process technologies for torrefying wood and other biomass is in its infancy, particularly in the U.S. Most of the focus has been on torrefying wood and making pellets for the power industry in Europe. While raw wood is hydrophilic and can be difficult to grind, torrefied wood is hydrophobic and brittle, and therefore easy to grind and feed (Koppejan 2012).

Several developers of torrefaction technologies in North America were contacted. NBE had the largest commercial capacity and was best able to meet the supply needs of the test. At their Quitman facility, wood chips are fed to torrefaction reactors. Time in the reactors ranges from 15 to 45 minutes, depending on the moisture of the wood. The torrefied wood is then ground in a hammer mill to European specifications (less than 4 millimeters). The ground chips are processed through pellet mills with proprietary dies developed by NBE. (The same pellet mills are used to produce raw and torrefied pellets.) CCAT purchased approximately 40 tons of torrefied wood pellets from NBE. The pellets were delivered in bulk to NCCC on June 27 and 28, 2012 and stored under cover until milled for the test. A picture of a sample of the torrefied pellets is shown on Source: Adapted from
Figure 4-3.

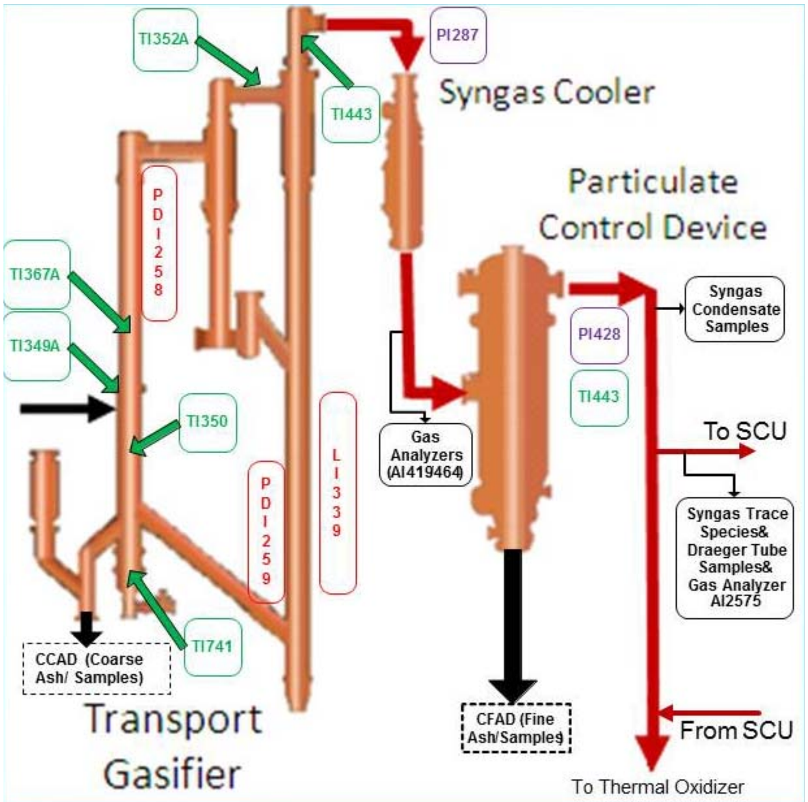
Source: Adapted from (Southern Company Services, Inc. 2012)

Figure 4-3: As Received and As Fed Torrefied Southern Pine Pellets from NBE

4.3 Instrumentation, Sampling, and Process Controls

To fulfill the test objectives, inputs and outputs to the gasifier and gasifier operational parameters were monitored by NCCC throughout the test. Fuel, oxygen, nitrogen, air, steam and product gas flow rates, temperature, pressure, and pressure differential at several locations in the gasifier; product gas composition; and thermal oxidizer flue gas emissions were monitored continuously. Samples of trace species in the product gas (NH_3, HCN, HCl, H_2S, moisture content, and benzene), product gas condensate, coarse solids from the CCAD, and fine solids from the CFAD were collected once per test condition during steady state conditions. Sample locations and monitoring instruments used are shown on Source: (NCCC, 2012)

Figure 4-4.



Source: (NCCC, 2012)

Figure 4-4: Key Instrumentation and Sample Locations

4.3.1 Feed Rate Measurements

Both feed systems, the original (used for biomass), and the PDAC (used for coal), were installed with feeder load cells. Load cell readings were taken at the beginning and end of each cycle when the valves to the pressurized lock vessels were closed. Feed rates for each test condition steady state period were calculated by averaging the feed rates for each cycle measured during the period. Cycle times ranged from 6 to 10 minutes for the PDAC and 15 to 35 minutes for the biomass feeder. A DensFlow flow meter from SWR Engineering was also tested on the coal feeder. Due to a discrepancy between the flow meter and the weigh cell calculated rates, the weigh cell rates were reported for the CCAT test.

4.3.2 Gasifier Process Controls

Thermocouples installed throughout the gasifier are critical for monitoring gasifier performance, for providing input for control logic, and for automation of parameters such as air flow rate and coal/biomass feed rates. To avoid ash agglomeration in the gasifier, the temperature needs to be maintained at about 300°F and 200°F below the ash fusion temperature in the lower mixing zone and upper mixing zone, respectively. Temperatures in the upper mixing zone are kept lower due to the higher solids-to-gas ratio and lower gas velocity in this region. However, the temperature in the upper part of the riser must be maintained sufficiently high to achieve the desired carbon conversion and targeted syngas heating value (Southern Company Services, Inc. 2009). Except for temperature readings listed on Source: (NCCC, 2012)

Figure 4-4, all other temperature readings are proprietary. Product gas velocity in the gasifier was calculated using flow measurements for various inputs to the gasifier and was not directly measured.

The gasifier pressure differential indicators are necessary for monitoring the gasifier solids inventory and solids circulation. The level of solids in the standpipe has a positive correlation with the solids circulation rate, which directly affects gasifier operation and performance by controlling the temperature profile and the rate at which the solids and gas interact. To achieve stable circulation around the gasifier loop, a constant solids level inside the standpipe must be maintained. The solids level is controlled by the rate of removal of coarse ash through the CCAD. The discharge rate is adjusted to achieve the desired level.

Proper fluidization of the seal leg, J-leg, and standpipe is also required to maintain stable solids circulation in the gasifier. Recycled syngas is used for aeration in these three sections of the gasifier. Fluidization is based on the physical characteristics of the material, which can change as the feedstock composition varies. Due to changes in gasifier temperature and pressure, velocities vary with a constant mass flow. Since constant velocity is the control parameter, NCCC employed velocity control loops to minimize the effect of pressure and temperature changes.

4.3.3 Gas Samples Collection

Product gas flow was measured via an orifice plate and is both temperature and pressure compensated. Other parameters that are specified in the sizing of the orifice include temperature and pressure range, average molecular weight (24 lbm/lbmol for oxygen-blown mode), flow range (varies based on application), average viscosity (0.03 cp), average compressibility factor (1.0), and specific heat ratio (1.3 – Cp/Cv). The total product gas flow rate is the sum of flows measured to the Recycle Gas Compressor and to downstream processes. These measurements are made downstream of the PCD to avoid interference with particulates in the gas stream.

To assess and optimize system performance and achieve test objectives, extensive solids and gas sampling and analysis were performed during gasification operation. Product gas was monitored continuously (every 200 seconds) for nine constituents (CO, H_2, CO_2, N_2, CH_4, C_2, Ar). A gas stream from immediately upstream of the PCD was sent to two gas analyzers (AI419/ AI464, Source: (NCCC, 2012)
Figure 4-4). Gas components were measured on a dry basis; energy content was calculated as the lower heating value. Details of the gas analyzer sampling process are presented in Appendix A.

4.3.4 Trace Species Samples Collection

Product gas samples were collected for trace species analysis from the slipstream to the SCU downstream of the quench cooler. Hydrogen sulfide (H_2S) was measured continuously with a Siemens Maxim II analyzer (AI2575 on Source: (NCCC, 2012)

Figure 4-4). Another sulfur species, COS, was measured twice an hour with a modified HP GC5890. Product gas trace species and Dräeger tube samples were collected from the same slipstream once for each test condition (i.e., each change in biomass co-feed percentage). Ammonia was extracted by bubbling product gas through chilled impinger tubes with 0.1N sulfuric acid and isopropanol for about 30 minutes. The extract was measured onsite with an ion selective electrode. Ammonia levels were used as one of the first indicators of steady state in the gasifier. To collect samples for the heavier hydrocarbons (tars), product gas was bubbled through isopropyl alcohol impingers in an ice bath for about 45 minutes. The isopropyl alcohol extracts were analyzed for volatile and semi-volatile organic compounds by gas chromatography (Method 8021) and gas chromatography–mass spectrometry (Method 8270), respectively in an offsite laboratory (DHL Analytical Inc. [DHL]). Note that while the lab (DHL) measured the mass of the hydrocarbons in the samples, the results reported in Section 5.5 below are on a volume basis. The total gas volume (calculated by total sample time and gas flow rate), moisture concentration, and product gas composition were used to calculate the mass and moles of the product gas. The DHL analyses (volume, density, and component analysis) were used to calculate the total component mass and moles in the selected sample. From these two mole calculations, the concentration as parts per million by volume (ppmv) of each component in the product gas was calculated (Northington 2013). In addition, Dräeger tube samples were collected directly from the hot product gas stream for NH_3, HCN, and HCl.

One product gas condensate sample was collected during each test condition from the syngas line downstream of the PCD and analyzed for chemical oxygen demand (COD), total organic carbon (TOC), and ammonia (NH_3). The product gas conditions at this location averaged 164 psig and 695^{o}F. When collecting the PCD particulate outlet sample a slipstream of syngas was pulled from this location through a filter to capture solids (a normal sample run was about 3-4 hours). The condensate trap was a series of coiled tubing immersed in an ice water bath with a sample cylinder connected at the lowest point to collect condensate. The temperature of the ice water bath was maintained around 40^{o}F which gave a syngas outlet temperature in the range of 60 to 80^{o}F. Condensate samples from seven test conditions (coal only, three torrefied pine blends, three raw pine blends) were sent to an offsite laboratory for analysis. The residence time between the gas condensate and trace species/Dräeger tube sample locations was about 1 to 2 seconds so syngas operating conditions were roughly the same (Northington 2013).

4.3.5 Solid Samples Collection

Feed and ash samples were collected four times a day during the test and analyzed for ultimate analysis, proximate analysis, ash minerals analysis, particle size distribution (PSD), and loss on ignition (LOI). Coal samples were collected from the PDAC and biomass samples from FD0210. Coarse ash samples were collected directly from the CCAD at the bottom of the gasifier riser. The ash collected here is the combination of solids collected in both the primary and secondary cyclones. The fine ash was collected downstream of the PCD in the proprietary fine ash removal system (CFAD) surge vessel outlet. The fine ash was backpulsed from the PCD filter elements and cooled. In addition, one coarse and one fine ash sample from tests 2, 3, 5, 7, and 9 were submitted to TestAmerica laboratory for analysis of metals, including heavy metals. The samples were analyzed by the Toxicity Characteristic Leachate Procedure (TCLP) and the leachate concentrations compared to federal criteria to determine if the material would be considered hazardous for disposal purposes.

4.4 Mass and Energy Balances

A mass balance was performed around the TRIG™ and supporting equipment to determine if the majority of all flows are represented by the measurements performed. A failure to close the mass balance would indicate an error in one or more measurement systems or that an important input or output stream had been omitted from the calculation. In this capacity the mass balance acts as a quality assurance measure. The mass balance relates the total mass outputs from the system to the total mass inputs to the system. A mass balance closure criterion of +/- 10 % was used for this report in line with the closure criteria used by NCCC.

The mass balance was done with the system boundary shown on Figure 4-5 below. The system boundaries were extended beyond the gasifier to include the gas cooler and PCD because both gas composition and gas flow measurements were made on product gas downstream of the PCD in order to avoid interference from particulates. The inputs to system boundary include coal, biomass, air, pure oxygen, steam, and pure nitrogen. The outputs from system boundary include product gas, fine ash, and coarse ash. The gas cooler is a heat exchanger and results in no change in mass input or output. Some nitrogen purges are added through the PCD, but this mass is included in the total nitrogen inputs. A detailed description of the streams accounted for is given in Appendix B.

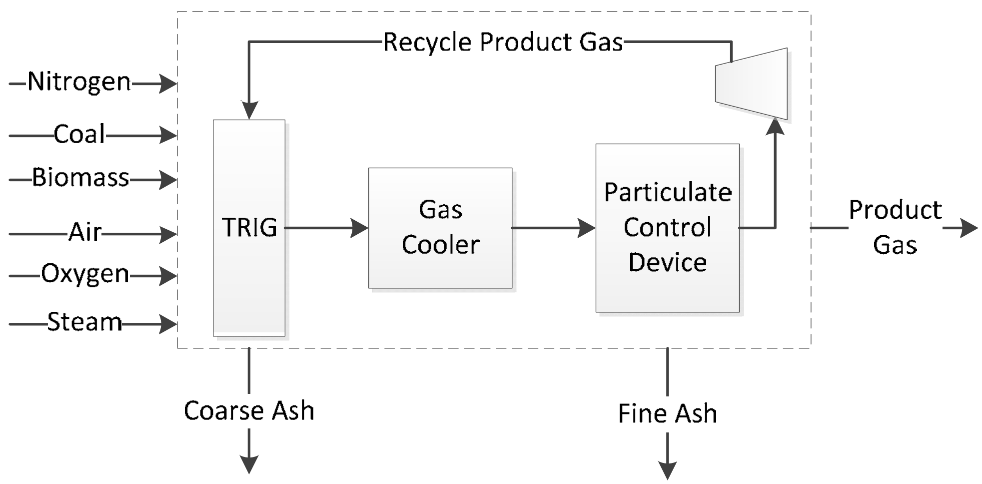


Figure 4-5: System Boundaries for Mass Balance

The majority of inputs to the system were used as directly measured for the mass balance. NCCC preferred to estimate steam from an elemental balance on hydrogen as the steam measurement system was not considered accurate over the entire measured range encountered in this test series. For the hydrogen balance, hydrogen was considered to be conserved from the hydrogen present in the fuel, steam input, hydrogen present in the coarse and fine ash output, and product gas stream, hydrogen, and methane.

Product gas is a major component of the mass exiting the system. Product gas flow rate is a critical parameter for the overall mass balance and, along with gas composition, for any elemental mass balance. Product gas flow rate was monitored by orifice plate measurements and corrected for temperature and pressure. The orifice plate measurements were calibrated to a 27.5 lb/lbmol wet molecular weight typical of air-blown operation; the average recorded flow was corrected by the CCAT team using the derived wet molecular weight for each steady state period. While dry product gas composition was measured continuously as described in section 4.3.2, moisture content of the gas was derived from condensate measurements over an integrated time period as described in section 4.3.4.

Ash is a minor component of the overall mass balance. For the mass balance, ash is considered as a single component as measured in proximate analysis. The amount of coarse ash output was not measured but was based on an ash balance. Ash inputs to the system are estimated from the feed rate and proximate analysis of the fuels. The output rate of fine ash; a mixture of moisture, volatiles, fixed carbon, and ash; was measured and the amount of ash output was calculated using the proximate analysis of the fine ash sample. The rate of ash component output in the coarse ash sample was determined by subtracting the ash component of the fine ash from the calculated ash inputs. The mass output rate of coarse ash was then determined from the ash component rate and coarse ash proximate analysis.

An energy balance, attached as Appendix C, was similarly performed around the TRIG™ to determine if the majority of the heat input as fuel was accounted for in the outputs of the system. The system boundaries for the energy balance are shown in Figure 4-6. The gas cooler and PCD were excluded from the energy balance because measurements of heat losses around these devices were not reported. The energy balance was limited to the heat of combustion and sensible heat of the inputs and outputs.

The energy inputs are coal, biomass, steam, air, and recycle product gas. Note that sensible heat from oxygen and nitrogen input streams are not accounted in the energy balance because they are fed at ambient temperature (a reference ambient temperature of 80°F was used in the energy balance calculations). Coal and biomass were fed at ambient temperature, which is also the reference temperature of 80°F assumed in these energy balance calculations. Therefore the only form of energy input from coal and biomass was the heating values and corresponding flow rates. The energy input from the steam is based on the sensible heat of the steam at the temperature and pressure of delivery. Energy input from the recycle product gas was calculated based on the sensible heat and heating value of the recycle product gas.

The energy outputs of the system include coarse ash, raw product gas, and heat loss. Raw product gas rate at the gasifier outlet was determined by mass balance. The energy in the coarse ash was defined by the sensible heat and heating value of the solids. The product gas energy was calculated based on the sensible heat of the product gas and the heating value of the product gas. Heat loss from the system, as a result of convection/conduction/radiation, is assumed to be 3.5 MMBtu/hr for all seven test runs (Northington 2013).

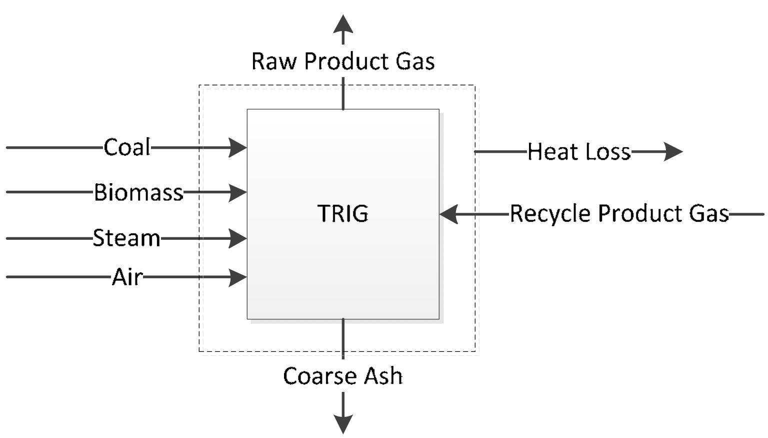


Figure 4-6: System Boundaries for Energy Balance

5 Results

5.1 Variances from Test Plan

The most significant variance from the test plan pertained to feeding two biomass feedstocks. As noted in the table below, the target percentage of biomass co-feed was not achieved in every case. The greatest variance was at the lower, i.e., 10%, target feed rate, particularly with the torrefied pine. Due to the physical characteristics of the ground torrefied feedstock, it was difficult to control the flow of biomass at the targeted rates.

When the mechanical rotary device of the biomass feeder was operating at the slowest speed possible, the safety interlock system tripped frequently. The interlock is programed to return the gasifier to a safe, oxygen-free state to prevent oxygen break through to the PCD and other backend equipment. Once the interlock is manually overridden, the gasifier must restart with an air-blown 100% coal feed. Oxygen-blown mode and biomass feed could then both (separately) be transitioned back online. The motor speed on the biomass feeder was increased until steady flow rates of torrefied biomass could be maintained. A plot of biomass feed rate as a function of feeder speed is shown on Source: Adapted from
Figure 5-1. The result was over 600 pounds per hour (double the rate in the test plan). The coal feed rate was increased as much as possible while maintaining temperature and pressure conditions required for safe gasifier operation. This resulted in approximately 16 to 17% torrefied biomass mixtures for the 10% target test. The actual percentage of biomass for all other tests was within two percentage points, as shown in Table 5-1. The total feed rate was 3,900 to 4,500 lb/hr, not 3,000 lb/hr as assumed in the test plan. During tests 3 and 4 with torrefied pine, two steady state periods were recorded at the 10% target and two steady state periods at the 20% target due to some operational problems during those tests. One steady state period was recorded for all the other tests.

The gasifier was started in air-blown operation until steady state coal feed was achieved. Then the transition to oxygen-blown operation began. Air flow through the air feed nozzles in the upper mixing zone was slowly decreased from nearly 14,000 lb/hr to about 3,000 lb/hr while the total oxygen flow through the oxygen feed nozzles at the upper and lower mixing zone was increased to about 2,350 lb/hr during this period (Table 5-1). While air flow was greatly minimized during oxygen-blown operation, it was never completely shut off to prevent nozzle plugging and provide operational stability if oxygen flow was to suddenly become unavailable. The air flow was fed to the upper mixing zone of the gasifier.

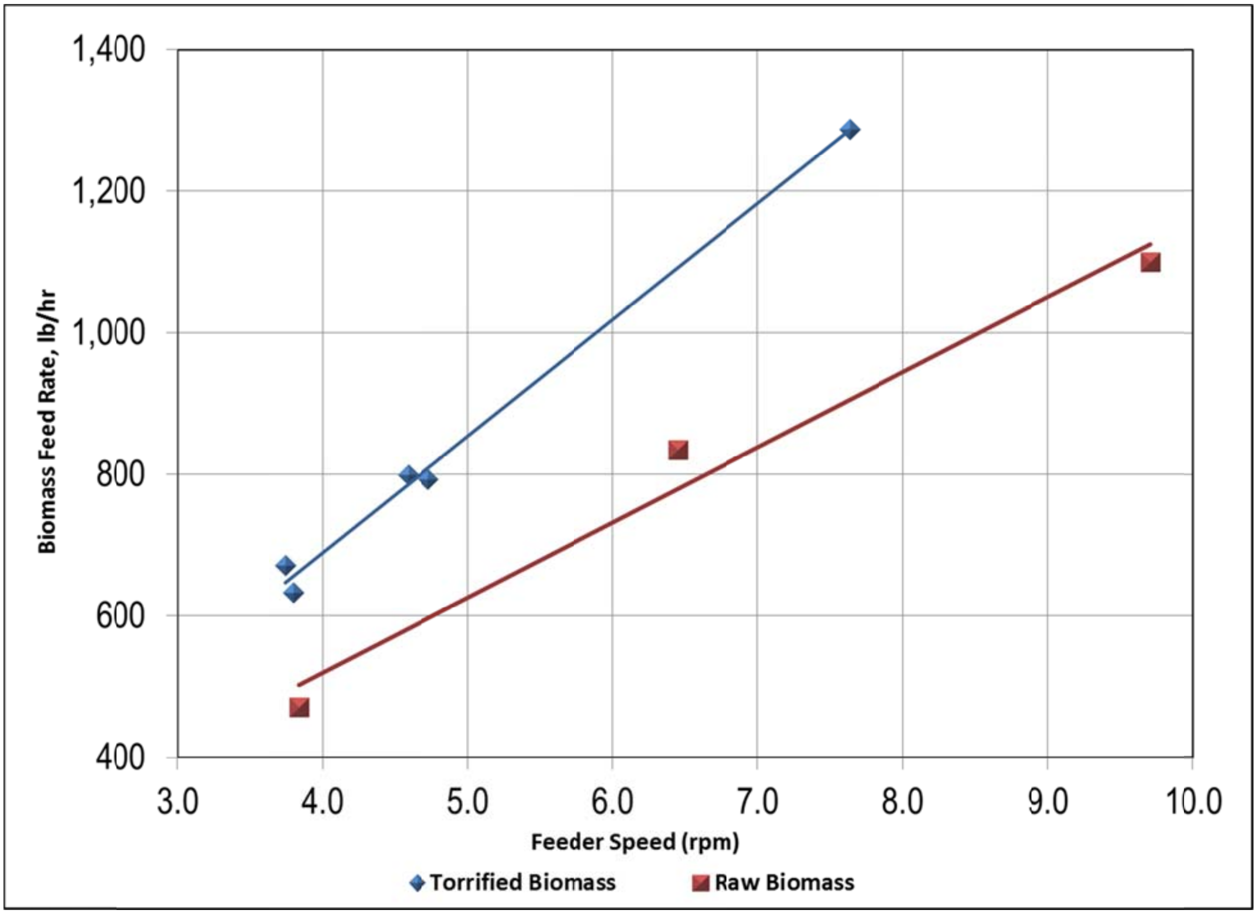
The issues described above in achieving a steady feed rate during test 3 caused delays in the test schedule. Every time the interlock system tripped, it took several hours to bring the system back to steady state under oxygen-blown conditions. However, all portions of the test were successfully completed and 219 hours of oxygen-blown gasification testing were conducted with biomass co-feed (compared with 208 hours target) from September 7 to 17, 2012.

In addition to CCAT's oxygen-blown testing, NCCC provided data for three coal only air-blown cases which were part of the DOE test. Because CCAT's DLA project objective is to make liquid fuel from product gas, this report focuses on oxygen-blown mode tests. It should be emphasized that Steady State Period 44 was selected as the baseline coal only case based on the system's operating temperature and pressure, which aligned more closely to the torrefied and raw biomass test runs. Also, the total mass outputs to total mass inputs ratio for Steady State Period 44 was closer to unity than the other two coal only, oxygen-blown test conditions (Steady State Periods

37 and 38). Data from Steady State period 44 and the steady state periods from all coal / biomass tests are presented in subsequent parts of Section 5. Data from other coal only steady state periods in air-blown and oxygen-blown mode (Steady State Periods 34, 35, 36, 37, and 38) can be found in appendices B, D, E, F, G and H.

Table 5-1: Actual Test Conditions

Steady State Period	NCCC Test Number	CCAT Name	Steady State Start Time	Steady State End Time	Steady State Duration (hr)	Coal Feed Rate (lb/hr)	Biomass Feed Rate (lb/hr)	Air Feed Rate (lb/hr)	Pure Oxygen Feed Rate (lb/hr)	Biomass Type	Target Biomass (wt%)	Actual Biomass (wt%)
44	6	NCCC-TRIG-20120913A	9/13/2012 22:45	9/14/2012 2:44	4.0	3,400	0	3,007	2,293	None	0	**0**
39	3	NCCC-TRIG-20120910A	9/10/2012 3:15	9/10/2012 8:14	5.0	3,401	632	3,208	2,450	Torrefied Pine	10	**15.7**
40	3	NCCC-TRIG-20120911A	9/11/2012 2:30	9/11/2012 6:44	4.2	3,203	671	3,224	2,341	Torrefied Pine	10	**17.3**
41	4	NCCC-TRIG-20120911B	9/11/2012 11:45	9/11/2012 15:59	4.2	3,170	792	3,275	2,379	Torrefied Pine	20	**20.0**
42	4	NCCC-TRIG-20120912A	9/12/2012 2:15	9/12/2012 7:44	5.5	3,348	799	3,226	2,380	Torrefied Pine	20	**19.3**
43	5	NCCC-TRIG-20120912B	9/12/2012 11:00	9/12/2012 14:39	3.6	3,201	1,288	3,224	2,544	Torrefied Pine	30	**28.7**
45	7	NCCC-TRIG-20120915A	9/15/2012 3:30	9/15/2012 7:44	4.2	3,552	472	3,013	2,371	Raw Pine	10	**11.7**
46	8	NCCC-TRIG-20120915B	9/15/2012 17:15	9/15/2012 21:44	4.5	3,386	835	3,121	2,357	Raw Pine	20	**19.8**
47	9	NCCC-TRIG-20120917A	9/17/2012 7:15	9/17/2012 11:14	4.0	2,784	1,100	3,064	2,231	Raw Pine	30	**28.3**
Note: Oxygen feed rate ranged from 0.6 to 1.0 lb. oxygen per lb. fuel to maintain reactor temperature.												



Source: Adapted from (Southern Company Services, Inc. 2012)

Figure 5-1: Biomass Feeder (FD0210) RPM vs. Biomass Mass Feed Rate

5.2 Feedstock Preparation and Analysis

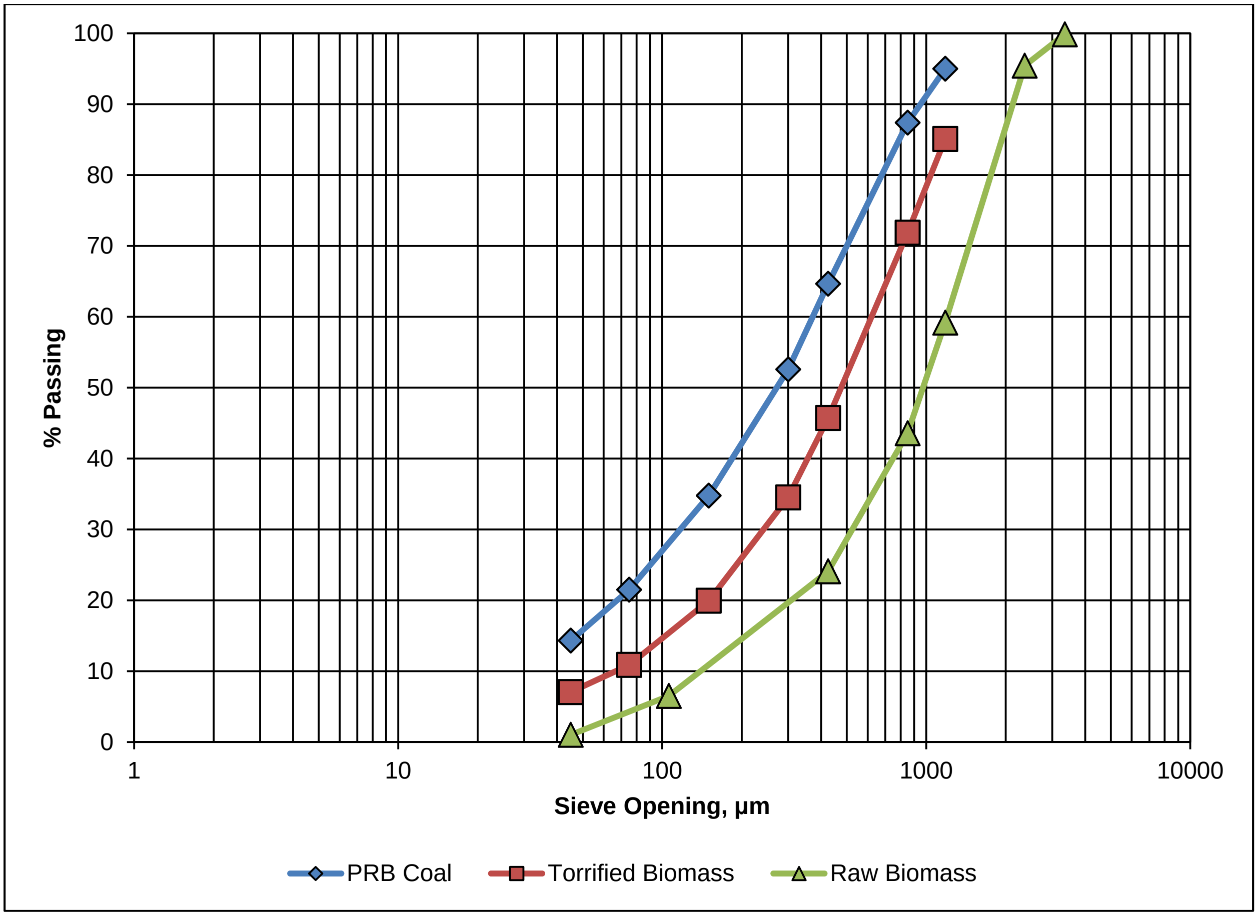
The complete proximate, ultimate, heating value, and ash analysis results of all feedstocks used in the CCAT test are presented in Table 5-2 on both an as received and as fed (i.e., after milling) basis. The as fed values shown are the average of samples collected every eight hours from each feeder during the test. The main differences between as received and as fed basis is the moisture content. The coal moisture was reduced due to milling but raw and torrefied biomass actually gained some moisture due to outdoor storing. Torrefied pine had the highest heating value; raw pine had the lowest of the feedstocks tested.

Table 5-2: Feedstocks Analysis: As Received and As Fed Basis

Basis	**As Received**			**As Fed**		
Feedstock Type	**PRB Black Thunder Coal**	**Southern Pine Torrefied**	**Southern Pine Raw**	**PRB Black Thunder Coal**	**Southern Pine Torrefied**	**Southern Pine Raw**
Proximate Analysis	**wt%**					
Moisture	24.63	4.24	6.26	17.96	7.82	7.98
Volatile Matter	42.33	65.26	72.23	36.06	56.92	73.96
Fixed Carbon	26.43	28.75	20.33	37.66	32.16	17.00
Ash	6.61	1.75	1.18	8.33	3.10	1.06
Ultimate Analysis	**wt%**					
C	52.06	57.51	48.47	54.46	56.54	49.10
H	3.47	5.29	5.67	3.8	4.9	5.4
N	0.89	0.29	0.02	0.89	0.40	0.17
O	12.12	30.91	38.36	14.3	27.1	36.3
S	0.22	0.01	0.06	0.32	0.08	0.05
Moisture	24.63	4.24	6.26	17.96	7.82	7.98
Ash	6.61	1.75	1.18	8.33	3.10	1.06
Heating Value, HHV (Btu/lb)	**8,960**	**9,670**	**8,070**	**9,294**	**9,624**	**8,414**
Ash Analysis As Oxides	**wt%**					
Al_2O_3	14.82	3.33	5.71	16.02	11.33	9.05
BaO	0.63	0.70	0.18	0.60	0.66	0.38
CaO	21.72	40.85	29.10	21.05	23.89	26.82
Fe_2O_3	5.17	2.75	4.43	5.82	5.25	8.86
MgO	4.17	6.08	6.72	4.55	4.59	6.52
MnO_2	0.03	3.20	NR	0.03	1.22	1.13
P_2O_5	1.72	3.55	3.23	1.40	2.33	3.20
K_2O	0.58	6.69	12.32	0.77	4.83	4.37
SiO_2	37.52	21.73	26.10	38.68	36.96	30.65
Na_2O	1.56	1.48	0.63	1.52	1.78	0.88
SrO	0.35	0.25	0.25	0.35	0.33	0.34
SO_3	10.55	9.12	11.04	7.97	6.01	7.24
TiO_2	1.18	0.27	0.32	1.22	0.83	0.57

Note: NR = Not Reported

The particle size distribution for each ground or milled feedstock is presented on Source: Figure 5-2. The mass median diameter particle size was 280 µm for PRB coal, 503 µm for torrefied pine, and 990 µm for raw pine.



Source: *(NCCC 2012)*

Figure 5-2: Particle Size Distributions for Ground/Milled Feedstocks

The complete proximate, ultimate, heating value, and ash analysis values of the blended feedstocks are presented in Table 5-3. Because the coal and biomass were not “blended” until they entered the gasifier, the values shown below were calculated based on the proportions of each feedstock fed determined from the load cells using the as fed basis feedstock analysis shown in Table 5-2. While all ash constituents are shown in the table, only the major components are presented on

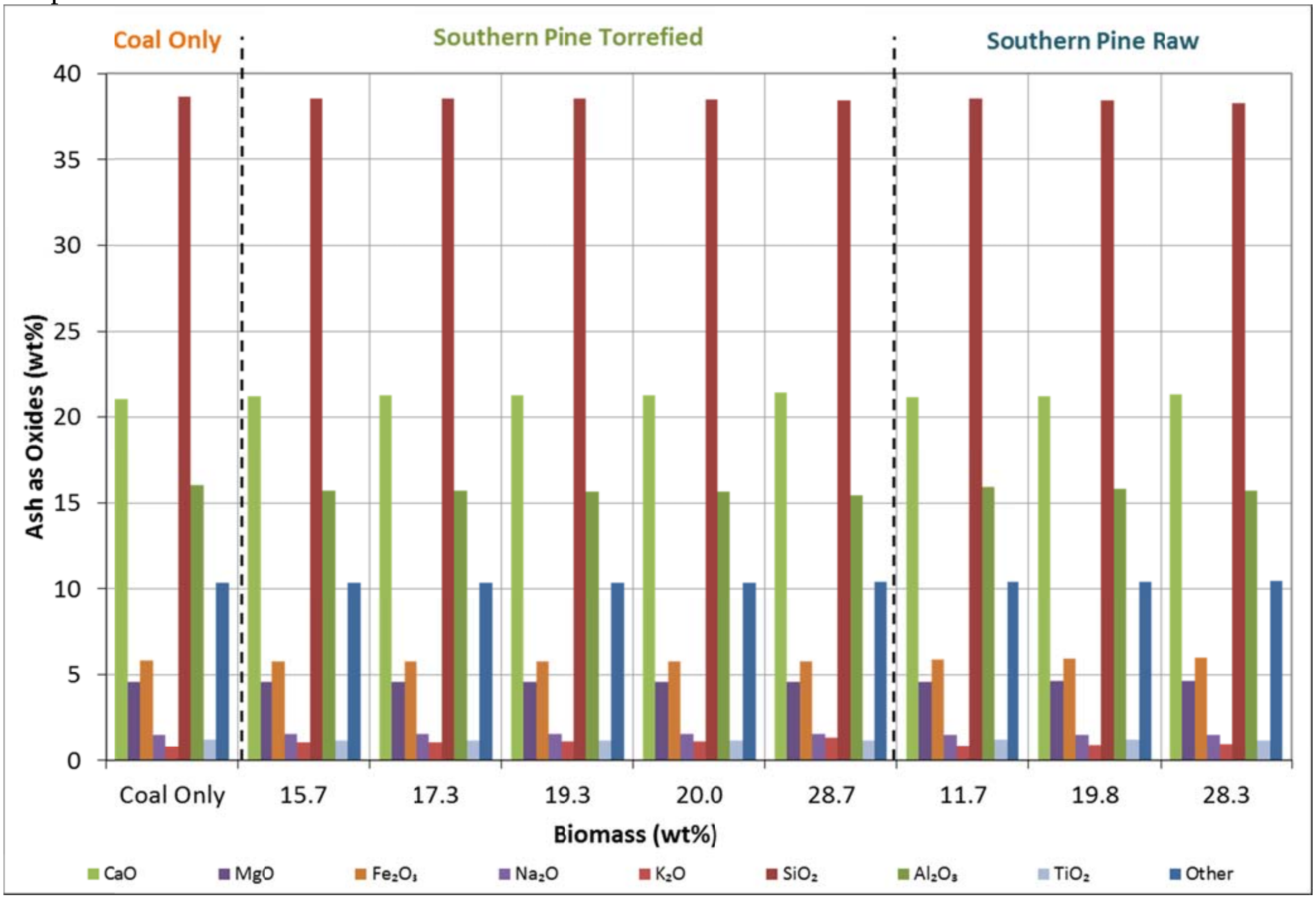


Figure 5-3.

Table 5-3: As Fed Basis Blended Feedstocks Analysis for NCCC Testing

NCCC Test Number	6	3	3	4	4	5	7	8	9
Steady State Period	**44**	**39**	**40**	**42**	**41**	**43**	**45**	**46**	**47**
Biomass (wt%)	**Coal Only**	**15.7**	**17.3**	**19.3**	**20.0**	**28.7**	**11.7**	**19.8**	**28.3**
Biomass Type	**None**	**Coal and Torrefied Biomass Blends**					**Coal and Raw Biomass Blends**		
Proximate Analysis	**wt%**								
Moisture	17.96	16.37	16.20	16.01	15.93	15.05	16.79	15.99	15.13
Volatile Matter	36.06	39.33	39.67	40.07	40.23	42.04	40.50	43.56	46.79
Fixed Carbon	37.66	36.80	36.71	36.60	36.56	36.08	35.23	33.57	31.81
Ash	8.33	7.51	7.42	7.32	7.28	6.83	7.47	6.89	6.27
Ultimate Analysis	**wt%**								
C	54.46	54.79	54.82	54.86	54.88	55.06	53.83	53.40	52.94
H	3.76	3.95	3.97	3.99	4.00	4.10	3.95	4.08	4.22
N	0.89	0.81	0.80	0.79	0.79	0.75	0.80	0.74	0.68
O	14.29	16.30	16.51	16.76	16.85	17.97	16.87	18.64	20.51
S	0.32	0.28	0.28	0.27	0.27	0.25	0.29	0.27	0.24
Moisture	17.96	16.37	16.20	16.01	15.93	15.05	16.79	15.99	15.13
Ash	8.33	7.51	7.42	7.32	7.28	6.83	7.47	6.89	6.27
Heating Value, HHV (Btu/lb)	**9,294**	**9,345**	**9,351**	**9,357**	**9,360**	**9,388**	**9,191**	**9,120**	**9,045**
Ash Analysis As Oxides	**wt%**								
Al_2O_3	16.02	15.72	15.68	15.64	15.62	15.41	15.91	15.81	15.69
BaO	0.60	0.60	0.60	0.60	0.60	0.61	0.60	0.59	0.59
CaO	21.05	21.24	21.26	21.28	21.29	21.42	21.15	21.23	21.33
Fe_2O_3	5.82	5.79	5.78	5.78	5.77	5.75	5.87	5.92	5.97
MgO	4.55	4.55	4.55	4.55	4.55	4.55	4.58	4.61	4.64
MnO_2	0.03	0.11	0.12	0.13	0.13	0.19	0.05	0.06	0.08
P_2O_5	1.40	1.46	1.47	1.48	1.48	1.52	1.43	1.46	1.49
K_2O	0.77	1.04	1.07	1.11	1.12	1.30	0.83	0.88	0.95
SiO_2	38.68	38.57	38.56	38.54	38.54	38.46	38.55	38.44	38.30
Na_2O	1.52	1.53	1.54	1.54	1.54	1.55	1.51	1.50	1.49
SrO	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
SO_3	7.97	7.85	7.83	7.81	7.81	7.72	7.96	7.95	7.94
TiO_2	1.22	1.19	1.19	1.18	1.18	1.17	1.21	1.20	1.18

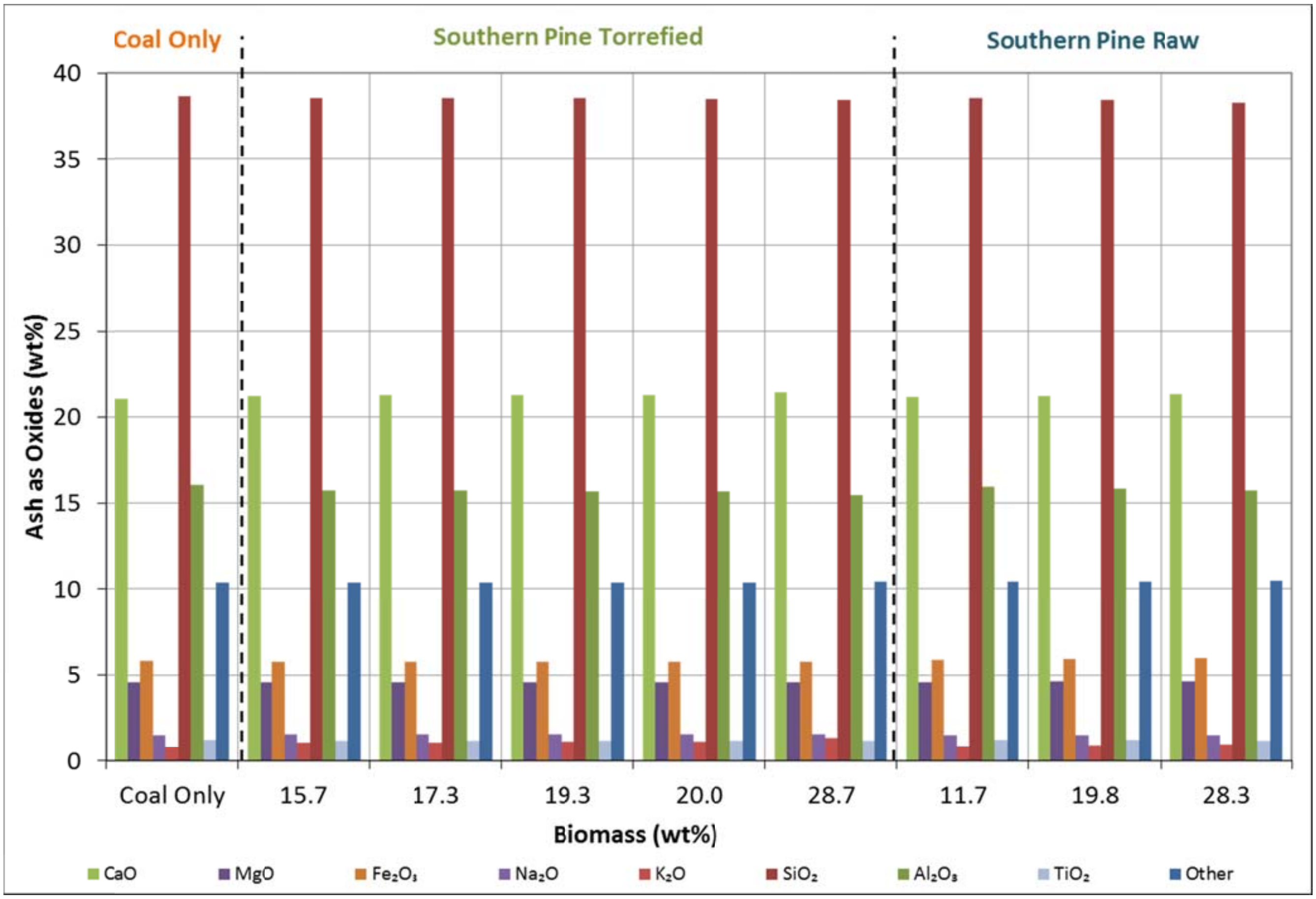


Figure 5-3: Blended Feedstock Ash Analysis

5.3 Gasifier Operation

The gasifier operated fairly smoothly with only two significant issues during testing. The first of which, as mentioned in Section 5.1, stemmed from the gasifier's safety interlocks and the biomass feeder. A second issue occurred during a planned oxygen vaporizer supply switch. Upon attempting to switch the vaporizer selection valve, it was noted that the valve was frozen. The gasifier was transitioned into air-blown gasification and the valve was allowed to thaw. Once thawed, the valve was confirmed functional and placed back into service, with testing only being delayed for a few hours.

The operating pressure and temperature for each of the tests are shown on Figure 5-4. Only one coal only case (NCCC-TRIG-20120913A) has been included for baseline comparison. During all tests, the gasifier outlet pressure was maintained at approximately 164 psig, except torrefied southern pine at 15.7%wt, which was operated at approximately 160 psig.

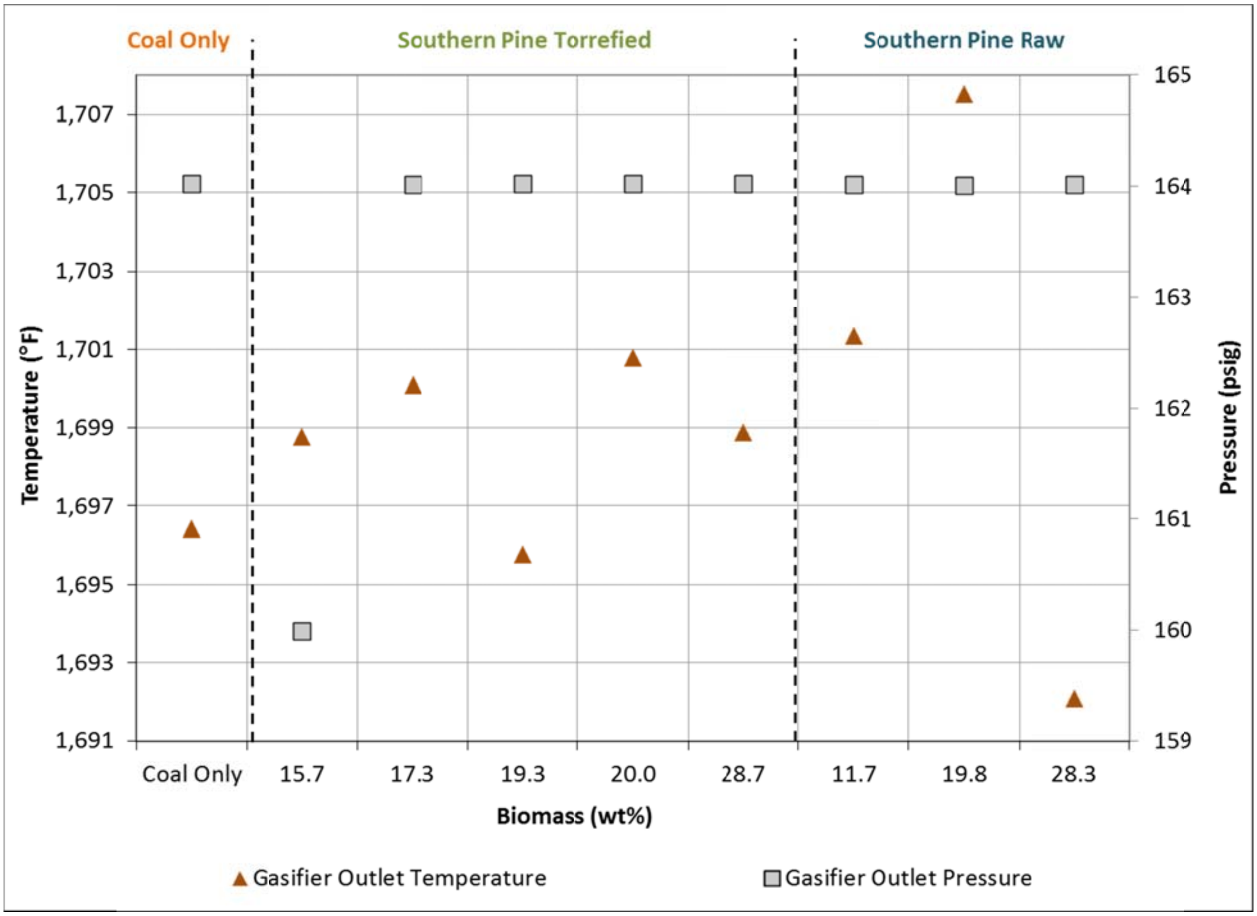


Figure 5-4: Gasifier Operating Parameters

Major operational parameters for "coal only" (oxygen-blown cases) and the biomass gasifier tests are presented in Table 5-4 through Table 5-12. Definitions of steady state periods were determined by NCCC and were reduced separately for presentation by the CCAT team. Data were recorded at 1-minute intervals. The average for each parameter for the steady state period, the acceptance range derived from NCCC criteria, and the observed range of these parameters are presented. In addition, the population standard deviation is presented to provide a basis for comparison of variability between runs.

Dry Product Gas Lower Heating Value (LHV) was calculated from the normalized gas composition of the continuously monitored gases (CO, H_2, CO_2, N_2, CH_4, C_2, Ar) and the LHV of each gas. The average dry product gas LHV for the pre-CCAT air-blown run, 63.7 Btu/SCF is significantly lower than the average dry product gas LHV for the oxygen-blown tests as a result of extra dilution associated with the N_2 and Ar in the air. The average dry product gas LHV varied in the oxygen-blown tests from 92.3 to 110 Btu/SCF. All runs met steady state criteria of <10% deviation from the average dry product gas LHV for the respective steady state period.

Average gasifier product gas flow rate ranged from 19,215 to 21,557 lb/hr. Gasifier product gas flow rate was measured continuously, but was corrected for deviations in molecular weight based on an integrated moisture sample as described in section 4.4. Applying the run average molecular weight correction to all flow measurements, all runs met steady state criteria of <10% deviation from the average product gas flow rates for the respective steady state period.

The average gasifier air flow rate was significantly higher for the pre-CCAT air-blown test, 13,622 lb/hr, than for the oxygen-blown tests. Average gasifier air flow rates for the oxygen-blown tests ranged from 3,007 to 3,275 lb/hr. All runs met steady state criteria of <10% deviation from the average gasifier air flow rate for the respective steady state periods. The ratio of recirculated solids to fresh feed was approximately 100:1 in air-blown mode, 40:1 in oxygen-blown mode with coal/raw pine mixtures, and 45:1 in oxygen-blown mode with coal/torrefied pine mixtures (Northington, Preliminary Results Review Meeting 2012).

Oxygen flow was metered to the lower and upper mixing zones of the gasifier and combined to derive gasifier oxygen flow rate. Average gasifier total oxygen flow rate in upper and lower mixing zone ranged from 2,231 to 2,544 lb/hr. All runs met steady state criteria of <10% deviation from the average gasifier oxygen flow rate for the respective steady state periods..

Gasifier nitrogen flow was comprised of metered flows to fuel feeders, metered flow for CFAD operation, estimated flow for CCAD operation, and metered balance of flows to several injection points. The average gasifier nitrogen flow rate ranged from 6,747 to 7,751 lb/hr. Two of the steady state periods identified by NCCC failed the <10% deviation from average gasifier nitrogen flow rate criteria, SS periods 43 and 47. Both of these test periods represent nominal 30% biomass feed tests. The high level of deviation appears to result from periodic spikes in nitrogen flow to the biomass feeder rather than a discernible trend or change in flow. This variability does not appear to affect the overall flow as measured by the product gas flow rate and was considered acceptable for the purposes of these tests.

Gasifier steam flow is not presented in Tables 5-4 to 5-12, but, as described in Section 4.4, has been calculated from a hydrogen mass balance.

Other operating parameters of interest include gasifier operating pressures, temperatures, and operating levels. Using gasifier outlet pressure as a proxy for all operating pressures, the pressures remained fairly constant, averaging between 160 and 164 psig for all oxygen-blown tests (vs. 200 psig for air-blown operation). Using gasifier exit temperature as a proxy for all operating temperatures of interest, temperatures remained fairly constant averaging between 1,692 and 1,708°F for all tests. Both these parameters were well within the specified steady state criteria for all runs.

Coal Only

Table 5-4: SS period 44 (NCCC-TRIG-20120913A) average operational parameters 100% coal oxygen-blown test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	91.9	19,214	3,007	2,293	7,042	164	1,696
Allowable Range	82.7 – 101	17,292 – 21,135	2,706 – 3,307	2,064 – 2,522	6,338 – 7,746	161 – 167	1,645 – 1,747
Observed Range	87.5 – 95.1	18,164 – 20,237	2,969 – 3,027	2,196 – 2,359	6,939 – 7,170	163 - 165	1,680 – 1,718

10% Torrefied Biomass

Table 5-5: SS period 39 (NCCC-TRIG-20120910A) average operational parameters for 15.7% torrefied biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	95.1	21,557	3,208	2,450	7,751	160.	1,699
Allowable Range	85.6 – 105	19,401 – 23,712	2,887 – 3,529	2,205 – 2,694	6,976 – 8,527	157 – 163	1,648 – 1,750
Observed Range	93.9 – 96.8	19,995 – 23,299	3,155 – 3,457	2,420 – 2,481	7,198 – 8,391	160. – 161	1,690 – 1,714

Table 5-6: SS period 40 (NCCC-TRIG-20120911A) average operational parameters for 17.3% torrefied biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	96.2	20,657	3,224	2,341	7,422	164	1,700.
Allowable Range	86.5 – 106	18,591 – 22,723	2,902 – 3,546	2,107 – 2,575	6,680 – 8,164	161 - 167	1,649 – 1,751
Observed Range	93.9 – 98.3	19,659 – 21,641	3,190 – 3,430	2,289 – 2,453	7,315 – 8,081	163 - 165	1,683 – 1,716

20% Torrefied Biomass

Table 5-7: SS period 41 (NCCC-TRIG-20120911B) average operational parameters for 20.0% torrefied biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	96.1	20,412	3,275	2,379	6,880	164	1,701
Allowable Range	86.5 – 106	18,371 – 22,453	2,948 – 3,603	2,141 – 2,616	6,192 – 7,567	161 - 167	1,650 – 1,752
Observed Range	90.5 – 98.5	19,360 – 21,421	3,224 – 3,350	2,339 – 2,437	6,555 – 7,795	163 - 165	1,683 – 1,715

Table 5-8: SS period 42 (NCCC-TRIG-20120912A) average operational parameters for 19.3% torrefied biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*Psig*	*°F*
Average	96.1	20,750.	3,226	2,380	7,175	164	1,696
Allowable Range	86.5 – 106	18,675 – 22,825	2,903 – 3,549	2,142 – 2,618	6,457 – 7,892	161 - 167	1,645 – 1,747
Observed Range	92.7 – 100.	19,883 – 21,836	3,192 – 3,244	2,332 – 2,511	6,993 – 7,815	164 - 164	1,679 – 1,717

30% Torrefied Biomass

Table 5-9:SS period 43 (NCCC-TRIG-20120912B) average operational parameters for 28.7% torrefied biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	109	20,581	3,224	2,544	6,747	164	1,699
Allowable Range	98.1 – 120.	18,523 – 22,639	2,902 – 3,547	2,290 – 2,798	6,072 – 7,421	161 – 167	1,648 – 1,750
Observed Range	107 – 111	19,393 – 21,690	3,181 – 3,297	2,483 – 2,609	6,483 – 7,590	164 – 164	1,680 – 1,716

10% Raw Biomass

Table 5-10: SS period 45 (NCCC-TRIG-20120915A) average operational parameters for 11.7% raw biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	96.5	19,761	3,013	2,371	7,178	164	1,701
Allowable Range	86.9 – 106	17,784 – 21,737	2,712 – 3,314	2,134 – 2,608	6,460 – 7,896	161 – 167	1,650 – 1,752
Observed Range	94.1 – 99.1	18,713 – 20,562	3,002 – 3,026	2,289 – 2,457	7,069 – 7,871	164 – 165	1,675 – 1,725

20% Raw Biomass

Table 5-11: SS period 46 (NCCC-TRIG-20120915B) average operational parameters for 19.8% raw biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	97.5	19,747	3,121	2,357	7,163	164	1,708
Allowable Range	87.8 – 107	17,772 – 21,721	2,809 – 3,433	2,122 – 2,593	6,447 – 7,880	161 – 167	1,656 – 1,759
Observed Range	95.7 – 101	18,418 – 20,550	3,057 – 3,237	2,328 – 2,388	6,993 – 7,819	163 – 165	1,686 – 1,725

30% Raw Biomass

Table 5-12: SS period 47 (NCCC-TRIG-20120917A) average operational parameters for 28.3 % raw biomass test.

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	93.7	19,438	3,064	2,231	6,911	164	1,692
Allowable Range	84.3 – 103	17,494 – 21,381	2,758 – 3,371	2,008 – 2,454	6,220 – 7,602	161 – 167	1,641 – 1,743
Observed Range	90.2 – 96.0	17,983 – 20,588	3,021 – 3,198	2,160 – 2,263	6,443 – 7,843	163 - 165	1,681 – 1,716

5.4 Product Gas Composition

Dry product gas composition was derived from the continuously monitored gases (CO, H_2, CO_2, N_2, CH_4, C_2, Ar). The monitored gas components were averaged over the extent of each steady state run. The sum of the measured components was typically slightly higher than 100% ranging from 100.2 to 105.3% for oxygen-blown tests. Dry component composition was normalized to total 100%. Product composition was subsequently diluted by the moisture measurements made during the steady state period. Wet product gas compositions for oxygen-blown tests are shown on Figure 5-5. The wet product gas composition was used to calculate wet product gas molecular weight used in correcting gasifier product gas flow rate. Wet product gas molecular weight ranged from 24.0 to 24.3 lb/lb-mol for all oxygen-blown tests. A table of product gas compositions and heating values for all test runs is provided in Appendix D.

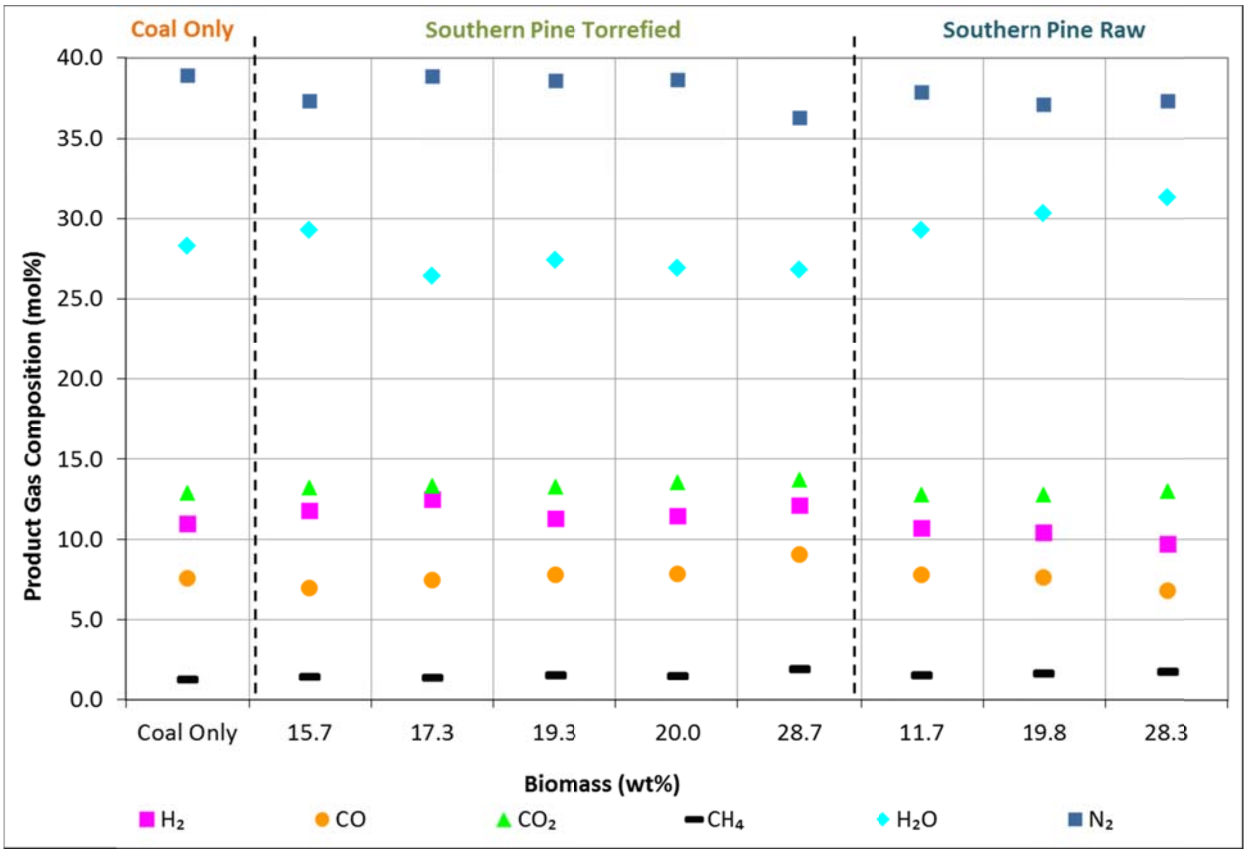


Figure 5-5: Wet Product Gas Composition

5.5 Trace Species Analysis

While most of the organic portion of the feedstocks is converted to the four major gas components discussed in Section 5.4 above, small amounts of other organic and inorganic gases (tars and contaminants) are formed in the gasifier. It is important to identify and quantify these to measure gasifier efficiency and determine the amount of product gas cleanup that is necessary before processing syngas into other products or discharging pollutants to the atmosphere.

Dräeger tube samples provide an immediate, rough qualitative analysis of certain trace species in the hot product gas. Table 5-13 presents the results of Dräeger tube samples for NH_3, HCN, and HCl. One tube of each type failed in one of the seven samples reported. Note that because the moisture content of the syngas was near 30 percent, the HCl readings may not be reliable (Lambrecht 2012). The ammonia levels detected may be both in the gas and water phases as the gas is cooled in the sample tube. Also presented in Table 5-13 are hydrogen sulfide concentrations measured with an online gas analyzer. For both 10% and 20% planned torrefied cases, there were two steady state periods and a sample was collected for only one of the steady state periods. If no sample was collected it is indicated with an asterisk - *.

Table 5-13: Trace Species in Product Gas

Test Cases					Analytes (ppm)			
NCCC Test Number	Steady State Period	CCAT Name	Biomass Type	Biomass (wt%)	Ammonia	Hydrochloric Acid	Hydrogen Cyanide	Hydrogen Sulfide
6	44	NCCC-TRIG-20120913A	None	Coal Only	4000	0	5	690
3	39	NCCC-TRIG-20120910A	Southern Pine Torrefied	15.7	*	*	*	512
3	40	NCCC-TRIG-20120911A	Southern Pine Torrefied	17.3	3500	tube failure	0	588
4	42	NCCC-TRIG-20120912A	Southern Pine Torrefied	19.3	*	*	*	600
4	41	NCCC-TRIG-20120911B	Southern Pine Torrefied	20.0	4125	1	0	601
5	43	NCCC-TRIG-20120912B	Southern Pine Torrefied	28.7	4250	6	tube failure	607
7	45	NCCC-TRIG-20120915A	Southern Pine Raw	11.7	4800	0	6.3	639
8	46	NCCC-TRIG-20120915B	Southern Pine Raw	19.8	2000	0	5.0	600
9	47	NCCC-TRIG-20120917A	Southern Pine Raw	28.3	tube failure	6	5.0	527

The results of the impinger samples collected from the product gas for eight test cases are presented in Table 5-14. (Two coal only cases are presented because, as discussed in Section 6.3, the trace species results from test 1 are more representative.) If no sample was collected it is indicated with an asterisk - *.

The DHL laboratory data report for volatile and semi-volatile organic compound (SVOC) analyses is provided in Attachment 2. Benzene was the only volatile hydrocarbon detected, while seven semi-volatile hydrocarbons were detected. The semi-volatile compounds are considered tars produced during gasification. Total tars as a function or biomass type and percent blend with coal is presented on Figure 5-6.

Table 5-14: Product Gas Impinger Samples

Test Cases					NH_3 and Detected Hydrocarbons, wet basis (ppmv)									
NCCC Test #	Steady State Period	CCAT Name	Biomass Type	Biomass (wt%)	Ammonia	Benzene	Acenaphthene	Acenaphthylene	Fluoranthene	Fluorene	Naphthalene	Phenanthrene	Pyrene	**Total SVOC (Tars)**
1	37	NCCC-TRIG-20120907A	None	Coal Only	1771.3	922.3	0.0	0.0	9.2	0.0	112.8	4.9	4.0	**131**
6	44	NCCC-TRIG-20120913A	None	Coal Only	2,536	542	13.9	30.9	16.6	4.6	1045	30.0	14.8	**1156**
3	39	NCCC-TRIG-20120910A	Southern Pine Torrefied	15.7	*	*	*	*	*	*	*	*	*	*****
3	40	NCCC-TRIG-20120911A	Southern Pine Torrefied	17.3	2,090	831	11.3	23.7	4.7	4.8	138	19.9	4.0	**206**
4	42	NCCC-TRIG-20120912A	Southern Pine Torrefied	19.3	*	*	*	*	*	*	*	*	*	*****
4	41	NCCC-TRIG-20120911B	Southern Pine Torrefied	20.0	2,386	548	5.9	12.1	3.1	0.0	247	8.5	2.8	**280**
5	43	NCCC-TRIG-20120912B	Southern Pine Torrefied	28.7	2,593	790	12.8	31.2	3.5	3.0	976	10.8	3.0	**1040**
7	45	NCCC-TRIG-20120915A	Southern Pine Raw	11.7	2,118	765	12.2	22.3	5.7	3.1	430	13.1	5.4	**492**
8	46	NCCC-TRIG-20120915B	Southern Pine Raw	19.8	2,024	615	6.8	16.0	1.6	0.0	873	8.3	1.5	**907**
9	47	NCCC-TRIG-20120917A	Southern Pine Raw	28.3	1,554	994	11.9	33.6	2.5	3.0	1564	11.4	2.2	**1628**

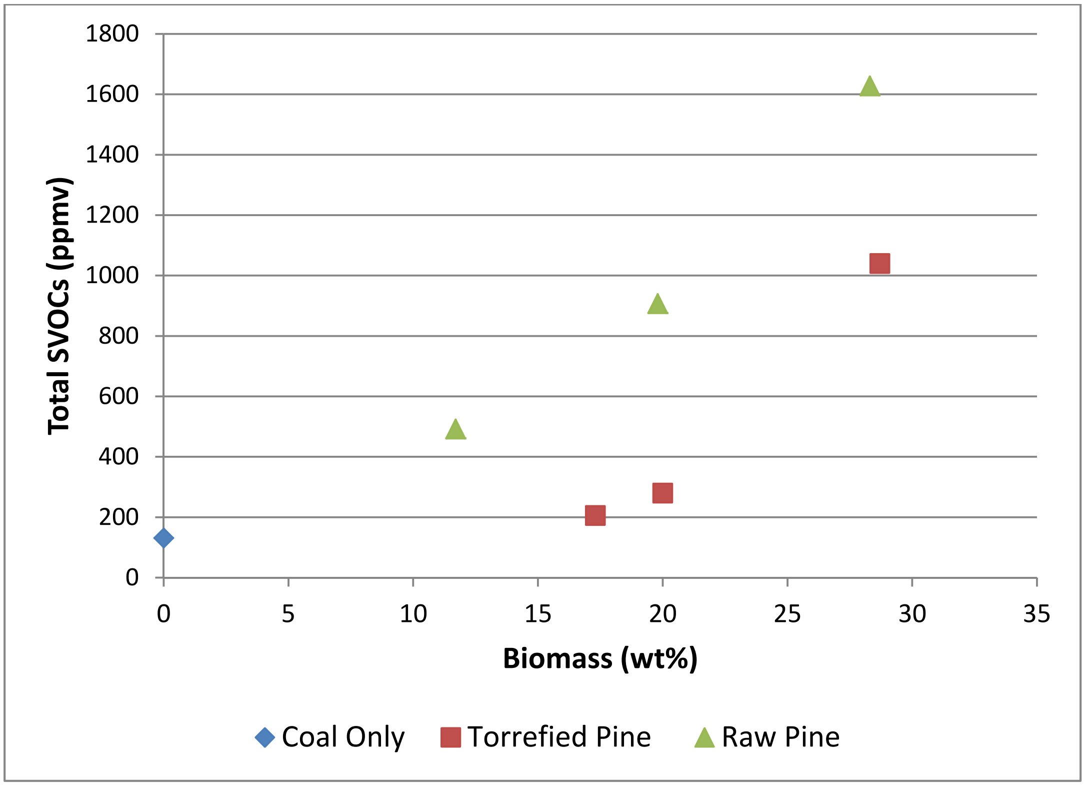


Figure 5-6: Concentration of Tars in Product Gas

Constituents dissolved in the water phase were measured from product gas condensate samples. Results from the seven test cases sampled for ammonia, COD, and TOC are presented in Table 5-15. If no sample was collected it is indicated with an asterisk - *. The ammonia concentrations reported here are higher than in the Dräeger tube and impinger samples because ammonia is more soluble in the water phase than the gas phase. Chemical oxygen demand provides a rough measurement of the amount of oxidizable material (not necessarily all organic) in the sample. Total organic carbon is a more direct measure of material that produces carbon dioxide when catalytically burned. For the coal only test case (condensate samples were only reported for Steady State period 37 (Test 1), not from 44 (Test 6)), the ratio of COD to TOC was 10, while for the biomass blend cases, the COD:TOC ranged from about 3 to 5.

Results of trace species analyses from all test conditions are provided in Appendix E.

Table 5-15: Product Gas Condensate Samples

Test Cases					Analytes (mg/L)		
NCCC Test #	Steady State Period	CCAT Name	Biomass Type	Biomass (wt%)	Ammonia	Chemical Oxygen Demand	Total Organic Carbon
1	37	NCCC-TRIG-20120907A	None	Coal Only	7070	592	59.5
6	44	NCCC-TRIG-20120913A	None	Coal Only	*	*	*
3	39	NCCC-TRIG-20120910A	Southern Pine Torrefied	15.7	*	*	*
3	40	NCCC-TRIG-20120911A	Southern Pine Torrefied	17.3	5600	270	48.1
4	42	NCCC-TRIG-20120912A	Southern Pine Torrefied	19.3	*	*	*
4	41	NCCC-TRIG-20120911B	Southern Pine Torrefied	20.0	5560	153	43.6
5	43	NCCC-TRIG-20120912B	Southern Pine Torrefied	28.7	5970	258	50.5
7	45	NCCC-TRIG-20120915A	Southern Pine Raw	11.7	5860	173	45.7
8	46	NCCC-TRIG-20120915B	Southern Pine Raw	19.8	4960	205	44.5
9	47	NCCC-TRIG-20120917A	Southern Pine Raw	28.3	4390	157	40.7

5.6 Solid Samples Analysis

Product gas downstream of the PCD was measured at least once a day for the presence of particulates. The concentration of ash in the product gas was typically 20,000 parts per million by weight (ppmw; 10,000 to 30,000) at the PCD inlet. The Outlet Particulate Loading was consistently below the sampling system lower detection limit of 0.1 ppmw. This also shows that the ash removed from the CFAD and CCAD accounts for all solids leaving the system.

The results for fine ash and coarse ash from each test condition for proximate, ultimate, heating value, LOI, and ash minerals analysis are presented in Table 5-16 and

Table 5-17, respectively. These analyses were used in calculating mass and energy balances. In both tables, ultimate analysis H (hydrogen) and O (oxygen) includes hydrogen and oxygen from moisture, as these values are used in the hydrogen and oxygen mass balance.

Table 5-18 presents the total mass analysis of coarse and fine ash samples representative from each condition tested for 25 metals, chloride, sulfur, and pH. The results of the TCLP analysis on the coarse and fine ash samples are presented in *Table 5-19*. The results are compared to the hazardous characteristic criteria for the eight heavy metals regulated under the Resource Conservation and Recovery Act (RCRA). The laboratory data report for these analyses is provided in Attachment 2.

Table 5-16: Fine Ash Proximate, Ultimate, Heating Value, LOI and Ash Analysis

	Test Cases								
NCCC Test #	6	3	3	4	4	5	7	8	9
Steady State Period	44	39	40	42	41	43	45	46	47
CCAT Name	NCCC-TRIG-20120913A	NCCC-TRIG-20120910A	NCCC-TRIG-20120911A	NCCC-TRIG-20120912A	NCCC-TRIG-20120911B	NCCC-TRIG-20120912B	NCCC-TRIG-20120915A	NCCC-TRIG-20120915B	NCCC-TRIG-20120917A
Biomass Type	None	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Raw	Southern Pine Raw	Southern Pine Raw
Biomass (wt%)	Coal Only	15.7	17.3	19.3	20.0	28.7	11.7	19.8	28.3
Proximate Analysis	**wt%**								
Moisture	0.15	1.12	0.43	0.20	0.39	0.44	0.04	0.12	0.17
Volatile Matter	4.35	3.30	3.13	4.20	3.12	3.45	4.97	4.92	4.11
Fixed Carbon	12.28	8.29	11.56	11.91	12.21	15.43	13.08	14.47	14.72
Ash	83.22	87.29	84.88	83.69	84.28	80.68	81.91	80.49	81.00
Ultimate Analysis	**wt%**								
C	15.52	10.43	14.05	14.68	14.55	17.76	16.75	17.84	17.21
H	0.05	0.16	0.08	0.05	0.07	0.08	0.03	0.04	0.04
N	0.16	0.12	0.12	0.10	0.12	0.19	0.20	0.15	0.19
O	0.13	0.99	0.38	0.18	0.35	0.39	0.04	0.11	0.15
S	0.04	0.06	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Cl	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
Ash	83.22	87.29	84.88	83.69	84.28	80.68	81.91	80.49	81.00
Heating Value, HHV (Btu/lb)	**2,312**	**1,643**	**2,162**	**2,155**	**2,246**	**2,723**	**2,501**	**2,696**	**2,635**
Loss On Ignition, LOI (wt%)	**16.65**	**11.72**	**14.75**	**16.14**	**15.39**	**18.96**	**18.06**	**19.41**	**18.86**

	Test Cases								
NCCC Test #	6	3	3	4	4	5	7	8	9
Steady State Period	44	39	40	42	41	43	45	46	47
CCAT Name	NCCC-TRIG-20120913A	NCCC-TRIG-20120910A	NCCC-TRIG-20120911A	NCCC-TRIG-20120912A	NCCC-TRIG-20120911B	NCCC-TRIG-20120912B	NCCC-TRIG-20120915A	NCCC-TRIG-20120915B	NCCC-TRIG-20120917A
Biomass Type	None	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Raw	Southern Pine Raw	Southern Pine Raw
Biomass (wt%)	Coal Only	15.7	17.3	19.3	20.0	28.7	11.7	19.8	28.3
Ash Analysis as Oxides	**wt%**								
Al_2O_3	16.38	15.19	15.67	16.26	15.18	15.90	16.35	16.66	16.59
BaO	0.60	0.60	0.52	0.58	0.56	0.57	0.63	0.66	0.69
CaO	23.94	22.12	24.26	24.00	23.64	24.14	24.02	24.13	22.30
Fe_2O_3	5.54	5.35	5.72	5.86	5.76	5.89	5.53	5.39	5.14
MgO	5.13	4.57	5.03	5.17	5.02	5.15	5.09	5.39	5.45
MnO_2	0.07	0.04	0.08	0.14	0.07	0.15	0.05	0.05	0.06
P_2O_5	1.77	1.55	1.47	1.57	1.52	1.63	1.77	1.77	1.75
K_2O	1.03	0.67	0.77	1.14	0.81	1.24	0.99	1.03	1.31
SiO_2	42.06	46.70	43.33	41.99	44.27	41.95	42.11	41.52	43.11
Na_2O	1.47	1.31	1.27	1.39	1.29	1.45	1.40	1.39	1.61
SrO	0.40	0.37	0.37	0.37	0.36	0.36	0.41	0.41	0.38
SO_3	0.29	0.31	0.30	0.29	0.29	0.30	0.31	0.30	0.32
TiO_2	1.32	1.22	1.21	1.24	1.23	1.27	1.34	1.30	1.29

Table 5-17: Coarse Ash Proximate, Ultimate, Heating Value, LOI and Ash Analysis

	Test Cases								
NCCC Test #	6	3	3	4	4	5	7	8	9
Steady State Period	44	39	40	42	41	43	45	46	47
CCAT Name	NCCC-TRIG-20120913A	NCCC-TRIG-20120910A	NCCC-TRIG-20120911A	NCCC-TRIG-20120912A	NCCC-TRIG-20120911B	NCCC-TRIG-20120912B	NCCC-TRIG-20120915A	NCCC-TRIG-20120915B	NCCC-TRIG-20120917A
Biomass Type	None	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Raw	Southern Pine Raw	Southern Pine Raw
Biomass (wt%)	Coal Only	15.7	17.3	19.3	20.0	28.7	11.7	19.8	28.3
Proximate Analysis	**wt%**								
Moisture	0.10	0.06	0.06	0.01	0.06	0.03	0.06	0.01	0.05
Volatile Matter	0.24	0.27	0.12	0.01	0.09	0.01	0.01	0.06	0.01
Fixed Carbon	0.16	0.26	0.33	0.01	0.69	0.65	0.01	0.96	0.01
Ash	99.50	99.41	99.49	99.95	99.16	99.31	99.38	98.97	99.22
Ultimate Analysis	**wt%**								
C	0.32	0.35	0.35	0.03	0.68	0.58	0.03	0.38	0.03
HR	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.01	0.02
N	0.01	0.01	0.01	0.02	0.01	0.01	0.04	0.01	0.03
O	0.09	0.05	0.05	0.01	0.05	0.03	0.05	0.01	0.04
S	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Cl	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
Ash	99.50	99.41	99.49	99.95	99.16	99.31	99.38	98.97	99.22
Heating Value, HHV (Btu/lb)	**50**	**657**	**559**	**110**	**472**	**312**	**39**	**207**	**39**
Loss On Ignition, LOI (wt%)	**0.40**	**0.53**	**0.45**	**0.04**	**0.78**	**0.66**	**0.56**	**1.02**	**0.73**

	Test Cases								
NCCC Test #	6	3	3	4	4	5	7	8	9
Steady State Period	44	39	40	42	41	43	45	46	47
CCAT Name	NCCC-TRIG-20120913A	NCCC-TRIG-20120910A	NCCC-TRIG-20120911A	NCCC-TRIG-20120912A	NCCC-TRIG-20120911B	NCCC-TRIG-20120912B	NCCC-TRIG-20120915A	NCCC-TRIG-20120915B	NCCC-TRIG-20120917A
Biomass Type	None	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Raw	Southern Pine Raw	Southern Pine Raw
Biomass (wt%)	Coal Only	15.7	17.3	19.3	20.0	28.7	11.7	19.8	28.3
Ash Analysis as Oxides	**wt%**								
Al_2O_3	17.46	17.47	17.46	17.82	17.76	17.93	17.48	17.32	17.81
BaO	0.58	0.48	0.50	0.56	0.51	0.55	0.61	0.60	0.60
CaO	21.02	16.64	18.00	18.65	17.66	18.74	21.79	22.11	21.48
Fe_2O_3	7.27	6.39	6.73	7.07	7.21	7.18	7.57	7.67	7.56
MgO	4.30	3.62	3.77	3.97	3.87	4.03	4.40	4.63	4.31
MnO_2	0.10	0.04	0.04	0.07	0.07	0.08	0.07	0.08	0.07
P_2O_5	0.85	0.66	0.69	0.75	0.70	0.76	0.97	0.97	0.93
K_2O	1.20	1.27	1.16	1.21	1.50	1.43	0.85	0.98	0.90
SiO_2	43.61	49.80	48.13	46.16	47.14	45.69	42.54	41.97	42.66
Na_2O	1.78	1.93	1.78	1.96	1.84	1.82	1.81	1.76	1.80
SrO	0.31	0.25	0.27	0.28	0.26	0.28	0.33	0.32	0.32
SO_3	0.30	0.31	0.32	0.31	0.30	0.30	0.32	0.29	0.31
TiO_2	1.22	1.14	1.15	1.19	1.18	1.21	1.26	1.30	1.25
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

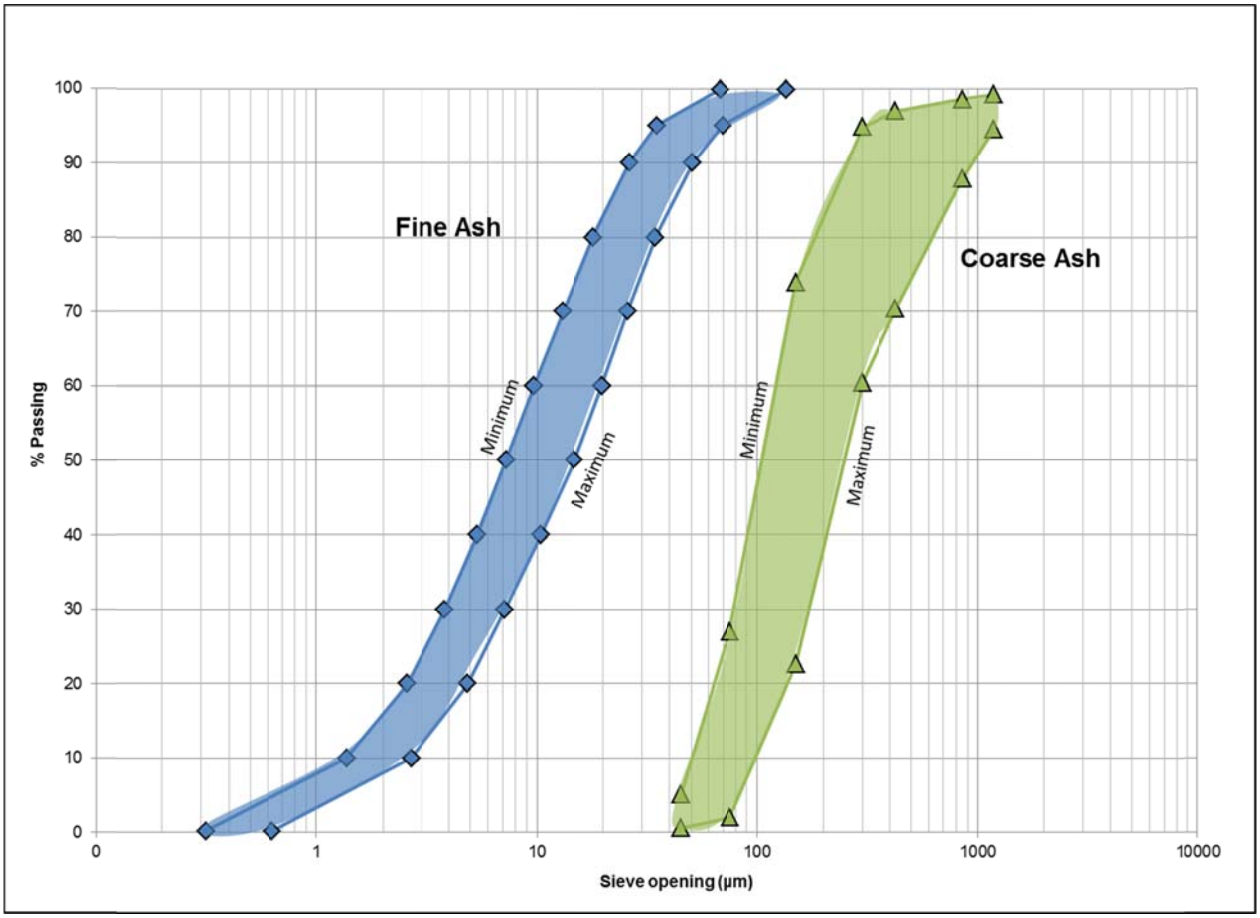
Table 5-18: NCCC TRIG Test Ash Samples - Total Metals and pH Results

Analyte	Units	Coarse Ash-100% PRB	Fine Ash - 100% PRB	Coarse Ash – 17.3% Torr	Fine Ash – 17.3 % Torr	Coarse Ash -28.7% Torr	Fine Ash-28.7% Torr	Coarse Ash - 11.7% Raw	Fine Ash - 11.7% Raw	Coarse Ash - 28.3% Raw	Fine Ash-28.3% Raw
Aluminum	mg/Kg	30,000	43,000	42,000	50,000	50,000	44,000	52,000	52,000	61,000	55,000
Antimony	mg/Kg	<5.9	<12	<10	<33	<8.1	<37	<55	<38	<38	<40
Arsenic	mg/Kg	2.9	16	2.6	22	3.9	<28	<41	22	<29	20
Barium	mg/Kg	2500	3600	2900	3700	3300	3400	3700	4000	4700	4500
Boron	mg/Kg	86	450	79	500	96	470	120	580	140	510
Cadmium	mg/Kg	<0.29	0.66	<0.26	<8.2	<0.40	<9.3	<14	<9.5	<9.6	<10
Calcium	mg/Kg	77,000	120,000	90,000	120,000	100,000	110,000	120,000	130,000	130,000	120,000
Chloride	mg/Kg	3.1	68	3.1	97	3.2	130	3.1	140	3.1	140
Chromium	mg/Kg	23	32	23	44	24	40	40	41	47	45
Cobalt	mg/Kg	11	9.6	8.3	19	10	17	19	17	21	17
Copper	mg/Kg	73	100	83	110	100	98	120	110	120	120
Iron	mg/Kg	22,000	25,000	31,000	29,000	31,000	25,000	39,000	27,000	40,000	27,000
Lead	mg/Kg	<2.2	23	<3.8	29	<3.0	20	<21	27	<14	29
Magnesium	mg/Kg	12,000	20,000	14,000	23,000	15,000	20,000	17,000	22,000	22,000	23,000
Manganese	mg/Kg	95	110	240	530	440	780	390	220	370	250
Mercury	mg/Kg	<0.015	<0.013	<0.013	<0.012	<0.012	<0.013	<0.011	<0.011	<0.011	<0.010
Molybdenum	mg/Kg	1.7	11	1.1	13	1.3	12	<27	15	<19	14
Nickel	mg/Kg	29	34	34	48	32	46	57	41	63	41
Potassium	mg/Kg	430	2,000	1,200	3,500	2,700	4,200	2,300	3,500	2,200	4,800
Selenium	mg/Kg	<0.88	2.1	0.56	<25	<1.2	<28	<41	<28	<29	<30
Silver	mg/Kg	<0.59	<0.62	<0.51	<8.2	<0.81	<9.3	<5.5	<9.5	<9.6	<10
Sodium	mg/Kg	2,900	4,800	4,800	6,200	6,400	5,300	6,900	6,400	7,700	6,800
Strontium	mg/Kg	1,300	1,900	1,300	2,300	1,600	2,100	2,100	2,300	2,300	2,400
Sulfur	mg/Kg	94	1100	94	420	48	530	36	460	35	420
Thallium	mg/Kg	<0.88	<0.93	<0.77	<25	<1.2	<28	<41	<28	<29	<30
Vanadium	mg/Kg	79	130	90	150	100	130	130	160	150	150
Zinc	mg/Kg	53	120	62	150	60	130	100	130	130	150
pH	SU	12	11.3	11.4	11.5	11.4	11.5	11.3	11.4	11.7	11.5

Table 5-19: NCCC TRIG Test TCLP Analysis of Ash Samples

Analyte	Units	Coarse Ash - 100% PRB	Fine Ash - 100% PRB	Coarse Ash - 17.3% Torr	Fine Ash – 17.3 % Torr	Coarse Ash - 28.7% Torr	Fine Ash- 28.7% Torr	Coarse Ash - 11.7% Raw	Fine Ash -11.7% Raw	Coarse Ash - 28.3% Raw	Fine Ash- 28.3% Raw	RCRA MCLs
Arsenic	mg/L	<0.25	<0.25	<0.25	0.06	<0.25	0.056	<0.25	<0.25	<0.25	<0.25	5
Barium	mg/L	1.4	4.5	1.5	10	1.4	13	1.4	4.7	1.4	13	100
Boron	mg/L	<7.5	10	<7.5	14	<7.5	14	<7.5	11	<7.5	15	NA
Cadmium	mg/L	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	1
Chromium	mg/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	5
Lead	mg/L	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	5
Nickel	mg/L	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	NA
Selenium	mg/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	1
Silver	mg/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	5
Vanadium	mg/L	<0.25	0.34	<0.25	0.42	<0.25	0.51	<0.25	0.52	<0.25	0.27	NA
Zinc	mg/L	0.2	<2.5	0.29	<2.5	0.37	<2.5	0.3	<2.5	0.34	<2.5	NA
Mercury	mg/L	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	0.2

The range of particle size distributions for each ash type from all the test runs is presented on Source: Adapted from
Figure 5-7. The mass median diameter particle size was 10 microns for fine ash and 170 microns for coarse ash. These analyses are necessary for determining disposal options for the materials and may be helpful in determining their suitability as a useful by-product, such as sand blasting grit, road base, and construction material.



Source: Adapted from *(NCCC 2012)*

Figure 5-7: Particle Size Distributions of Fine Ash and Coarse Ash

5.7 Mass and Energy Balances

As part of the analysis of the test data from NCCC, a mass balance was performed. The balance was conducted as described at a top level in Section 4 and as detailed in Appendix B.

The system boundaries, as shown on Figure 4-5, encompassed the recycled product gas causing these streams to fall outside the scope of the mass balance. Figure 5-8 presents the overall mass balance for all runs inclusive of pre-CCAT air-blown runs. Table 5-20 presents a summary of the process stream data and the results of this mass balance for oxygen-blown tests. Air-blown tests and two redundant coal only tests have been omitted from Table 5-20 for brevity. Mass balance closure was greater than 90 % for all oxygen-blown tests.

An energy Balance was performed around the gasifier using the flows developed from the mass balance, heating value of components, and sensible heat of inputs and outputs. On this basis, energy balance closure ranged from 91 to 103%, lending confidence that the majority of fuels are accounted for in the product gas. The energy balance is attached as Appendix C.

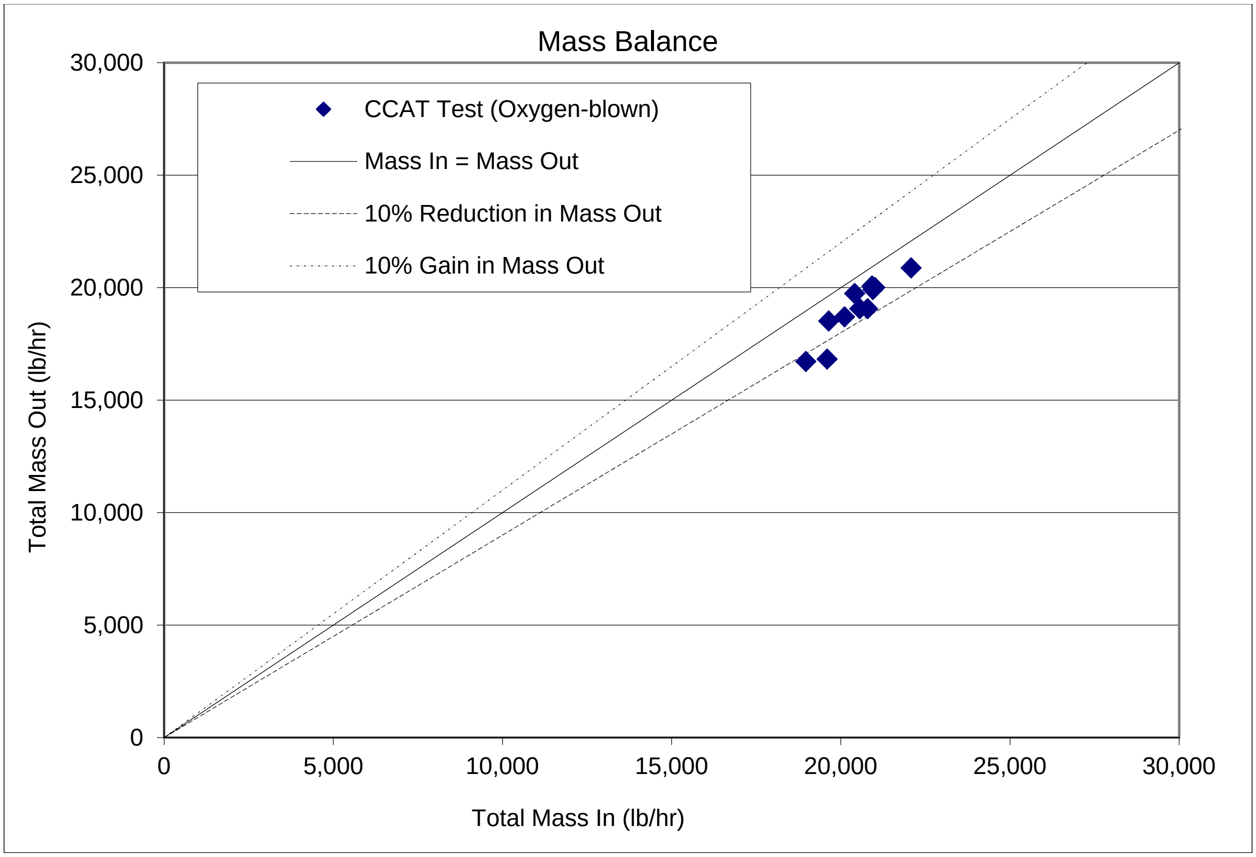


Figure 5-8: Overall Mass Balance Check

Table 5-20: Overall Process Stream Data

	Test Cases								
NCCC Test #	6	3	3	4	4	5	7	8	9
Steady State Period	44	39	40	42	41	43	45	46	47
CCAT Name	NCCC-TRIG-20120913A	NCCC-TRIG-20120910A	NCCC-TRIG-20120911A	NCCC-TRIG-20120912A	NCCC-TRIG-20120911B	NCCC-TRIG-20120912B	NCCC-TRIG-20120915A	NCCC-TRIG-20120915B	NCCC-TRIG-20120917A
Gasification Mode	Oxygen-blown	Oxygen-blown	Oxygen-blown	Oxygen-blown	Oxygen-blown	Oxygen-blown	Oxygen-blown	Oxygen-blown	Oxygen-blown
Biomass (wt%)	Coal Only	15.7	17.3	19.3	20.0	28.7	11.7	19.8	28.3
Biomass Type	None	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Raw	Southern Pine Raw	Southern Pine Raw
Steady State Duration (hr)	4.0	5.0	4.2	5.5	4.2	3.6	4.2	4.5	4.0
Mass Inputs	**lb/hr**								
Coal	3,400	3,401	3,203	3,348	3,170	3,201	3,552	3,386	2,784
Biomass	0	632	671	799	792	1,288	472	835	1,100
Air	3,007	3,208	3,224	3,226	3,275	3,224	3,013	3,121	3,064
Oxygen	2,293	2,450	2,341	2,380	2,379	2,544	2,371	2,357	2,231
Nitrogen	7,042	7,751	7,422	7,175	6,880	6,747	7,178	7,163	6,911
Steam	3,899	4,635	4,140	3,994	3,911	3,942	3,974	3,927	4,020
Total Mass Inputs	**19,640**	**22,077**	**21,001**	**20,921**	**20,407**	**20,946**	**20,560**	**20,790**	**20,110**
Mass Outputs	**lb/hr**								
Product Gas	18,184	20,535	19,634	19,721	19,383	19,555	18,733	18,723	18,412
Fine Ash, CFAD	279	281	364	271	273	275	210	261	235
Coarse Ash, CCAD	55	60	14	81	88	86	125	82	57
Total Mass Outputs	**18,518**	**20,876**	**20,011**	**20,073**	**19,744**	**19,916**	**19,068**	**19,066**	**18,703**
Mass Balance Closure	**94.29%**	**94.56%**	**95.29%**	**95.94%**	**96.75%**	**95.08%**	**92.75%**	**91.71%**	**93.00%**

6 Discussion

6.1 Feedstock Preparation and Feeding

One objective for the CCAT test was to gasify two types of biomass at three different ratios with coal. The two types of biomass used for this test were raw and torrefied southern pine pellets. NCCC had no prior experience with torrefied biomass. The ability to achieve target feed ratios was limited by the simultaneous operation of the motor controls of the separate coal and biomass feed systems. The torrefied material behaved more like coal than raw biomass and flowed faster through the biomass feeder than anticipated, even at the lowest feeder speed. By making modifications to both feed systems, the operators were able to achieve three distinct feed ratios with the raw pine, ranging from 11.7 to 28.3 percent, and five distinct feed ratios with the torrefied pine, ranging from 15.7 to 28.7 percent. The objective of feeding two biomass types at three different ratios with coal under steady state gasifier conditions was achieved.

6.2 Product Gas Composition

Product gas compositions produced in the NCCC pilot plant are excessively dilute compared to any potential commercial application of TRIG™ technology. The primary dilution issue is the large amount of nitrogen introduced with fuel feed, solids fluidization, and as purges for various components in the gasifier. Nitrogen purges associated with fuel flow are expected to be replaced with recycled product gas in large scale operation. As the process scales up, purge flows are likely to remain nearly constant making these nitrogen inputs increasingly small on a percentage basis of the total product gas. Also, a commercial-scale transport gasifier will operate at much higher pressure than at NCCC; therefore, it will require much lower nitrogen for solids fluidization per mass of feedstock. Dry product gas composition corrected for all nitrogen dilution is presented on Figure 6-1 for the oxygen-blown tests. The dry nitrogen-free composition contains nominally 40% CO_2, re-enforcing the importance of CO_2 removal in controlling the F-T synthesis reactor size while maintaining a constant space velocity. In the NCCC TRIG™ system, the CO_2 composition is much higher that what would be expected on a commercial scale. Because the NCCC TRIG™ system is much smaller in scale, the heat loss is much greater per volume of product gas generated than what it would be on a commercial scale. This requires more feedstock to be combusted to maintain the operating temperature required. Also the NCCC TRIG™ system requires much higher nitrogen per mass basis of feedstocks compared to what it would need on a commercial scale. High nitrogen means some of the thermal energy generated from combustion just goes to heat all the nitrogen in the gasifier to maintain the operating temperature.

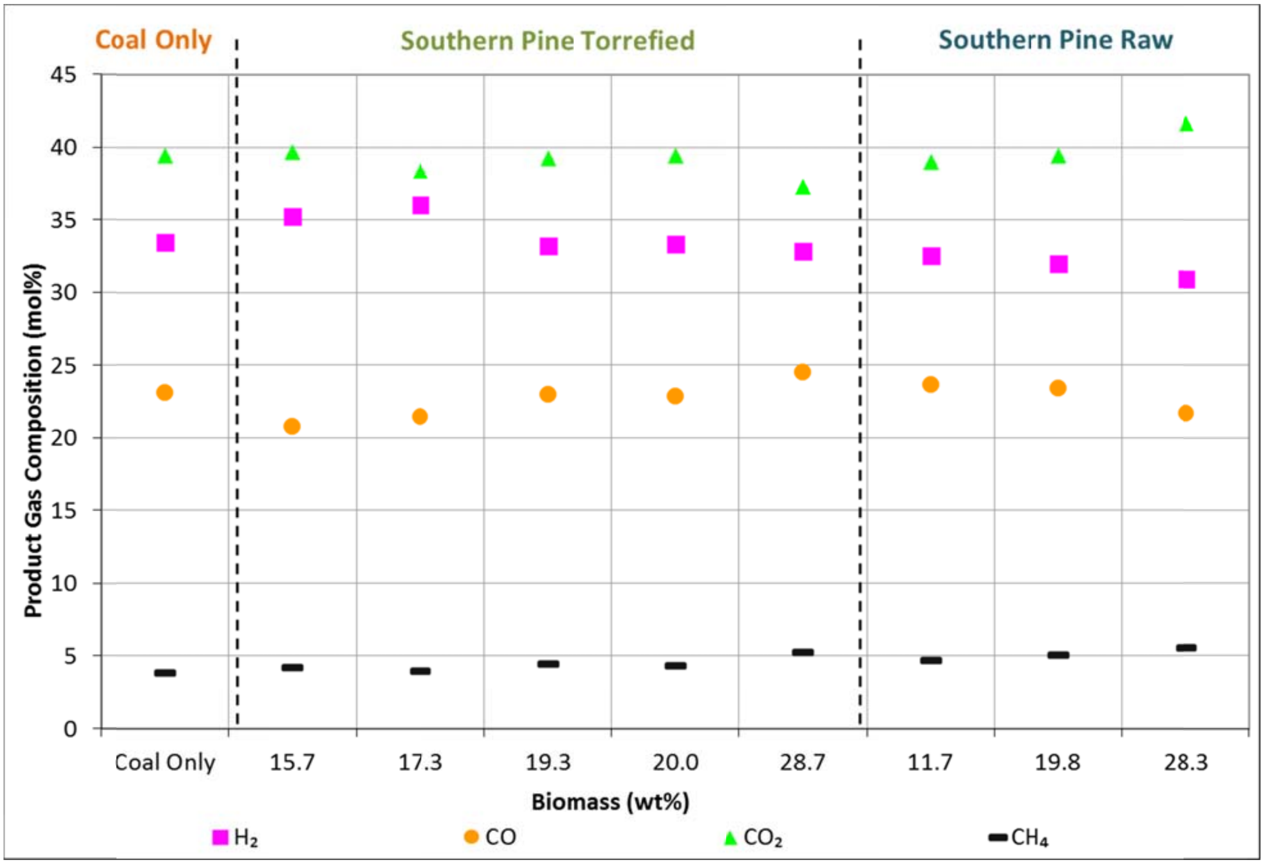


Figure 6-1: Dry and N_2-Free Product Gas Composition

F-T synthesis of fuels is dependent on the product gas composition and F-T catalyst type used, as well as other factors such as temperature and pressure. With respect to F-T catalysts, iron and cobalt are two major types typically used. Iron catalyst is significantly cheaper and is more flexible and robust with respect to the quality of the syngas feed, as iron catalyst can use syngas H_2:CO ratios ranging from 0.7 to 2.1. However, the iron catalyst has a much shorter life span. For F-T conversion using cobalt catalyst, the desired H_2:CO ratio is 2.1:1 (Smith, Asaro and Naqvi 2008). This ratio can be adjusted using the water gas shift reaction. This may be done in the gasifier, a catalytic shift converter, or the F-T reactor itself by using catalysts with water gas shift selectivity (e.g., iron). The H_2:CO molar ratio of the product gas from NCCC tests are presented in Table 6-1. Figure 6-2 shows the H_2:CO ratio ranged from 1.34 to 1.70 and was fairly consistent with the various biomass feed fractions. However, relationships between multiple independent operating variables, e.g. steam and oxygen to fuel ratios, are confounded within the matrix making it difficult to ascribe effects to particular variables.

Table 6-1: Carbon Conversion and Cold Gas Efficiency

	Test Cases								
Steady State Period	44	39	40	42	41	43	45	46	47
CCAT Name	NCCC-TRIG-20120913A	NCCC-TRIG-20120910A	NCCC-TRIG-20120911A	NCCC-TRIG-20120912A	NCCC-TRIG-20120911B	NCCC-TRIG-20120912B	NCCC-TRIG-20120915A	NCCC-TRIG-20120915B	NCCC-TRIG-20120917A
Biomass Type	None	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Torrefied	Southern Pine Raw	Southern Pine Raw	Southern Pine Raw
Biomass (wt%)	Coal Only	15.7	17.3	19.3	20.0	28.7	11.7	19.8	28.3
Steady State Duration (hr)	4.0	5.0	4.2	5.5	4.2	3.6	4.2	4.5	4.0
H_2:CO molar Ratio	1.45	1.70	1.68	1.46	1.45	1.34	1.38	1.37	1.42
CO:CO_2 molar Ratio	0.59	0.52	0.56	0.58	0.58	0.66	0.61	0.59	0.52
Steam to Fuel Ratio (lb/lb)	1.15	1.15	1.07	0.96	0.99	0.88	0.99	0.93	1.03
Oxygen to Fuel Ratio (lb/lb)	0.88	0.79	0.80	0.76	0.79	0.73	0.76	0.73	0.76
Carbon Conversion (%)	**97.7**	**98.7**	**97.6**	**98.2**	**98.2**	**98.0**	**98.4**	**97.9**	**98.0**
Cold Gas Efficiency (%)	**67.8**	**66.9**	**69.7**	**64.2**	**66.4**	**66.9**	**62.5**	**59.6**	**61.6**

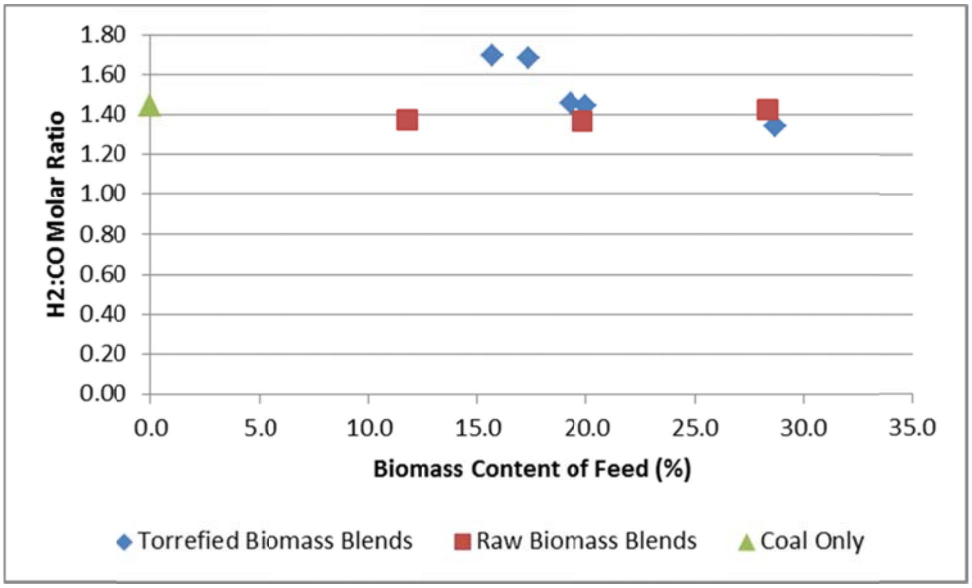


Figure 6-2 Correlation of Biomass Content to Product Gas Composition

6.3 Trace Species Analysis

Ammonia (a base) was measured three different ways. As expected, the highest concentrations were observed in the liquid phase (condensate samples) and lowest in the gas phase (impinger samples). Generally, the highest concentrations were in the coal only case and the lowest in the raw biomass blends. Ammonia levels tended to increase with higher percentage of torrefied biomass and decrease with higher percentage of raw biomass. Of the acids present in the product gas, H_2S was detected at the most significant concentrations. Due to the much higher sulfur level in coal than in the biomass, the highest concentration of H_2S was in the coal only case. All acid and base contaminants need to be removed before the syngas is processed to avoid fouling of catalysts in the F-T reactors. The amount of contaminants removed during gas cleanup has implications on how much and what type of waste is generated by the facility. If they enter a wastewater stream, there may be restrictions on how the waste can be handled and disposed. However, this also presents opportunities to recover the ammonia and sulfur, which may be used to produce ammonia sulfate fertilizer or treated as separate valuable commodities.

No discernable relationship was observed between benzene concentration in product gas and biomass feed percentage for either biomass type.

Of the tar species detected in the product gas, naphthalene is the most prevalent. Due to the higher proportion of volatile matter, biomass is expected to produce more tars than coal. As shown on Figure 5-6, tar levels increased with higher percentage of biomass for both raw and torrefied feedstock blends. A portion of the tars present in wood are expected to be removed during the torrefaction process. This is supported by the amount of tars observed in the product gas from the various test conditions. Product gas from feedstock containing torrefied biomass had significantly fewer tars than gas from raw biomass blends. The lowest amount of tars was observed in the coal only sample from Test 1 (Steady State 37). The results from Test 6 (Steady State 44) do not appear to be representative and may be attributed to residual tars in the Transport Gasifier system from the five torrefied biomass tests that were run prior to the other coal only test. Tars would need to be reformed into syngas or removed from the product gas to avoid fouling of the F-T equipment and catalyst for liquid fuel production.

6.4 Solid Samples Analysis

NCCC did not report any evidence of agglomeration or formation of deposits of ash in the gasifier during operation for the CCAT test. Based on the results from the analysis and flow rates of gasifier ash (Table 5-16, *Table 5-17*, and Table 5-20), it can be shown that for all test conditions most of the total carbon (>99%), LOI (>98%), and heating value (92-99%) lost from the gasifier was in the fine ash, not the coarse ash. This is attributed to the fact that most of the coarse ash is recycled through the gasifier while most of the fine ash is captured in the PCD after only one pass through the gasifier. The total carbon losses in fine ash ranged from 29 to 51 lb/hr, although there was no correlation to percent biomass in the feedstock in the nine test cases. Very little volatile matter was present in the coarse ash. In the fine ash, the volatile matter was higher when raw pine was fed than when torrefied pine was fed. This is expected as volatile compounds are removed from wood during the torrefaction process. There was no observed correlation between volatile matter and percent biomass in the feedstock. The average fine ash flow rate for all test conditions was 79% of the total gasifier solid ash residue flow rate (fine ash + coarse ash).

As in the ash mineral analysis, the total metals analysis (*Table 5-19*) reveals that the predominant metals in ash are calcium, aluminum, iron, magnesium, sodium, and potassium (silicon was not measured). Antimony, cadmium, mercury, selenium, silver, and thallium were rarely detected in any ash samples. For most metals, the lowest concentration detected was in the coarse ash sample from 100% coal. This was most pronounced for potassium, which is present in pine at much higher levels than in PRB coal. The concentrations of aluminum, arsenic, boron, calcium, chromium, magnesium, molybdenum, potassium, and especially sulfur were greater in fine ash than in coarse ash. Sulfur levels were lower in coarse ash samples from raw pine tests than from torrefied pine tests. The concentrations of aluminum, barium, boron, calcium, chromium, cobalt, copper, iron, magnesium, strontium, vanadium, and zinc were greater in coarse ash from raw pine tests than in coarse ash from torrefied tests. Metals in fine ash observed at higher concentrations in samples from raw pine tests over torrefied pine tests were barium, boron, and sodium. The pH of all ash samples ranged from 11.3 to 12 standard units.

The leachate results from the TCLP analysis (*Table 5-19*) also reveal several apparent differences between the fine and coarse ash in general and between ash from different feed mixtures. These trends are often different than noted above for the total metals analysis:

- The concentration of barium, boron, and vanadium is greater in fine ash than coarse ash.
- Boron and vanadium were not detected in coarse ash samples.
- Zinc was detected in coarse ash, but not fine ash samples.
- Cadmium, chromium, lead, mercury, nickel, selenium, and silver were not detected in any leachate samples.
- For analytes that were detected, concentrations were generally greater in samples from biomass mixtures than in ash from 100% coal.
- The differences in concentration in samples from raw and torrefied biomass mixtures is negligible.
- The concentration of barium appears to increase with increased biomass percentage, particularly with raw biomass; boron concentration increased slightly with raw biomass.

- No apparent difference in concentration of arsenic, vanadium, and zinc was observed with different percentage of biomass.

Results of the leaching and pH analyses of the coarse and fine ash are well below the criteria; therefore the ash would not be considered hazardous waste for disposal purposes under RCRA. The cost of disposal in a non-hazardous landfill is significantly lower than in a hazardous waste landfill. However, if the material has suitable characteristics for alternative use, it could be considered a by-product and not a waste. Therefore, the ash samples were analyzed for a broad array of metals and particle size distribution.

6.5 Mass Balance

The mass balance closure remained between 90 and 110% for all tests. The actual mass balance closure, presented in Appendix B was significantly tighter than the NCCC's general acceptance criteria ranging from 91.71 and 96.80% for oxygen-blown tests. This closure confirms the sufficiency of the measurement procedures to capture all major flows in the TRIG^{TM}.

The mass balance with respect to carbon provides a basis for calculating carbon conversion efficiency. Carbon conversion is calculated based on 1 minus carbon in the fine ash and coarse ash divided by carbon in the feedstocks. Carbon conversions are presented in **Error! Reference source not found.**. Carbon conversion ranged from 97.6 and 98.7% for the oxygen-blown tests.

Conversion of feedstocks to product gas was quantified by Cold Gas Efficiency (CGE) as presented in **Error! Reference source not found.**. Cold gas efficiency is calculated from the HHV of the product gas exiting the TRIG^{TM} system boundary and the HHV of the fuels entering the TRIG^{TM} system boundary at 60°F and 14.7 psia. Cold gas efficiency does not include other energy inputs to the system such as compression work or steam energy. The CGE ranged from 59.6% to 69.7% for oxygen-blown tests. The CGE appears to be slightly lower for the raw biomass tests averaging 61.2% compared to torrefied biomass tests averaging 66.8% and 67.8% for the coal only case. These results may be attributed to the lower heating value and energy density of raw biomass compared to that of torrefied biomass and coal; however there is no apparent trend with biomass feed percentage for either feedstock. Inspection of **Error! Reference source not found.** does not suggest any correlation of CGE with either steam to fuel ratio or oxygen to fuel ratio.

7 Conclusions

The CCAT demonstration test conducted on the TRIG™ at NCCC fulfilled all major test objectives. Gasification of PRB coal alone and with varying amounts of both raw and torrefied pine in oxygen-blown conditions was successfully achieved. Major gasifier operating conditions, including feed rates, temperatures, pressures, solids recirculation rate, product gas recirculation rate, and product gas composition were monitored for each test case. NCCC completed the CCAT test with 219 hours of nearly continuous operation in oxygen-blown mode.

Separate feeding of coal and biomass to the gasifier showed that target mixtures could be obtained at all but the lowest percent biomass mixtures. It was particularly difficult to control the flow of the ground torrefied feedstock at low feeder speed. Operation of the biomass feeder at its lowest speed resulted in actual biomass mixtures of 11.7% raw pine and 15.7% and 17.3% torrefied pine compared with the 10% targets. The 20% and 30% target mixtures were nearly obtained for both raw and torrefied pine (19.8% and 28.3% - raw; 19.3/20.0% and 28.7% - torrefied). These results demonstrate the importance of having reliable and robust feedstock preparation and feeder systems. In future tests using torrefied biomass, it would be interesting to see if better flow control could be achieved if the material was ground to a larger size, similar to that of the raw biomass.

This test demonstrated that the TRIG™ gasifier at NCCC, approximately 10 times the size of the unit at EERC, can gasify the selected coal/biomass mixtures under the target operating conditions. Very few discernable differences in the operating conditions or quality of the product gas were observed between the feedstock test cases performed on the TRIG™ at NCCC.

A mass and energy balance was calculated for each test condition. The mass balance closure was significantly tighter than the general acceptance criteria, ranging from 91.71% for the 19.8% raw biomass mixture to 96.80% for 20% torrefied biomass mixture. This closure confirms the sufficiency of the measurement procedures to capture all major flows in the TRIG™. The mass balance with respect to carbon provides a basis for calculating carbon conversion efficiency. Carbon conversion for the oxygen-blown tests ranged from 97.6% for the 17.3% torrefied biomass mixture to 98.7% for the 15.7% torrefied biomass mixture. Cold gas efficiency ranged from 59.6% for the 19.8% raw biomass mixture to 69.7% for the 17.3% torrefied biomass mixture. The average CGE of the five torrefied test mixtures is similar to that of the coal only test. The consistency of results obtained demonstrates the reliability of the NCCC TRIG™ gasifier (and its operators) under a variety of feed mixtures tested. Parametric studies on multiple independent operating variables, e.g. steam and oxygen to fuel ratios, are needed to evaluate the effects of biomass type and feed percentage on gasifier outputs relative to their potential use for liquid fuel production.

Naphthalene was the predominant tar compound found under all test conditions. Use of torrefied biomass offers the advantage of producing fewer tars than raw biomass or coal. Product gas from feedstock containing torrefied biomass had significantly fewer tars than gas from raw biomass blends. Tar levels increased with higher percentage of biomass for both raw and torrefied feedstock blends. The greatest amount of tars was observed in the 28% raw biomass case.

Virtually no particulates (less than 0.1 ppmw) were present in the product gas downstream of the particulate collection device. NCCC did not report any evidence of agglomeration or formation of deposits of ash in the gasifier during operation for the CCAT test. While the fine and coarse ash have different chemical characteristics, neither material would need to be handled as hazardous waste.

Adequate data were collected to allow comparison with the testing of similar feedstock mixtures at the smaller scale EERC TRIG™ gasifier. In addition, the data collected by NCCC will be used by DOE NETL for modeling and for validation of the models.

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Appendix A: Sample Collection QA/QC Procedures

Gas Analyzer Sampling Process (process is the same for analyzer upstream of the PCD and at the SCU)

1. Moisture and hydrocarbons are removed by cooling the gas. These condensable components drop out and the gas continues. Cooling media (regardless of location) is in the 30-40F range.
2. The gas is then filtered to remove any particulates. These filters also capture any moisture or hydrocarbon carryover.
3. A single stage regulator is used to drop the pressure from process conditions (180-250psig) down to a more manageable level (typically 10-20psig).
4. The gas sample is then delivered to the sample system in PFA or FEP tubing.
5. Flows and pressures are measured at the system. Flows are maintained at 0.5-1.0 L/min. Pressures are generally maintained above 5 psig although this is not critical due to the GC sampling process (see #6 below). From there the sample travels to the analyzer. The sample system is equipped to reduce the pressure even further, but normally this is not done.
6. At the analyzer, the sample flows through a valve system called an SSO/ARV. This stands for Sample Shut Off/Atmospheric Relief Valve. Immediately before injection, the sample flow is stopped and the sample loop is relieved to atmosphere. The instrument (GC) analyzes the sample at atmospheric pressure, regardless of the incoming pressure. This allows us to vary the standard and sample pressures without affecting accuracy or results.
7. Once the sample has been injected, it passes through a backflush column which removes any remaining water and other non-desirable components. At a pre-determined time the injection/backflush valve actuates, reversing backflush column flow and removing undesirable components from the column. Components of interest continue through an analytical column to the thermal conductivity detector where the analysis takes place.
8. Results are reported in the same units as the standard gas. In this case the reporting units are mole percent.

PSDF/NCCC Gas Analysis Calibration/Check Schedule
Pre-run calibration is performed for all components on all instruments. This includes retention time adjustments if needed.

During the test run, standards are checked weekly to verify instrument operation. Sample scans are checked twice per week to check retention times and chromatography. All analyzers are calibrated/checked using certified standards from Airgas:

Blend Tolerance +5%

This means that the concentration of the components will be within 5% of the requested concentration.

Analytical Tolerance +2%

This is the actual accuracy of the concentration listed on the Certificate of Analysis.

The quality control process at SGS is designed to verify the validity of all phases of data generation, sample preparation and analytical determinations. The items listed below specify the particular measures SGS incorporates in daily operations:

- Standards
  - To calibrate the sulfur analyzer and verify sulfur results, SGS uses a variety of NIST Standards (National Institute of Standards and Technology) with certified values encompassing the range of sulfur values within the unknown analysis samples
  - The analysis of the NIST standard must generate a value within a tight, proximal range to the certified value of the NIST prior to unknown sample analysis
    - If the value of an unknown sample is found to be above or below the range of sulfur values used for calibration, the instrument is re-calibrated to include the value of the unknown sample found to be outside of the calibration curve and the unknown sample is re-analyzed
  - Benzoic Acid tablets are used to verify the appropriate readings in our bombs for calorimetry
    - The certified calorific value of benzoic acid is 11373 btu/lb
    - If our benzoic acid runs, within a given range, are not close enough to 11373 btu/lb, the bomb is re-calibrated before analysis of an unknown sample
    - Benzoic acid runs are also incorporated, for all bombs, after every 20 unknown samples and at the end of the batch analysis
      - **Example:** Run a conditioning sample in both bombs, then a benzoic acid tablet in each bomb, run twenty samples, run a benzoic acid tablet in each bomb, run twenty samples and finally run a benzoic acid tablet in each bomb again - this practice is called "bracketing" batches
  - NIST standards also typically have certified values for Volatile Matter and Mercury and these analytical determinations are performed in accordance with the same principles referenced above
    - However, one must note that a variation in NIST values for volatile matter most likely is a temperature controller issue and not a calibration issue - given that volatile matter is determined by loss of mass by the application of heat
    - Conversely, the determination of Mercury is similar to that of the sulfur analyzer scope and procedure, in that a calibration curve is required that is broad enough to encompass the expected range of mercury in the unknown samples and the NIST value must be within the tight range of acceptability upon analysis
- Process
    - Residual Moisture (Hydration -60 mesh moisture) is always analyzed with one batch sample duplicate
    - A Daily Control Sample (DCS) is analyzed with every batch of unknown samples
      - The DCS is a stock material purchased from Laboratory Quality Services International (LQSI) with a known value that we chart

daily in excel to determine standard deviation, min, max, acceptable ranges of values, etc.
        - Any value determined to be out of the acceptable range for the DCS results in an Internal Corrective Action Request (Internal CAR)
    - Daily Random -8 Mesh and -60 Mesh re-preps
        - Every day, a -8 Mesh reserve sample is randomly selected, re-prepped and re-analyzed
        - The analysis is then compared to the original analysis, charted and evaluated the same as the DCS
        - Internal CARs are generated for any values outside of accepted reproducibility limits
        - The -60 Mesh sample is a sample randomly selected and re-analyzed out of the same original jar
        - The analysis is then compared to the original analysis, charted and evaluated the same as the DCS
        - The differentiation between the 8 & 60 mesh random samples is simple
            - The -8 Mesh samples tell us how well the prep group can reproduce the preparation of the original sample and then how well the lab can reproduce their results
            - The -60 Mesh samples tell us how well the lab can reproduce their results whilst analyzing the exact same sample they've analyzed previously
    - All ovens and analyzers are verified for temperature with a certified pyrometer and probe on a routine basis and documented
    - All balance verifications with certified weights are performed - per shift and documented
    - All crushers/pulverizers undergo screen verification tests routinely and documented
- Quality Program Participation
    - As previously mentioned, LQSI is an organization that provides reference material and operates a global inter-laboratory round-robin program
    - SGS participates in this round-robin program, along with other laboratories from over 70 countries
    - If SGS' results deviate too far from the group mean, an External CAR is issued to SGS and the results of the investigation must be reported to LQSI within a specific timeframe

Appendix B: Overall and Component Mass Balance

Overall Mass Balance

Figure 4-5 represents an overall mass balance around the transport gasification system. The input to the system includes coal, biomass, pure oxygen, air, pure nitrogen, and steam. Coal and biomass feed rates are metered into the gasifier based on the specific feed systems' design PDAC and FD0210, respectively. The steam is metered in through FI522. Pure oxygen is metered in through two meters, FI726_COMP, which supplies oxygen at lower mixing zone and FIC790MEAS, which supplies oxygen to upper mixing zone. The oxygen used has a purity of 99.5% by volume. Air is metered in through FI205_comp. Pure nitrogen is used at various locations. Pure nitrogen is used as a feedstock conveying gas, which is metered through FI1610A and FI9177calc for PDAC feeder (coal feeder) and FI667 and FI666 for FD0210 feeder (biomass feeder). Pure nitrogen is also used for solids fluidization and instrumentation purging, which is metered through FI609. A portion of pure fluidization nitrogen was used for "Adjustment for SRI N_2 Use" at an average rate of 500 lb/hr and "Adjustment for CFAD Operation, FI9205", which was metered via FI9205, which was in the range of 216 lb/hr to 263 lb/hr. Recycle product gas is the sum of product gas used in Standpipe, J-Leg, and Seal Leg. Recycle product gas into standpipe was metered via FI290_COMP and FI913_COMP, recycle product gas into J-Leg was metered via FI681_COMP FI689_COMP, and recycle product gas into seal leg was measured via FI203_COMP, FI297_COMP, FI299_COMP, and FI444_COMP. The output from the system includes product gas, fine ash, and coarse ash. The total mass flow rate at gasifier outlet includes raw gas, which contains fine particulates. Due to high particulates in the raw gas at the gasifier outlet, raw gas flow rate couldn't be measured at that location. Therefore raw gas flow rate was calculated by mass balance using downstream Product Gas flow rate, Product Gas to Recycle Gas Compressor and Fine Ash (CFAD) flow rate (see Figure 4-5). The product gas flow rate is measured via FI465_Comp, Product Gas to Recycle Gas Compressor is measured via FI9452_COMP, and fine ash flow rate via CFAD system. The coarse ash (CCAD) flow rate is calculated based on mass balance using ash input from coal and biomass and ash output from fine ash. Note that during air-blown mode testing no pure oxygen was used but the total air usage was significantly higher than oxygen-blown mode testing. Also, during air-blown mode testing the steam usage was significantly lower than oxygen-blown mode testing. Detailed averaged mass flow stream data are provided in Table B-1 for both air-blown mode and oxygen-blown mode operation, which correspond to the overall system boundary provided on Figure 4-5. Appendix G has additional (non-averaged) time dependent data presented graphically over the entire steady state period.

Table B-1: Overall Mass Balance

Test Cases							Mass Inputs (lb/hr)							Mass Outputs (lb/hr)				Ratio
Steady State Period	CCAT Name	Gasification Mode	Nominal Biomass (wt%)	Actual Biomass (wt%)	Biomass Type	Steady State Duration (hr)	Coal	Biomass	Air	Oxygen	Nitrogen	Steam	**Total Mass Inputs**	Product Gas	Fine Ash, CFAD	Coarse Ash, CCAD	**Total Mass Outputs**	**Total Outputs to Total Inputs**
35	NCCC-TRIG-20120906A	Air-blown	Coal Only	Coal Only	None	3.98	3,812	0	13,744	0	7,573	1,197	**26,325**	25,571	225	109	**25,905**	**0.98**
36	NCCC-TRIG-20120906B	Air-blown	Coal Only	Coal Only	None	5.98	3,847	0	13,622	0	7,520	1,187	**26,176**	25,368	225	121	**25,713**	**0.98**
34	NCCC-TRIG-20120905A	Air-blown	Coal Only	Coal Only	None	4.98	3,930	0	13,756	0	8,097	1,071	**26,854**	26,077	225	118	**26,419**	**0.98**
38	NCCC-TRIG-20120907B	Oxygen-blown	Coal Only	Coal Only	None	3.98	3,630	0	2,989	2,263	5,818	4,265	**18,966**	16,422	281	17	**16,720**	**0.88**
37	NCCC-TRIG-20120907A	Oxygen-blown	Coal Only	Coal Only	None	6.98	3,584	0	2,974	2,258	6,642	4,136	**19,594**	16,531	281	13	**16,825**	**0.86**
44	NCCC-TRIG-20120913A	Oxygen-blown	Coal Only	Coal Only	None	3.98	3,400	0	3,007	2,293	7,042	3,899	**19,640**	18,184	279	55	**18,518**	**0.94**
39	NCCC-TRIG-20120910A	Oxygen-blown	10	15.7	Southern Pine Torrefie	4.98	3,401	632	3,208	2,450	7,751	4,635	**22,077**	20,535	281	60	**20,876**	**0.95**
40	NCCC-TRIG-20120911A	Oxygen-blown	10	17.3	Southern Pine Torrefie	4.23	3,203	671	3,224	2,341	7,422	4,140	**21,001**	19,634	364	14	**20,011**	**0.95**
42	NCCC-TRIG-20120912A	Oxygen-blown	20	19.3	Southern Pine Torrefie	5.48	3,348	799	3,226	2,380	7,175	3,994	**20,921**	19,721	271	81	**20,073**	**0.96**
41	NCCC-TRIG-20120911B	Oxygen-blown	20	20.0	Southern Pine Torrefie	4.23	3,170	792	3,275	2,379	6,880	3,911	**20,407**	19,383	273	88	**19,744**	**0.97**
43	NCCC-TRIG-20120912B	Oxygen-blown	30	28.7	Southern Pine Torrefie	3.65	3,201	1,288	3,224	2,544	6,747	3,942	**20,946**	19,555	275	86	**19,916**	**0.95**
45	NCCC-TRIG-20120915A	Oxygen-blown	10	11.7	Southern Pine	4.23	3,552	472	3,013	2,371	7,178	3,974	**20,560**	18,733	210	125	**19,068**	**0.93**
46	NCCC-TRIG-20120915B	Oxygen-blown	20	19.8	Southern Pine	4.48	3,386	835	3,121	2,357	7,163	3,927	**20,790**	18,723	261	82	**19,066**	**0.92**
47	NCCC-TRIG-20120917A	Oxygen-blown	30	28.3	Southern Pine	3.98	2,784	1,100	3,064	2,231	6,911	4,020	**20,110**	18,412	235	57	**18,703**	**0.93**

Ash Balance

An ash mass balance was done based on Figure 4-5 similar to overall mass balance. Ash input includes ash in from coal and biomass. The ash input from the coal and biomass are calculated from ultimate (chemical) analysis of the feedstock and the measured mass flow rates from PDAC coal feeder and FD0210 biomass feeder, respectively. Ash output from the system includes ash out from coarse ash (CCAD) and fine ash (CFAD). The ash output from the coarse ash and fine ash are calculated from ultimate (chemical) analysis of the coarse ash and fine ash samples and corresponding coarse ash (CCAD) and fine ash (CFAD) mass flow rate. Coarse ash (CCAD) flow rate was calculated based on ash inputs from coal and biomass minus the ash content of the fine ash. Results of the ash balance are shown in Table B-2.

Table B-2: Ash Mass Balance

Test Cases							Ash Inputs			Ash Outputs			Ratio
Steady State Period	CCAT Name	Gasification Mode	Nominal Biomass (wt%)	Actual Biomass (wt%)	Biomass Type	Steady State Duration (hr)	Ash In from Coal (lb/hr)	Ash In from Biomass (lb/hr)	**Total Ash In (lb/hr)**	Ash Out from Fine Ash (lb/hr)	Ash Out from Coarse Ash (lb/hr)	**Total Ash Out (lb/hr)**	**Total Outputs to Total Inputs**
35	NCCC-TRIG-20120906A	Air-blown	Coal Only	Coal Only	None	3.98	191	92	**283**	174	108	**282**	**1.00**
36	NCCC-TRIG-20120906B	Air-blown	Coal Only	Coal Only	None	5.98	209	87	**296**	175	119	**294**	**1.00**
34	NCCC-TRIG-20120905A	Air-blown	Coal Only	Coal Only	None	4.98	194	97	**291**	174	117	**290**	**1.00**
38	NCCC-TRIG-20120907B	Oxygen-blown	Coal Only	Coal Only	None	3.98	262	0	**262**	246	16	**262**	**1.00**
37	NCCC-TRIG-20120907A	Oxygen-blown	Coal Only	Coal Only	None	6.98	259	0	**259**	246	13	**259**	**1.00**
44	NCCC-TRIG-20120913A	Oxygen-blown	Coal Only	Coal Only	None	3.98	288	0	**288**	232	55	**287**	**1.00**
39	NCCC-TRIG-20120910A	Oxygen-blown	10	15.7	Southern Pine Torrefied	4.98	280	25	**305**	245	59	**305**	**1.00**
40	NCCC-TRIG-20120911A	Oxygen-blown	10	17.3	Southern Pine Torrefied	4.23	302	21	**323**	309	14	**323**	**1.00**
42	NCCC-TRIG-20120912A	Oxygen-blown	20	19.3	Southern Pine Torrefied	5.48	284	24	**308**	227	80	**307**	**1.00**
41	NCCC-TRIG-20120911B	Oxygen-blown	20	20.0	Southern Pine Torrefied	4.23	294	24	**318**	230	88	**318**	**1.00**
43	NCCC-TRIG-20120912B	Oxygen-blown	30	28.7	Southern Pine Torrefied	3.65	265	42	**307**	222	85	**307**	**1.00**
45	NCCC-TRIG-20120915A	Oxygen-blown	10	11.7	Southern Pine Raw	4.23	292	5	**297**	172	124	**296**	**1.00**
46	NCCC-TRIG-20120915B	Oxygen-blown	20	19.8	Southern Pine Raw	4.48	284	8	**292**	210	81	**291**	**1.00**
47	NCCC-TRIG-20120917A	Oxygen-blown	30	28.3	Southern Pine Raw	3.98	236	10	**247**	190	56	**246**	**1.00**

Carbon Mass Balance

A carbon mass balance was done based on Figure 4-5 similar to overall mass balance. Carbon input to the system includes carbon in from coal and biomass. The carbon input from the coal and biomass are calculated from ultimate (chemical) analysis of the feedstock and the measured feed rates from PDAC coal feeder and FD0210 biomass feeder, respectively. Carbon output includes coarse ash, fine ash and product gas. Carbon in the coarse ash and fine ash is calculated from the carbon content of ash (provided in ash ultimate analysis) and coarse ash (CCAD) and fine ash (CFAD) mass flow rate. The carbon content of product gas stream is accounted carbon in the form of CO, CO_2, CH_4, and C_2H_6 and corresponding flow rate. In all cases of product gas composition, minor sources of carbon, such as benzene and naphthalene, were excluded as inconsequential. Results of the carbon component balance are shown in Table B-3.

Table B-3: Carbon Mass Balance

Test Cases								Carbon Inputs			Carbon Outputs				Ratio
Steady State Period	CCAT Name	Gasification Mode	Nominal Biomass (wt%)	Actual Biomass (wt%)	Biomass Type	Steady State Duration (hr)	Carbon In from Coal (lb/hr)	Carbon In from Biomass (lb/hr)	**Total Carbon In (lb/hr)**	Carbon Out from Product Gas (lb/hr)	Carbon Out from Fine Ash (lb/hr)	Carbon Out from Coarse Ash (lb/hr)	**Total Carbon Out (lb/hr)**	**Total Outputs to Total Inputs**
35	NCCC-TRIG-20120906A	Air-blown	Coal Only	Coal Only	None	3.98	1,396	708	**2,105**	2,198	48	0.23	**2,246**	**1.07**
36	NCCC-TRIG-20120906B	Air-blown	Coal Only	Coal Only	None	5.98	1,451	683	**2,133**	2,169	46	0.91	**2,215**	**1.04**
34	NCCC-TRIG-20120905A	Air-blown	Coal Only	Coal Only	None	4.98	1,419	750	**2,170**	2,177	48	0.25	**2,226**	**1.03**
38	NCCC-TRIG-20120907B	Oxygen-blown	Coal Only	Coal Only	None	3.98	1,992	0	**1,992**	1,981	33	0.00	**2,014**	**1.01**
37	NCCC-TRIG-20120907A	Oxygen-blown	Coal Only	Coal Only	None	6.98	1,967	0	**1,967**	2,037	33	0.00	**2,070**	**1.05**
44	NCCC-TRIG-20120913A	Oxygen-blown	Coal Only	Coal Only	None	3.98	1,850	0	**1,850**	1,962	43	0.18	**2,005**	**1.08**
39	NCCC-TRIG-20120910A	Oxygen-blown	10	15.7	Southern Pine Torrefie	4.98	1,845	353	**2,199**	2,222	29	0.21	**2,251**	**1.02**
40	NCCC-TRIG-20120911A	Oxygen-blown	10	17.3	Southern Pine Torrefie	4.23	1,725	385	**2,111**	2,171	51	0.05	**2,222**	**1.05**
42	NCCC-TRIG-20120912A	Oxygen-blown	20	19.3	Southern Pine Torrefie	5.48	1,821	456	**2,277**	2,210	40	0.55	**2,250**	**0.99**
41	NCCC-TRIG-20120911B	Oxygen-blown	20	20.0	Southern Pine Torrefie	4.23	1,744	442	**2,186**	2,193	40	0.03	**2,233**	**1.02**
43	NCCC-TRIG-20120912B	Oxygen-blown	30	28.7	Southern Pine Torrefie	3.65	1,743	733	**2,476**	2,405	49	0.50	**2,455**	**0.99**
45	NCCC-TRIG-20120915A	Oxygen-blown	10	11.7	Southern Pine	4.23	1,943	237	**2,180**	2,062	35	0.04	**2,097**	**0.96**
46	NCCC-TRIG-20120915B	Oxygen-blown	20	19.8	Southern Pine	4.48	1,827	405	**2,232**	2,060	47	0.31	**2,107**	**0.94**
47	NCCC-TRIG-20120917A	Oxygen-blown	30	28.3	Southern Pine	3.98	1,508	538	**2,046**	1,973	40	0.02	**2,013**	**0.98**

Hydrogen Mass Balance

A hydrogen mass balance was done based on Figure 4-5 similar to overall mass balance. Hydrogen input includes hydrogen in from coal, biomass, and steam. The hydrogen input from the coal and biomass are calculated from ultimate (chemical) analysis of the feedstock and the measured feed rates from PDAC coal feeder and FD0210 biomass feeder, respectively. The steam input is back calculated from a hydrogen balance; the steam flow indicator (FI522) rate was not used to calculate the hydrogen input. This was done because the flow indicator FI522 is believed to be inaccurate at the levels used during this testing. Once the steam rate was known, the hydrogen in the steam is calculated as the rate times 2.016/18.016 ("mass fraction" of hydrogen in water). Hydrogen in the coarse ash and fine ash is calculated from the hydrogen content of ash (provided in ash ultimate analysis) and the corresponding ash flow rate. Hydrogen output includes hydrogen in the coarse ash, fine ash and product gas. Hydrogen in the coarse ash and fine ash is calculated from the hydrogen content of ash (provided in ash ultimate analysis) and corresponding ash flow rate. The hydrogen in the product gas stream is accounted in the form of H_2O, H_2, CH_4, and C_2H_6 and corresponding flow rate. In all cases of product gas composition, minor sources of hydrogen, such as ammonia and hydrogen cyanide, were excluded as inconsequential. Results of the hydrogen component balance are shown in Table B-4.

Table B-4: Hydrogen Mass Balance

Test Cases							Hydrogen Inputs				Hydrogen Outputs				Ratio
Steady State Period	CCAT Name	Gasification Mode	Nominal Biomass (wt%)	Actual Biomass (wt%)	Biomass Type	Steady State Duration (hr)	Hydrogen In from Coal (lb/hr)	Hydrogen In from Biomass (lb/hr)	Hydrogen In from Steam (lb/hr)	**Total Hydrogen In (lb/hr)**	Hydrogen Out from Product Gas (lb/hr)	Hydrogen Out from Fine Ash (lb/hr)	Hydrogen Out from Coarse Ash (lb/hr)	**Total Hydrogen Out (lb/hr)**	**Total Outputs to Total Inputs**
35	NCCC-TRIG-20120906A	Air-blown	Coal Only	Coal Only	None	3.98	146	76	134	**356**	356	0.07	0.01	**356**	**1.00**
36	NCCC-TRIG-20120906B	Air-blown	Coal Only	Coal Only	None	5.98	149	74	133	**356**	356	0.07	0.01	**356**	**1.00**
34	NCCC-TRIG-20120905A	Air-blown	Coal Only	Coal Only	None	4.98	149	80	120	**349**	349	0.07	0.01	**349**	**1.00**
38	NCCC-TRIG-20120907B	Oxygen-blown	Coal Only	Coal Only	None	3.98	210	0	477	**687**	687	0.03	0.00	**687**	**1.00**
37	NCCC-TRIG-20120907A	Oxygen-blown	Coal Only	Coal Only	None	6.98	207	0	463	**670**	670	0.03	0.00	**670**	**1.00**
44	NCCC-TRIG-20120913A	Oxygen-blown	Coal Only	Coal Only	None	3.98	196	0	436	**632**	632	0.08	0.01	**632**	**1.00**
39	NCCC-TRIG-20120910A	Oxygen-blown	10	15.7	Southern Pine Torrefied	4.98	201	37	519	**756**	756	0.08	0.01	**756**	**1.00**
40	NCCC-TRIG-20120911A	Oxygen-blown	10	17.3	Southern Pine Torrefied	4.23	182	39	463	**685**	685	0.11	0.00	**685**	**1.00**
42	NCCC-TRIG-20120912A	Oxygen-blown	20	19.3	Southern Pine Torrefied	5.48	190	46	447	**683**	683	0.08	0.01	**683**	**1.00**
41	NCCC-TRIG-20120911B	Oxygen-blown	20	20.0	Southern Pine Torrefied	4.23	181	46	438	**664**	664	0.08	0.02	**664**	**1.00**
43	NCCC-TRIG-20120912B	Oxygen-blown	30	28.7	Southern Pine Torrefied	3.65	182	75	441	**698**	698	0.08	0.01	**698**	**1.00**
45	NCCC-TRIG-20120915A	Oxygen-blown	10	11.7	Southern Pine Raw	4.23	201	27	445	**672**	672	0.06	0.03	**672**	**1.00**
46	NCCC-TRIG-20120915B	Oxygen-blown	20	19.8	Southern Pine Raw	4.48	197	52	439	**688**	688	0.08	0.01	**688**	**1.00**
47	NCCC-TRIG-20120917A	Oxygen-blown	30	28.3	Southern Pine Raw	3.98	161	70	450	**681**	681	0.05	0.01	**681**	**1.00**

Nitrogen Mass Balance

A nitrogen mass balance was done based on Figure 4-5 similar to overall mass balance. Nitrogen input includes nitrogen in from coal, biomass, air, and pure nitrogen. The nitrogen input from the coal and biomass are calculated from ultimate (chemical) analysis of the feedstock and the measured feed rates from PDAC coal feeder and FD0210 biomass feeder, respectively. The nitrogen input from air is assumed at 76.71 wt% of the total air flow through FI205_comp. Pure nitrogen is also used as a feedstock conveying gas in PDAC feeder via FI1610A and FI9177calc and FD0210 feeder via FI667 and FI666, respectively. Pure nitrogen is also used as solids fluidization and instrumentation purging gas, which is metered through FI609. A portion of pure fluidization nitrogen was used for "Adjustment for SRI N_2 Use" at an average rate of 500 lb/hr and "Adjustment for CFAD Operation, FI9205", which was metered via FI9205 (see Table B-5). Nitrogen output includes nitrogen in the coarse ash, fine ash and product gas. Nitrogen in the coarse ash and fine ash is calculated from the nitrogen content of ash (provided in ash ultimate analysis) and corresponding ash flow rate. The nitrogen in the product gas stream is accounted in the form of N_2 and corresponding flow rate. In all cases of product gas composition, minor sources of nitrogen, such as ammonia and hydrogen cyanide, were excluded as inconsequential. Results of the nitrogen component balance are shown in Table B-5.

Table B-5: Nitrogen Mass Balance

Test Cases							Nitrogen Inputs							Nitrogen Outputs				Ratio
Steady State Period	CCAT Name	Gasification Mode	Nominal Biomass (wt%)	Actual Biomass (wt%)	Biomass Type	Steady State Duration (hr)	Nitrogen In from Coal (lb/hr)	Nitrogen In from Biomass (lb/hr)	Nitrogen In from Air In (lb/hr)	Pure Nitrogen used in PDAC Coal Feeder Operation (lb/hr)	Pure Nitrogen used in FD0210 Biomass Feeder Operation (lb/hr)	Pure Nitrogen used for Solids Fluidization and Instrumentations Purging (lb/hr)	**Total Nitrogen In (lb/hr)**	Nitrogen Out from Product Gas (lb/hr)	Nitrogen Out from Fine Ash (lb/hr)	Nitrogen Out from Coarse Ash (lb/hr)	**Total Nitrogen Out (lb/hr)**	**Total Outputs to Total Inputs**
35	NCCC-TRIG-20120906A	Air-blown	Coal Only	Coal Only	None	3.98	21.5	11.1	10,543	973	2,439	4,161	**18,148**	17,312	0.59	0.01	**17,313**	**0.95**
36	NCCC-TRIG-20120906B	Air-blown	Coal Only	Coal Only	None	5.98	23.5	10.8	10,449	970	2,409	4,141	**18,004**	17,148	0.50	0.01	**17,149**	**0.95**
34	NCCC-TRIG-20120905A	Air-blown	Coal Only	Coal Only	None	4.98	21.9	11.8	10,553	975	2,443	4,679	**18,683**	17,916	0.59	0.01	**17,917**	**0.96**
38	NCCC-TRIG-20120907B	Oxygen-blown	Coal Only	Coal Only	None	3.98	32.7	0.0	2,293	813	1,062	3,943	**8,144**	6,116	0.31	0.01	**6,116**	**0.75**
37	NCCC-TRIG-20120907A	Oxygen-blown	Coal Only	Coal Only	None	6.98	32.3	0.0	2,281	810	1,937	3,894	**8,955**	6,279	0.31	0.01	**6,279**	**0.70**
44	NCCC-TRIG-20120913A	Oxygen-blown	Coal Only	Coal Only	None	3.98	32.0	0.0	2,306	832	2,538	3,672	**9,380**	8,174	0.45	0.01	**8,174**	**0.87**
39	NCCC-TRIG-20120910A	Oxygen-blown	10	15.7	Southern Pine Torrefied	4.98	31.0	3.0	2,461	811	2,764	4,176	**10,246**	8,955	0.34	0.01	**8,955**	**0.87**
40	NCCC-TRIG-20120911A	Oxygen-blown	10	17.3	Southern Pine Torrefied	4.23	28.8	2.7	2,473	829	2,720	3,873	**9,926**	8,872	0.44	0.00	**8,872**	**0.89**
42	NCCC-TRIG-20120912A	Oxygen-blown	20	19.3	Southern Pine Torrefied	5.48	30.5	3.4	2,475	827	2,710	3,638	**9,683**	8,780	0.27	0.01	**8,781**	**0.91**
41	NCCC-TRIG-20120911B	Oxygen-blown	20	20.0	Southern Pine Torrefied	4.23	29.5	2.9	2,513	827	2,668	3,384	**9,424**	8,625	0.33	0.02	**8,625**	**0.92**
43	NCCC-TRIG-20120912B	Oxygen-blown	30	28.7	Southern Pine Torrefied	3.65	29.1	5.2	2,473	806	2,684	3,257	**9,254**	8,233	0.52	0.01	**8,234**	**0.89**
45	NCCC-TRIG-20120915A	Oxygen-blown	10	11.7	Southern Pine Raw	4.23	33.4	0.6	2,311	828	2,729	3,621	**9,523**	8,218	0.42	0.05	**8,218**	**0.86**
46	NCCC-TRIG-20120915B	Oxygen-blown	20	19.8	Southern Pine Raw	4.48	29.8	1.3	2,394	812	2,725	3,626	**9,588**	8,068	0.39	0.01	**8,068**	**0.84**
47	NCCC-TRIG-20120917A	Oxygen-blown	30	28.3	Southern Pine Raw	3.98	22.3	2.1	2,351	804	2,761	3,346	**9,286**	7,940	0.45	0.02	**7,940**	**0.86**

Oxygen Mass Balance

An oxygen mass balance was done based on Figure 4-5 similar to overall mass balance. Oxygen input includes oxygen into the gasifier from coal, biomass, air, steam, and pure oxygen. The oxygen input from the coal and biomass are calculated from ultimate (chemical) analysis of the feedstock and the measured feed rates from PDAC coal feeder and FD0210 biomass feeder, respectively. The oxygen input from air is assumed at 23.29 wt% of the total air flow through FI205_comp. Again the steam input is back calculated from a hydrogen balance; the steam flow indicator (FI522) rate was not used to calculate the oxygen input. This was done because the flow indicator FI522 is believed to be inaccurate at the levels used during this testing. Once the steam rate was known the oxygen in the steam is calculated as the rate times 16.00/18.016 (“mass fraction” of oxygen in water). Oxygen input from pure oxygen is metered in through two meters, FI726_COMP, which supplies oxygen at lower mixing zone and FIC790MEAS, which supplies oxygen to upper mixing zone. The oxygen used has a purity of 99.5% by volume. Oxygen output includes oxygen in the coarse ash, fine ash, and product gas. Oxygen in the coarse ash and fine ash is calculated from the oxygen content of ash (provided in ash ultimate analysis) and corresponding ash flow rate. The oxygen in the product gas (FI465_Comp) stream is accounted in the form of H_2O, CO, and CO_2 and corresponding flow rate. Results of the oxygen component balance are shown in Table B-6.

Table B-6: Oxygen Mass Balance

Test Cases							Oxygen Inputs							Oxygen Outputs				Ratio
Steady State Period	CCAT Name	Gasification Mode	Nominal Biomass (wt%)	Actual Biomass (wt%)	Biomass Type	Steady State Duration (hr)	Oxygen In from Coal (lb/hr)	Oxygen In from Biomass (lb/hr)	Oxygen In from Steam (lb/hr)	Oxygen In from Air (lb/hr)	Pure Oxygen used in Lower Mixing Zone (lb/hr)	Pure Oxygen in Upper Mixing Zone (lb/hr)	**Total Oxygen In (lb/hr)**	Oxygen Out from Fine Ash (lb/hr)	Oxygen Out from Coarse Ash (lb/hr)	Oxygen Out from Product Gas (lb/hr)	**Total Oxygen Out (lb/hr)**	**Total Outputs to Total Inputs**
35	NCCC-TRIG-20120906A	Air-blown	Coal Only	Coal Only	None	3.98	769	389	1,063	3,201	0	0	**5,422**	1.02	0.06	5,546	**5,547**	**1.02**
36	NCCC-TRIG-20120906B	Air-blown	Coal Only	Coal Only	None	5.98	767	382	1,054	3,172	0	0	**5,376**	1.22	0.02	5,539	**5,540**	**1.03**
34	NCCC-TRIG-20120905A	Air-blown	Coal Only	Coal Only	None	4.98	782	412	951	3,204	0	0	**5,349**	1.02	0.06	5,480	**5,481**	**1.02**
38	NCCC-TRIG-20120907B	Oxygen-blown	Coal Only	Coal Only	None	3.98	1,123	0	3,788	696	1,169	1,094	**7,870**	0.70	0.00	7,630	**7,631**	**0.97**
37	NCCC-TRIG-20120907A	Oxygen-blown	Coal Only	Coal Only	None	6.98	1,108	0	3,674	693	1,231	1,027	**7,733**	0.70	0.00	7,537	**7,538**	**0.97**
44	NCCC-TRIG-20120913A	Oxygen-blown	Coal Only	Coal Only	None	3.98	1,025	0	3,462	700	1,100	1,192	**7,480**	0.37	0.05	7,409	**7,409**	**0.99**
39	NCCC-TRIG-20120910A	Oxygen-blown	10	15.7	Southern Pine Torrefied	4.98	1,034	214	4,116	747	1,489	960	**8,560**	2.80	0.03	8,591	**8,594**	**1.00**
40	NCCC-TRIG-20120911A	Oxygen-blown	10	17.3	Southern Pine Torrefied	4.23	954	223	3,677	751	1,276	1,065	**7,946**	1.39	0.01	7,895	**7,896**	**0.99**
42	NCCC-TRIG-20120912A	Oxygen-blown	20	19.3	Southern Pine Torrefied	5.48	1,013	268	3,547	751	1,235	1,144	**7,959**	0.48	0.04	8,037	**8,038**	**1.01**
41	NCCC-TRIG-20120911B	Oxygen-blown	20	20.0	Southern Pine Torrefied	4.23	914	276	3,473	763	1,255	1,124	**7,805**	0.94	0.01	7,887	**7,888**	**1.01**
43	NCCC-TRIG-20120912B	Oxygen-blown	30	28.7	Southern Pine Torrefied	3.65	973	431	3,501	751	1,340	1,204	**8,200**	1.07	0.02	8,207	**8,208**	**1.00**
45	NCCC-TRIG-20120915A	Oxygen-blown	10	11.7	Southern Pine Raw	4.23	1,072	203	3,529	702	1,127	1,244	**7,876**	0.07	0.07	7,773	**7,773**	**0.99**
46	NCCC-TRIG-20120915B	Oxygen-blown	20	19.8	Southern Pine Raw	4.48	1,039	369	3,488	727	1,154	1,203	**7,980**	0.28	0.01	7,895	**7,895**	**0.99**
47	NCCC-TRIG-20120917A	Oxygen-blown	30	28.3	Southern Pine Raw	3.98	847	479	3,570	714	1,174	1,057	**7,840**	0.35	0.03	7,806	**7,806**	**1.00**

Appendix C: Energy Balance

Figure C-1 below represents an energy balance around the gasifier. For this balance the control volume only contains the TRIG™ gasifier – none of the downstream equipment (gas cooler, PCD, etc.) is included. The system inputs are coal, biomass, steam, air, and recycle product gas. Note that sensible heat from oxygen and nitrogen input streams are not accounted in the energy balance because they are fed at ambient temperature (a reference ambient temperature of 80°F was used in the energy balance calculations). Coal and biomass were fed at ambient temperature, which is also the reference temperature of 80°F assumed in this energy balance calculations. Therefore the only form of energy input from coal and biomass was in the form of heat input based on the heating values and corresponding flow rate. The energy input from the steam is based on the sensible heat of the steam at the temperature, pressure, and heat capacity of the steam, the steam flow rate (calculated from hydrogen balance), and a reference ambient temperature of 80°F. Likewise the energy from the air is based on the sensible heat of the air at the air input temperature, pressure, and heat capacity (with reference temperature of 80°F). Energy input from the recycle product gas was calculated based on the sensible heat of the recycle product gas and heating value of the recycle product gas aeration stream and recycle product gas aeration flow rate. The recycle product gas aeration flow rate is the sum of product gas used in Standpipe (FI290_COMP and FI913_COMP), J-Leg (FI681_COMP and FI689_COMP), and Seal-Leg (FI203_COMP, FI297_COMP, FI299_COMP, and FI444_COMP) of the gasifier. The outputs of the system include coarse ash, raw product gas, and heat loss. Because raw product gas rate at the gasifier outlet cannot be measured due to heavy particulate, raw product gas at the gasifier outlet was calculated by mass balance. Raw product gas flow rate is equal to sum of fine ash (CFAD) flow rate, product gas (FI465_Comp) flow rate, and product gas to recycle gas compressor (FI9452_COMP) flow rate (see Section 4.4 and Figure 4-5). The energy in both the coarse ash and fine ash are in part defined by the sensible heat of the solids at corresponding temperature, pressure, and heat capacity. Also because both coarse ash and fine ash have some remaining carbon content, the balance accounts for this small energy output based on the heating value of the corresponding ash (provided in the coarse and fine ash chemical analysis) and the corresponding flow rate. The product gas energy was calculated based on the sensible heat of the product gas and the heating value of the product gas. Heat loss from the system, as a result of convection/conduction/radiation, is assumed to be 3.5MMBtu/hr for all seven test runs.

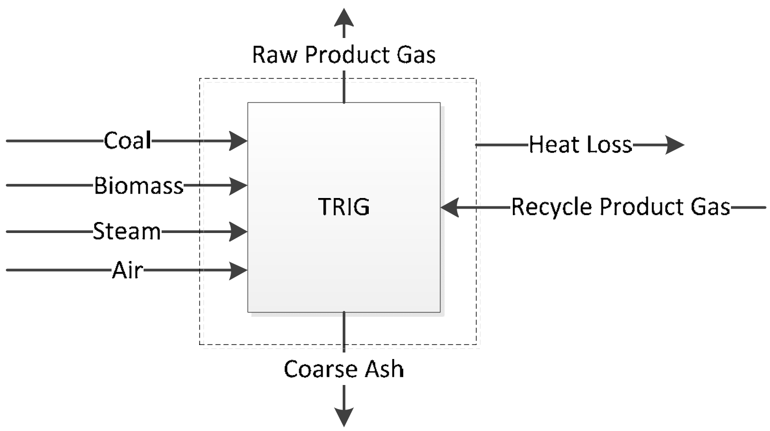

Figure C-1 Energy Balance

Table C-1: Overall Energy Balance

Test Cases							Energy Inputs (MMBtu/hr)						Energy Outputs (MMBtu/hr)					Ratio
Steady State Period	CCAT Name	Gasification Mode	Nominal Biomass (wt%)	Actual Biomass (wt%)	Biomass Type	Steady State Duration (hr)	Coal	Biomass	Steam	Air	Ancillary, Recycle Syngas Compressor	**Total Energy Inputs**	Product Gas	Fine Ash	Coarse Ash	Heat Loss	**Total Energy Outputs**	**Total Energy Outputs to Total Energy Inputs**
35	NCCC-TRIG-20120906A	Air-blown	Coal Only	Coal Only	None	3.98	36.19	0	0.34	0.85	1.18	**38.57**	37.57	0.88	0.09	3.50	**42.05**	**1.09**
36	NCCC-TRIG-20120906B	Air-blown	Coal Only	Coal Only	None	5.98	36.49	0	0.34	0.85	1.17	**38.86**	36.99	0.85	0.08	3.50	**41.42**	**1.07**
34	NCCC-TRIG-20120905A	Air-blown	Coal Only	Coal Only	None	4.98	37.30	0	0.31	0.86	1.15	**39.62**	37.52	0.88	0.10	3.50	**42.00**	**1.06**
38	NCCC-TRIG-20120907B	Oxygen-blown	Coal Only	Coal Only	None	3.98	33.97	0	1.19	0.17	1.58	**36.92**	34.77	0.65	0.01	3.50	**38.93**	**1.05**
37	NCCC-TRIG-20120907A	Oxygen-blown	Coal Only	Coal Only	None	6.98	33.54	0	1.16	0.17	1.62	**36.50**	35.49	0.65	0.01	3.50	**39.64**	**1.09**
44	NCCC-TRIG-20120913A	Oxygen-blown	Coal Only	Coal Only	None	3.98	31.77	0	1.09	0.17	1.35	**34.39**	33.12	0.78	0.03	3.50	**37.43**	**1.09**
39	NCCC-TRIG-20120910A	Oxygen-blown	10	15.7	Southern Pine Torrefied	4.98	31.73	6.03	1.29	0.18	1.39	**40.61**	38.54	0.60	0.07	3.50	**42.71**	**1.05**
40	NCCC-TRIG-20120911A	Oxygen-blown	10	17.3	Southern Pine Torrefied	4.23	29.72	6.56	1.15	0.18	1.45	**39.06**	37.86	0.96	0.01	3.50	**42.34**	**1.08**
42	NCCC-TRIG-20120912A	Oxygen-blown	20	19.3	Southern Pine Torrefied	5.48	30.67	7.79	1.12	0.18	1.42	**41.17**	37.25	0.72	0.08	3.50	**41.54**	**1.01**
41	NCCC-TRIG-20120911B	Oxygen-blown	20	20.0	Southern Pine Torrefied	4.23	29.32	7.44	1.09	0.19	1.43	**39.46**	36.75	0.75	0.05	3.50	**41.05**	**1.04**
43	NCCC-TRIG-20120912B	Oxygen-blown	30	28.7	Southern Pine Torrefied	3.65	29.53	12.52	1.10	0.19	1.61	**44.95**	40.72	0.88	0.07	3.50	**45.17**	**1.01**
45	NCCC-TRIG-20120915A	Oxygen-blown	10	11.7	Southern Pine Raw	4.23	32.93	3.95	1.11	0.17	1.40	**39.56**	35.11	0.63	0.07	3.50	**39.30**	**0.99**
46	NCCC-TRIG-20120915B	Oxygen-blown	20	19.8	Southern Pine Raw	4.48	31.51	7.00	1.10	0.18	1.39	**41.19**	35.11	0.83	0.06	3.50	**39.50**	**0.96**
47	NCCC-TRIG-20120917A	Oxygen-blown	30	28.3	Southern Pine Raw	3.98	25.32	9.25	1.12	0.18	1.32	**37.19**	33.17	0.73	0.03	3.50	**37.43**	**1.01**

Appendix D: Product Gas Composition and Heating Value

Table D-1: Product Gas Composition and Heating Value

Test Cases							Product Gas Composition (mol%)								Product Gas Molar Mass and Heating Value	
Steady State Period	CCAT Name	Steady State Duration (hr)	Gasification Mode	Biomass Type	Nominal Biomass (wt%)	Actual Biomass (wt%)	H_2O	CO	H_2	CO_2	CH_4	C_2H_6	Ar	N_2	Product Gas Molar Mass (lb/lb-mol)	Product Gas Heating Value, HHV (Btu/lb)
35	NCCC-TRIG-20120906A	4.0	Air-blown	None	Coal Only	Coal Only	9.3	9.2	6.9	8.8	1.1	0.0	0.4	64.3	26.6	932.8
36	NCCC-TRIG-20120906B	6.0	Air-blown	None	Coal Only	Coal Only	9.5	9.0	6.9	8.9	1.0	0.0	0.4	64.2	26.6	920.0
34	NCCC-TRIG-20120905A	5.0	Air-blown	None	Coal Only	Coal Only	9.0	9.0	6.7	8.5	1.0	0.0	0.4	65.4	26.7	902.1
38	NCCC-TRIG-20120907B	4.0	Oxygen-blown	None	Coal Only	Coal Only	32.1	8.4	13.5	13.6	1.4	0.0	0.0	31.0	23.3	1440.6
37	NCCC-TRIG-20120907A	7.0	Oxygen-blown	None	Coal Only	Coal Only	30.3	8.6	13.9	13.9	1.5	0.0	0.0	31.8	23.4	1478.5
44	NCCC-TRIG-20120913A	4.0	Oxygen-blown	None	Coal Only	Coal Only	28.3	7.6	11.0	12.9	1.3	0.0	0.0	38.9	24.3	1185.1
39	NCCC-TRIG-20120910A	5.0	Oxygen-blown	Southern Pine Torrefied	10	15.7	29.3	6.9	11.8	13.3	1.4	0.0	0.0	37.3	24.0	1229.3
40	NCCC-TRIG-20120911A	4.2	Oxygen-blown	Southern Pine Torrefied	10	17.3	26.4	7.4	12.5	13.4	1.4	0.0	0.0	38.9	24.1	1287.8
42	NCCC-TRIG-20120912A	5.5	Oxygen-blown	Southern Pine Torrefied	20	19.3	27.4	7.8	11.3	13.3	1.5	0.0	0.0	38.6	24.3	1252.3
41	NCCC-TRIG-20120911B	4.2	Oxygen-blown	Southern Pine Torrefied	20	20.0	26.9	7.9	11.5	13.6	1.5	0.0	0.0	38.7	24.3	1258.8
43	NCCC-TRIG-20120912B	3.6	Oxygen-blown	Southern Pine Torrefied	30	28.7	26.8	9.0	12.1	13.8	1.9	0.0	0.0	36.3	24.2	1437.6
45	NCCC-TRIG-20120915A	4.2	Oxygen-blown	Southern Pine Raw	10	11.7	29.3	7.8	10.7	12.8	1.5	0.0	0.0	37.9	24.2	1230.6
46	NCCC-TRIG-20120915B	4.5	Oxygen-blown	Southern Pine Raw	20	19.8	30.3	7.6	10.4	12.9	1.6	0.0	0.0	37.1	24.1	1225.6
47	NCCC-TRIG-20120917A	4.0	Oxygen-blown	Southern Pine Raw	30	28.3	31.3	6.8	9.7	13.1	1.8	0.0	0.0	37.3	24.2	1157.4

Appendix E: Trace Species Analysis

Test Case							Detected Hydrocarbons, wet basis (ppmv)									Draeger Tube Samples (ppm)			Product Gas Condensate Samples (mg/L)		
Steady State Period	CCAT Name	Steady State Duration (hr)	Gasification Mode	Biomass Type	Target Biomass (wt%)	Actual Biomass (wt%)	Ammonia	Benzene	Acenaphthene	Acenaphthylene	Fluoranthene	Fluorene	Naphthalene	Phenanthrene	Pyrene	Ammonia	Hydrochloric Acid	Hydrogen Cyanide	Ammonia	Chemical Oxygen Demand	Total Oxygen Demand
35	NCCC-TRIG-20120906A	4.0	Air-blown	None	Coal Only	Coal Only	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
36	NCCC-TRIG-20120906B	6.0	Air-blown	None	Coal Only	Coal Only	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
34	NCCC-TRIG-20120905A	5.0	Air-blown	None	Coal Only	Coal Only	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
37	NCCC-TRIG-20120907A	4.0	Oxygen-blown	None	Coal Only	Coal Only	1771.3	922.3	0.0	0.0	9.2	0.0	112.8	4.9	4.0	TF	6.0	13.8	7070.0	592.0	59.5
38	NCCC-TRIG-20120907B	7.0	Oxygen-blown	None	Coal Only	Coal Only	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
44	NCCC-TRIG-20120913A	4.0	Oxygen-blown	None	Coal Only	Coal Only	2536.3	542.4	13.9	30.9	16.6	4.6	1045.0	30.0	14.8	4000.0	0.0	5.0	*	*	*
39	NCCC-TRIG-20120910A	5.0	Oxygen-blown	Southern Pine Torrefied	10	15.7	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
40	NCCC-TRIG-20120911A	4.2	Oxygen-blown	Southern Pine Torrefied	10	17.3	2090.3	830.6	11.3	23.7	4.7	4.8	137.6	19.9	4.0	3500.0	TF	0	5600.0	270.0	48.1

Test Case							Detected Hydrocarbons, wet basis (ppmv)									Draeger Tube Samples (ppm)			Product Gas Condensate Samples (mg/L)		
Steady State Period	CCAT Name	Steady State Duration (hr)	Gasification Mode	Biomass Type	Target Biomass (wt%)	Actual Biomass (wt%)	Ammonia	Benzene	Acenaphthene	Acenaphthylene	Fluoranthene	Fluorene	Naphthalene	Phenanthrene	Pyrene	Ammonia	Hydrochloric Acid	Hydrogen Cyanide	Ammonia	Chemical Oxygen Demand	Total Oxygen Demand
42	NCCC-TRIG-20120912A	5.5	Oxygen-blown	Southern Pine Torrefied	20	19.3	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
41	NCCC-TRIG-20120911B	4.2	Oxygen-blown	Southern Pine Torrefied	20	20.0	2385.7	548.1	5.9	12.1	3.1	0.0	247.4	8.5	2.8	4125.0	1.0	0.0	5560.0	153.0	43.6
43	NCCC-TRIG-20120912B	3.6	Oxygen-blown	Southern Pine Torrefied	30	28.7	2593.0	789.6	12.8	31.2	3.5	3.0	976.1	10.8	3.0	4250.0	6.0	TF	5970.0	258.0	50.5
45	NCCC-TRIG-20120915A	4.2	Oxygen-blown	Southern Pine Raw	10	11.7	2117.7	765.0	12.2	22.3	5.7	3.1	430.0	13.1	5.4	4800.0	0.0	6.3	5860.0	173.0	45.7
46	NCCC-TRIG-20120915B	4.5	Oxygen-blown	Southern Pine Raw	20	19.8	2023.6	614.7	6.8	16.0	1.6	0.0	873.1	8.3	1.5	2000.0	0.0	5.0	4960.0	205.0	44.5
47	NCCC-TRIG-20120917A	4.0	Oxygen-blown	Southern Pine Raw	30	28.3	1554.2	993.8	11.9	33.6	2.5	3.0	1563.8	11.4	2.2	TF	6.0	5.0	4390.0	157.0	40.7

Note:* = Not Sampled
TF = Tube Failure

Appendix F: Carbon Conversion and Cold Gas Efficiency

Test Cases							Carbon Conversion and Cold Gas Efficiency (%)	
Steady State Period	CCAT Name	Steady State Duration (hr)	Gasification Mode	Biomass Type	Nominal Biomass (wt%)	Actual Biomass (wt%)	Carbon Conversion (%)	Cold Gas Efficiency, HHV (%)
35	NCCC-TRIG-20120906A	4.0	Air-blown	None	Coal Only	Coal Only	97.7	65.9
36	NCCC-TRIG-20120906B	6.0	Air-blown	None	Coal Only	Coal Only	97.8	63.9
34	NCCC-TRIG-20120905A	5.0	Air-blown	None	Coal Only	Coal Only	97.8	63.1
38	NCCC-TRIG-20120907B	4.0	Oxygen-blown	None	Coal Only	Coal Only	98.4	69.6
37	NCCC-TRIG-20120907A	7.0	Oxygen-blown	None	Coal Only	Coal Only	98.3	72.9
44	NCCC-TRIG-20120913A	4.0	Oxygen-blown	None	Coal Only	Coal Only	97.7	67.8
39	NCCC-TRIG-20120910A	5.0	Oxygen-blown	Southern Pine Torrefied	10	15.7	98.7	66.9
40	NCCC-TRIG-20120911A	4.2	Oxygen-blown	Southern Pine Torrefied	10	17.3	97.6	69.7
42	NCCC-TRIG-20120912A	5.5	Oxygen-blown	Southern Pine Torrefied	20	19.3	98.2	64.2
41	NCCC-TRIG-20120911B	4.2	Oxygen-blown	Southern Pine Torrefied	20	20.0	98.2	66.4
43	NCCC-TRIG-20120912B	3.6	Oxygen-blown	Southern Pine Torrefied	30	28.7	98.0	66.9
45	NCCC-TRIG-20120915A	4.2	Oxygen-blown	Southern Pine Raw	10	11.7	98.4	62.5
46	NCCC-TRIG-20120915B	4.5	Oxygen-blown	Southern Pine Raw	20	19.8	97.9	59.6
47	NCCC-TRIG-20120917A	4.0	Oxygen-blown	Southern Pine Raw	30	28.3	98.0	61.6

Appendix G: Steady State Period Time Dependent Data

Pre-CCAT

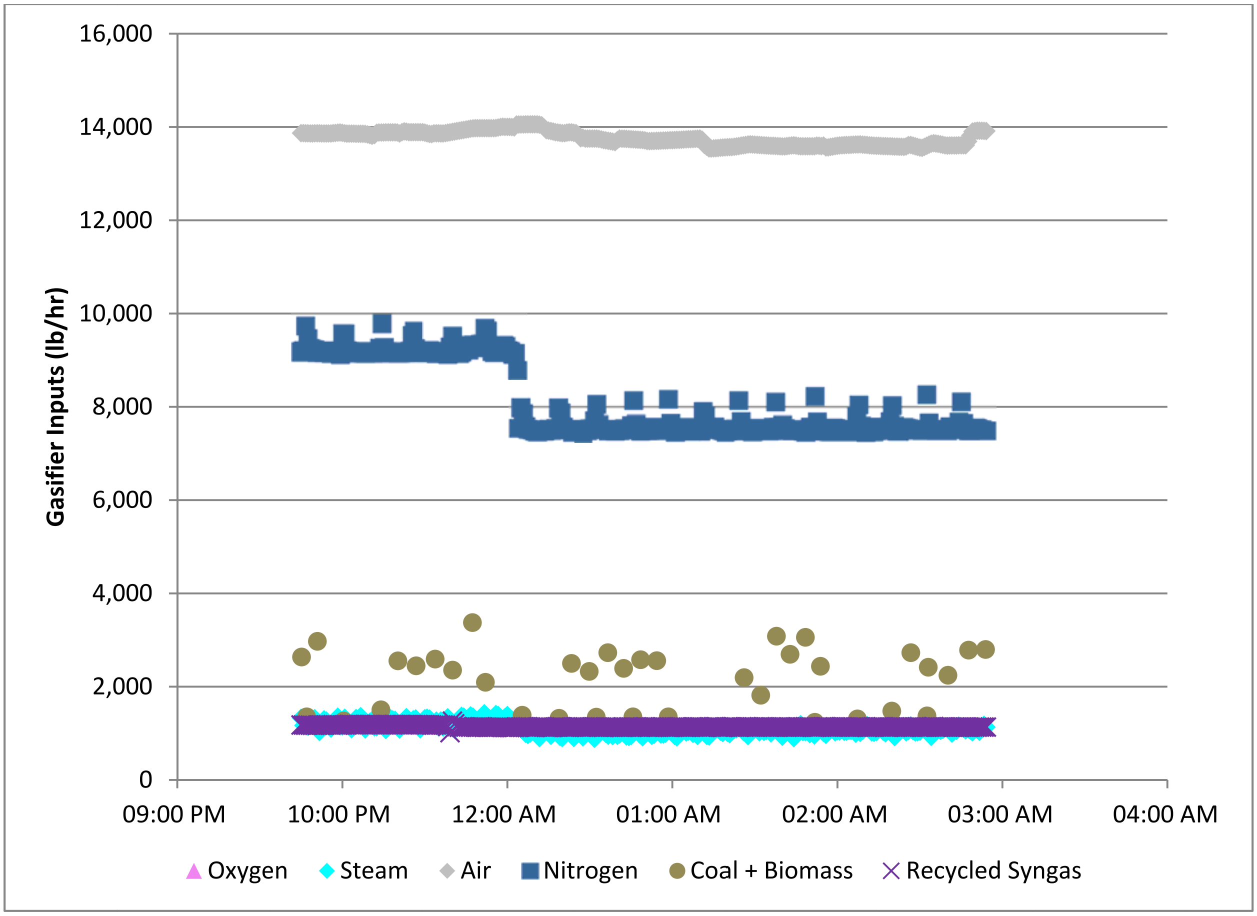

Figure G-1: SS Period 34 (NCCC-TRIG-20120905A) for Gasifier Inputs

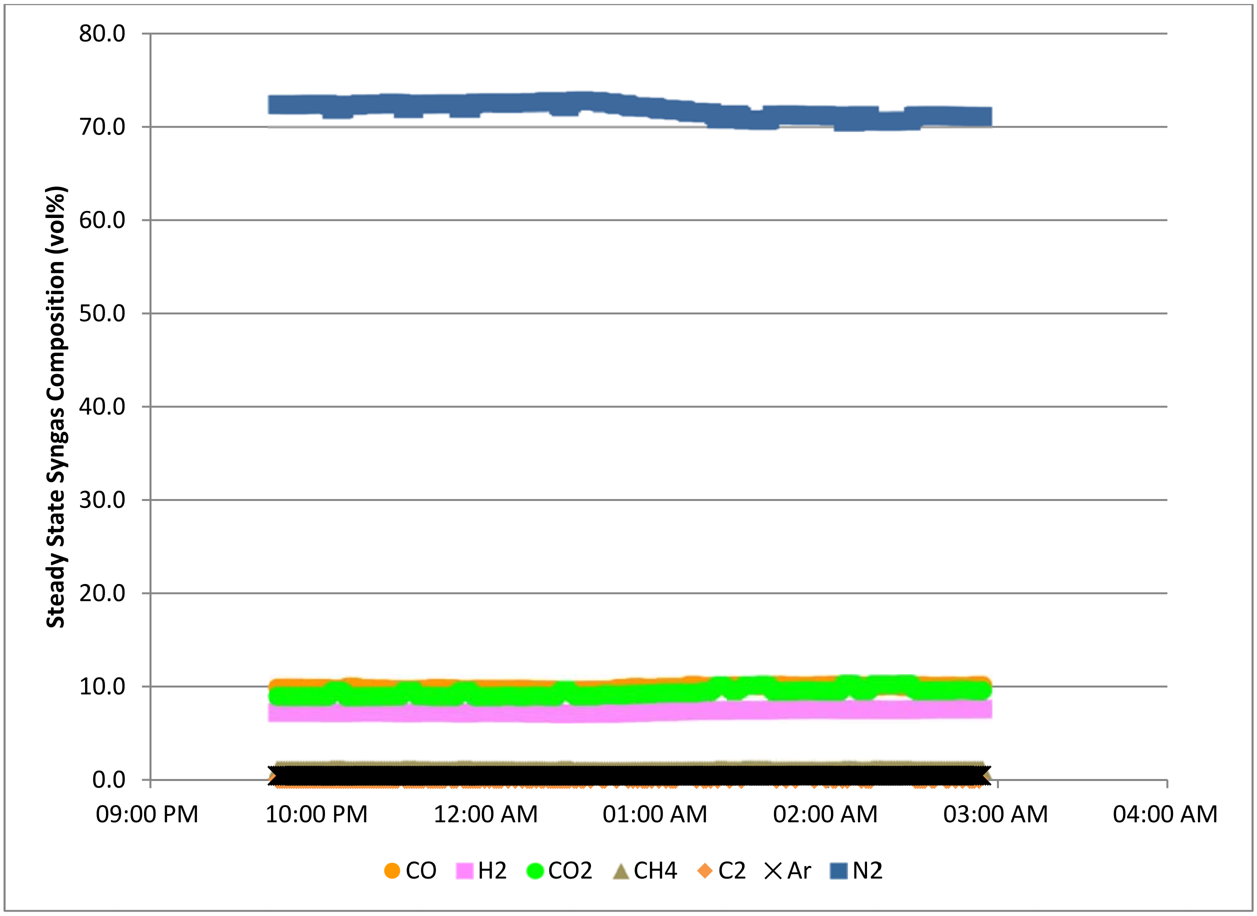

Figure G-2: SS Period 34 (NCCC-TRIG-20120905A) for Exiting Gas Composition

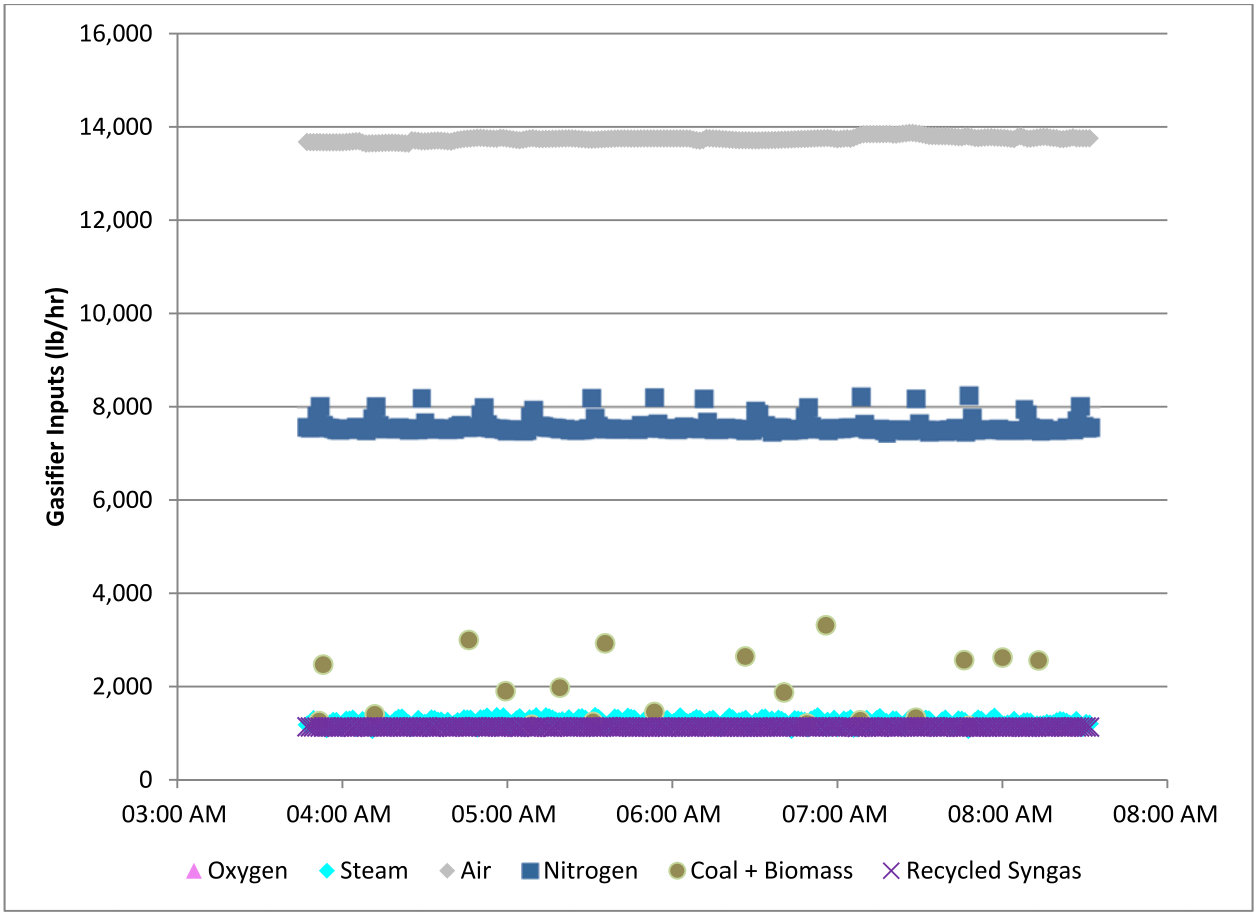

Figure G-3: SS Period 35 (NCCC-TRIG-20120906A) for Gasifier Inputs

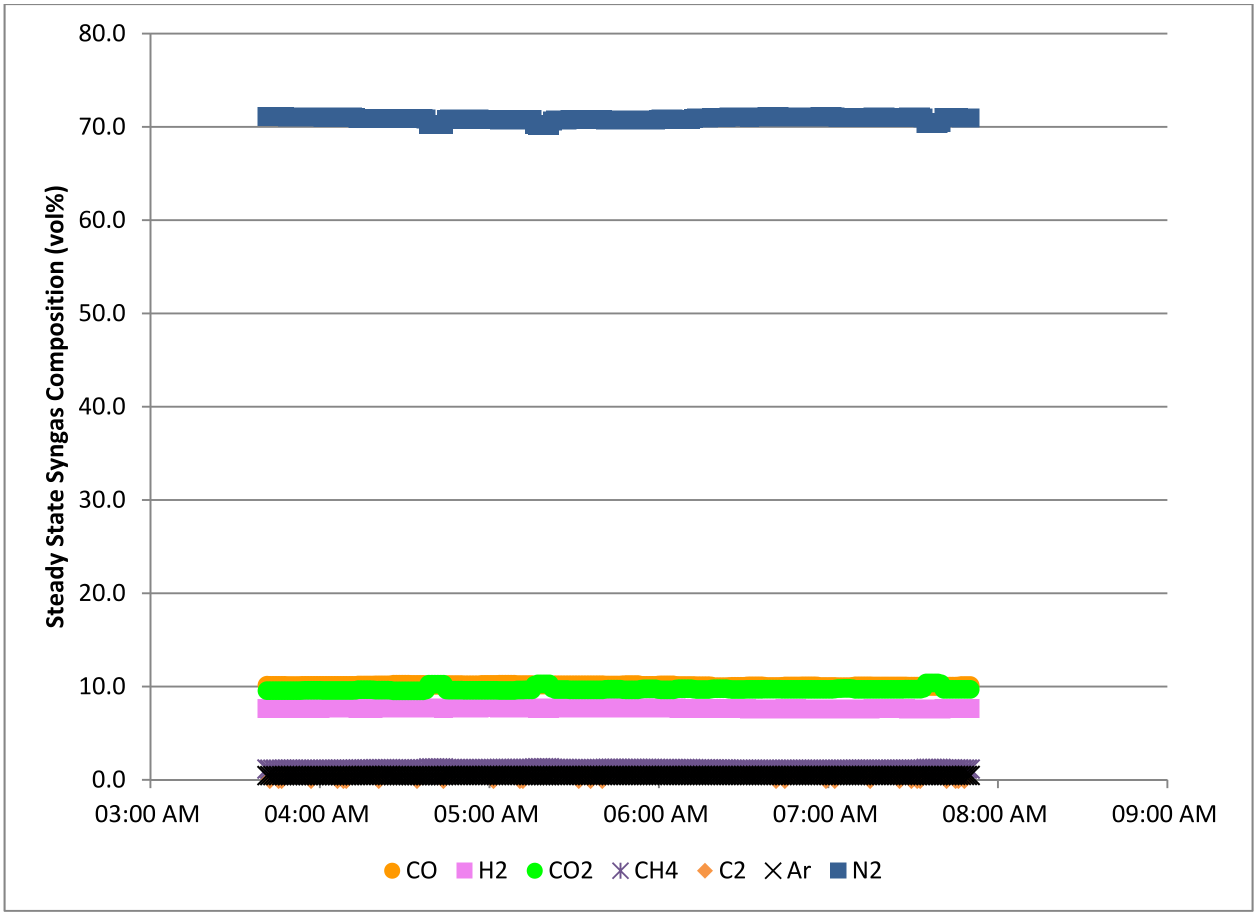

Figure G-4: SS Period 35 (NCCC-TRIG-20120906A) for Exiting Gas Composition

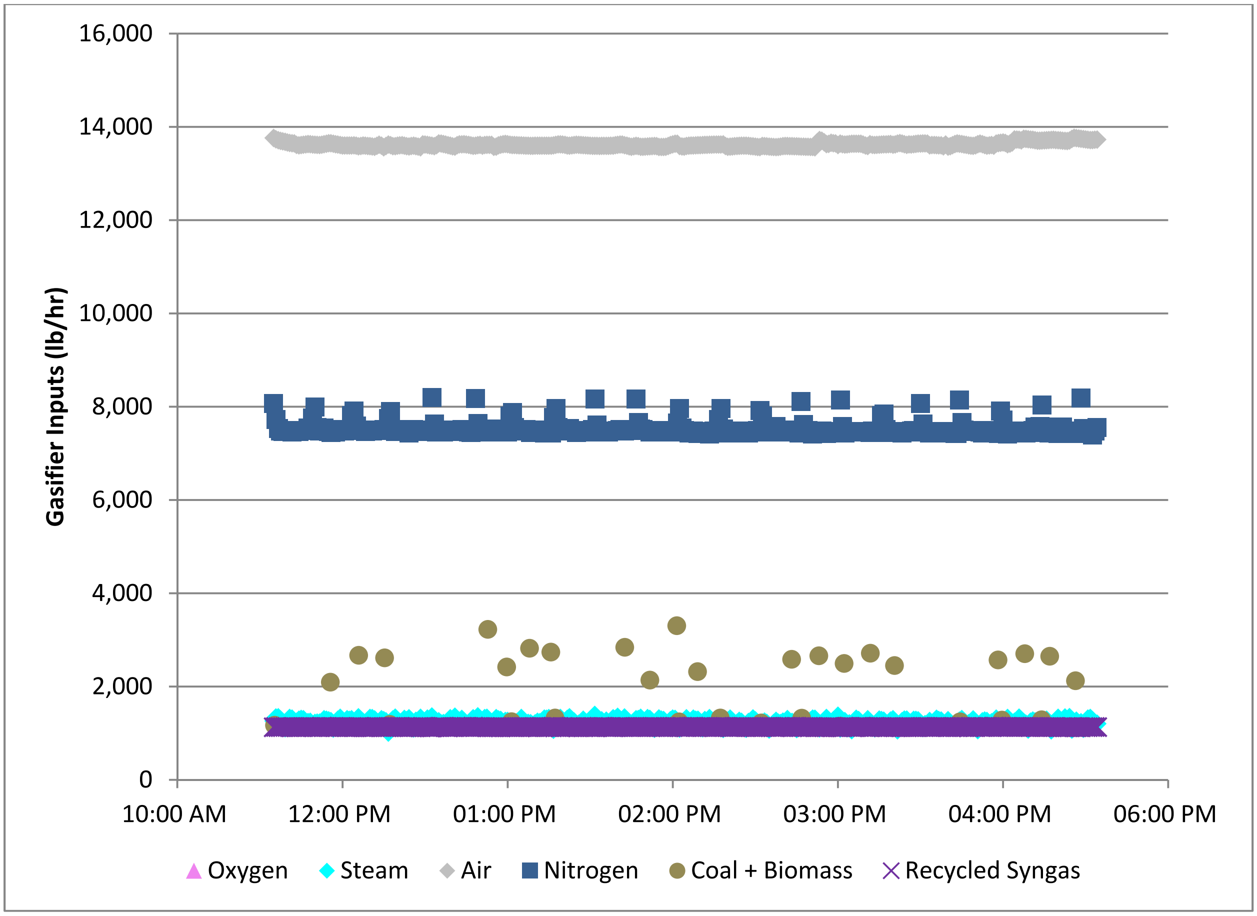

Figure G-5: SS Period 36 (NCCC-TRIG-20120906B) for Gasifier Inputs

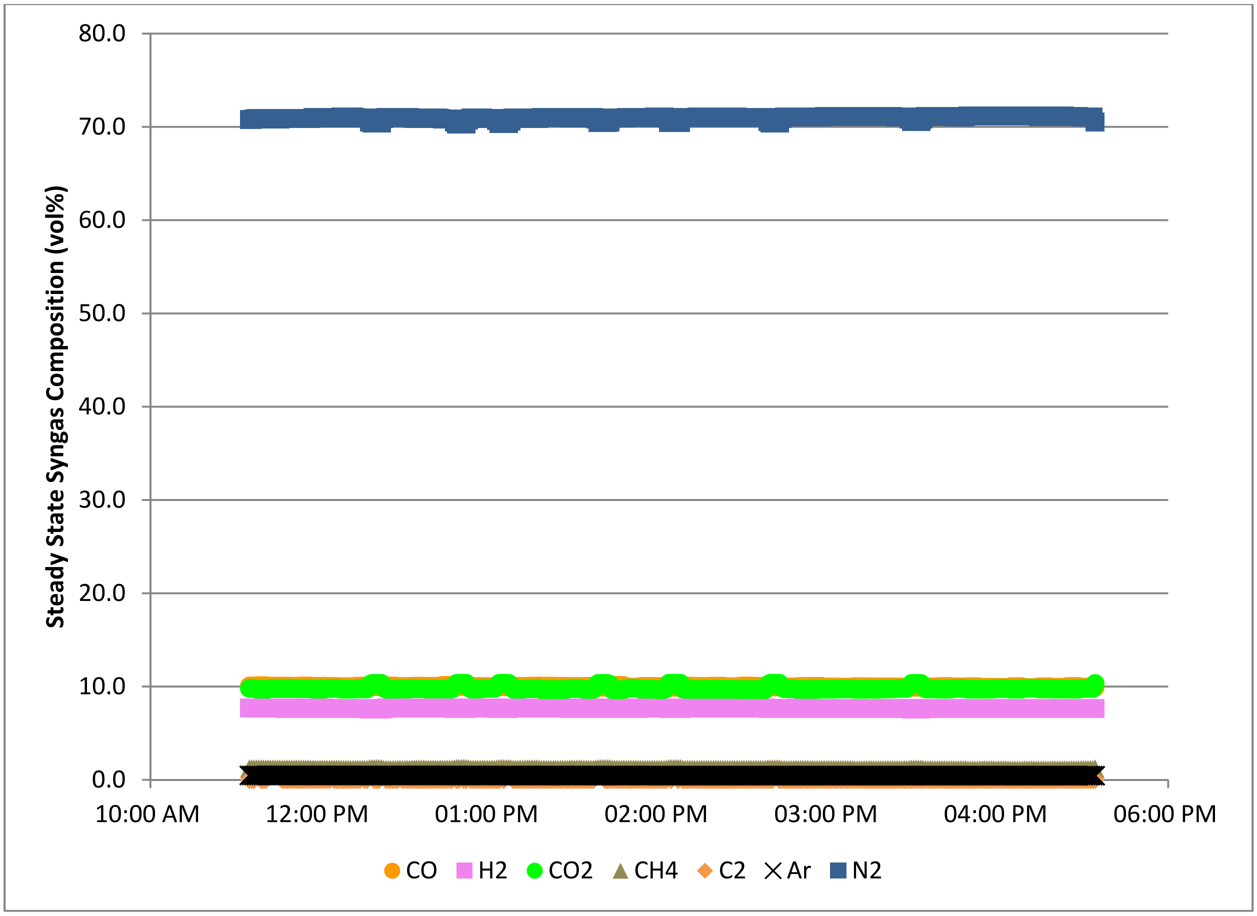

Figure G-6: SS Period 36 (NCCC-TRIG-20120906B) for Exiting Gas Composition

Coal Only

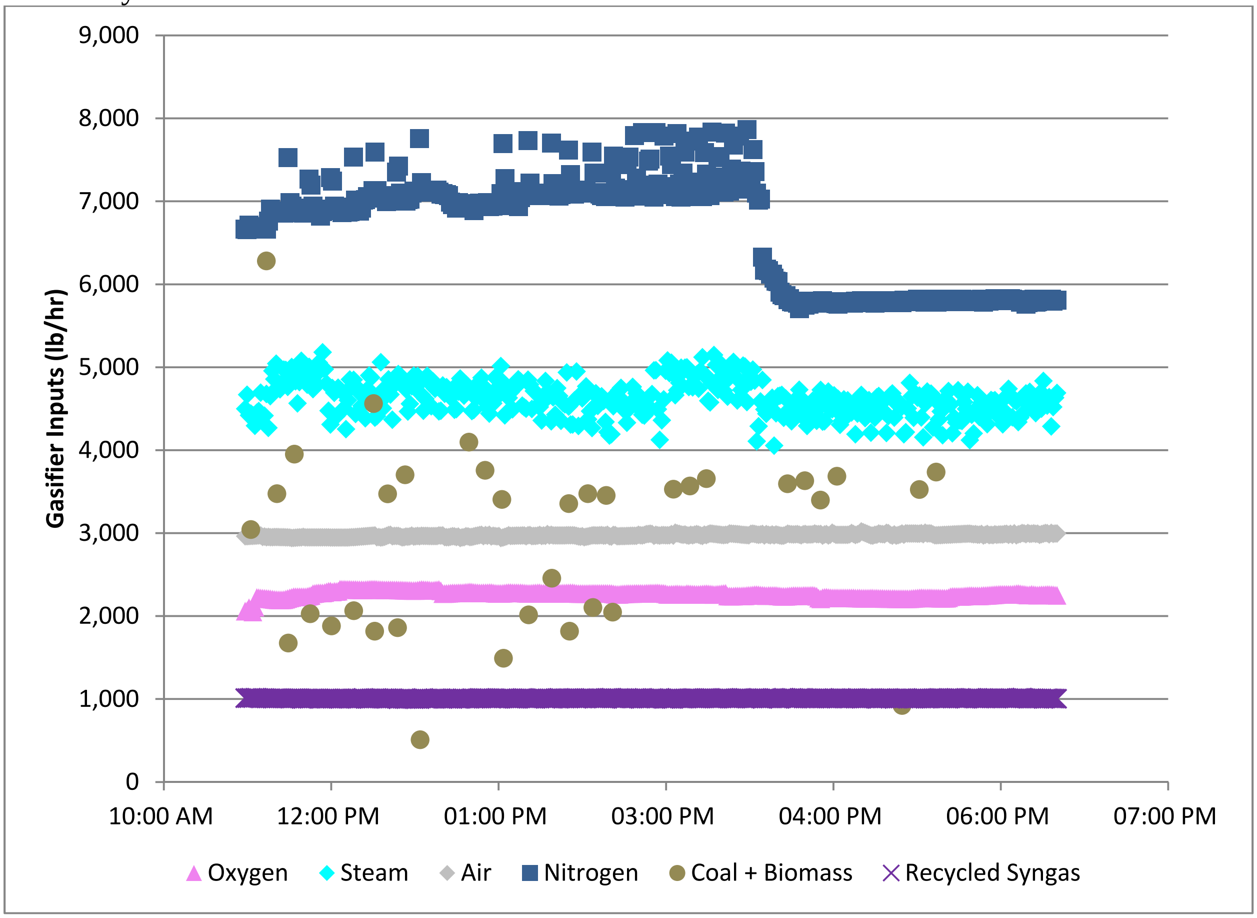

Figure G-7: SS Period 37 (NCCC-TRIG-20120907A) for Gasifier Inputs

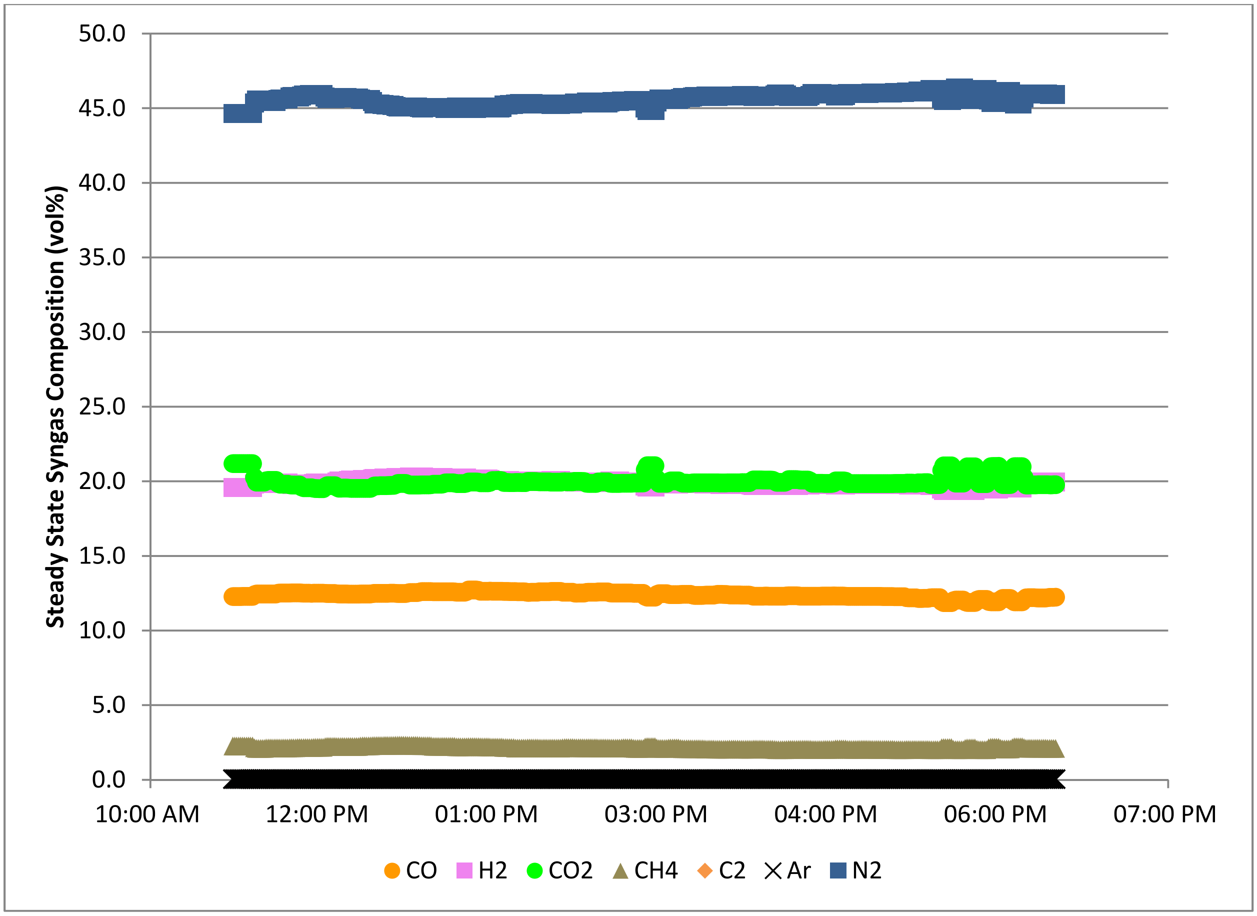

Figure G-8: SS Period 37 (NCCC-TRIG-20120907A) for Exiting Gas Composition

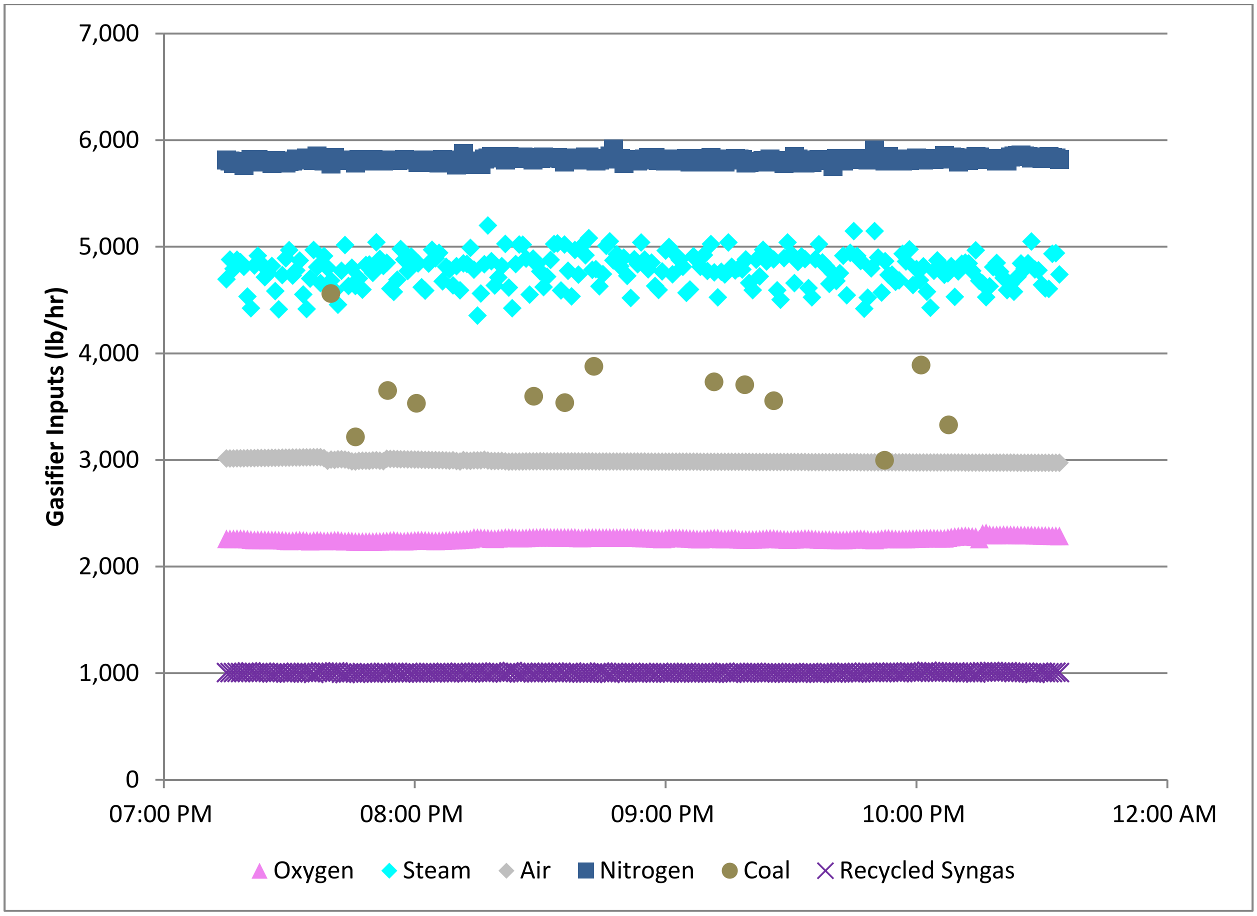

Figure G-9: SS Period 38 (NCCC-TRIG-20120907B) for Gasifier Inputs

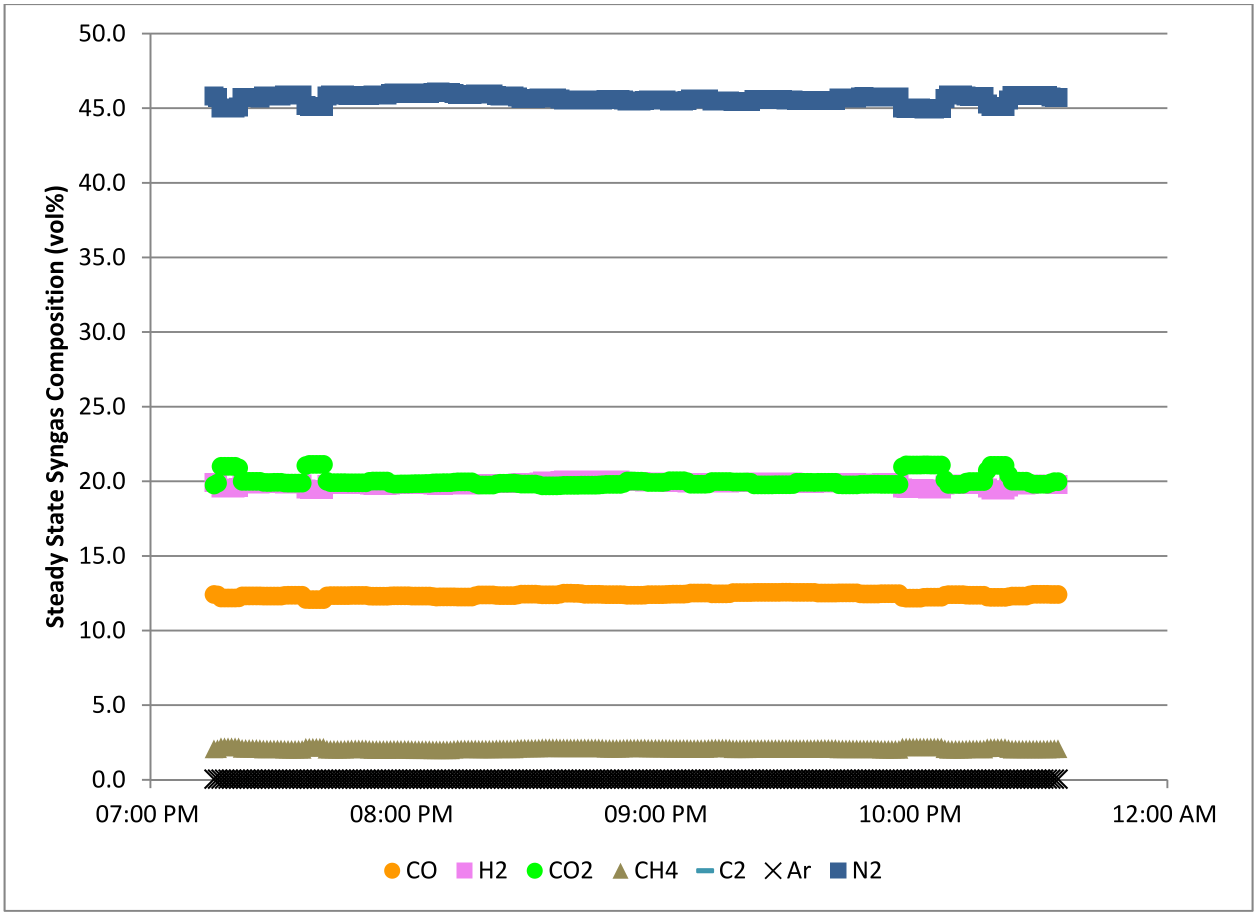

Figure G-10: SS Period 38 (NCCC-TRIG-20120907B) for Exiting Gas Composition

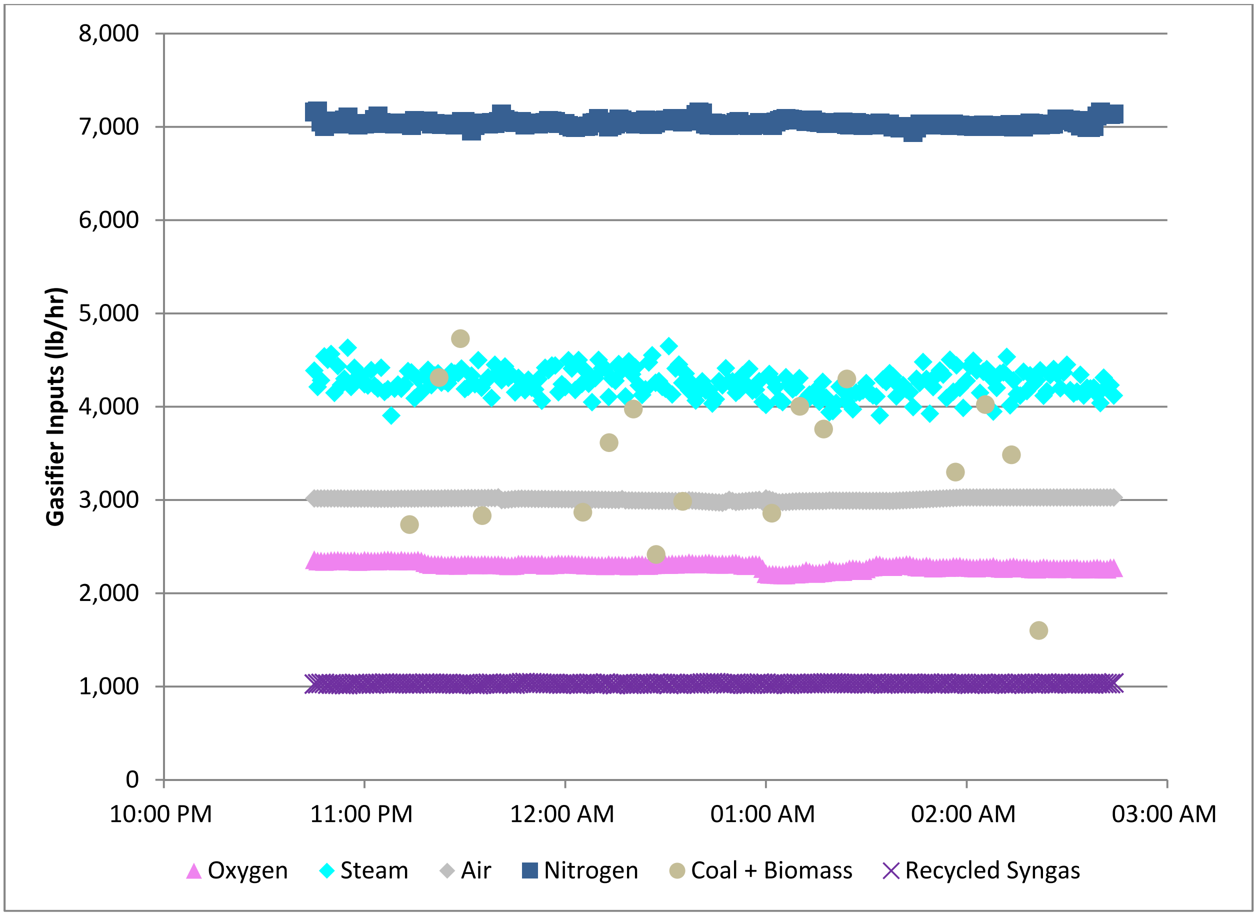

Figure G-11: SS Period 44 (NCCC-TRIG-20120913A) for Gasifier Inputs

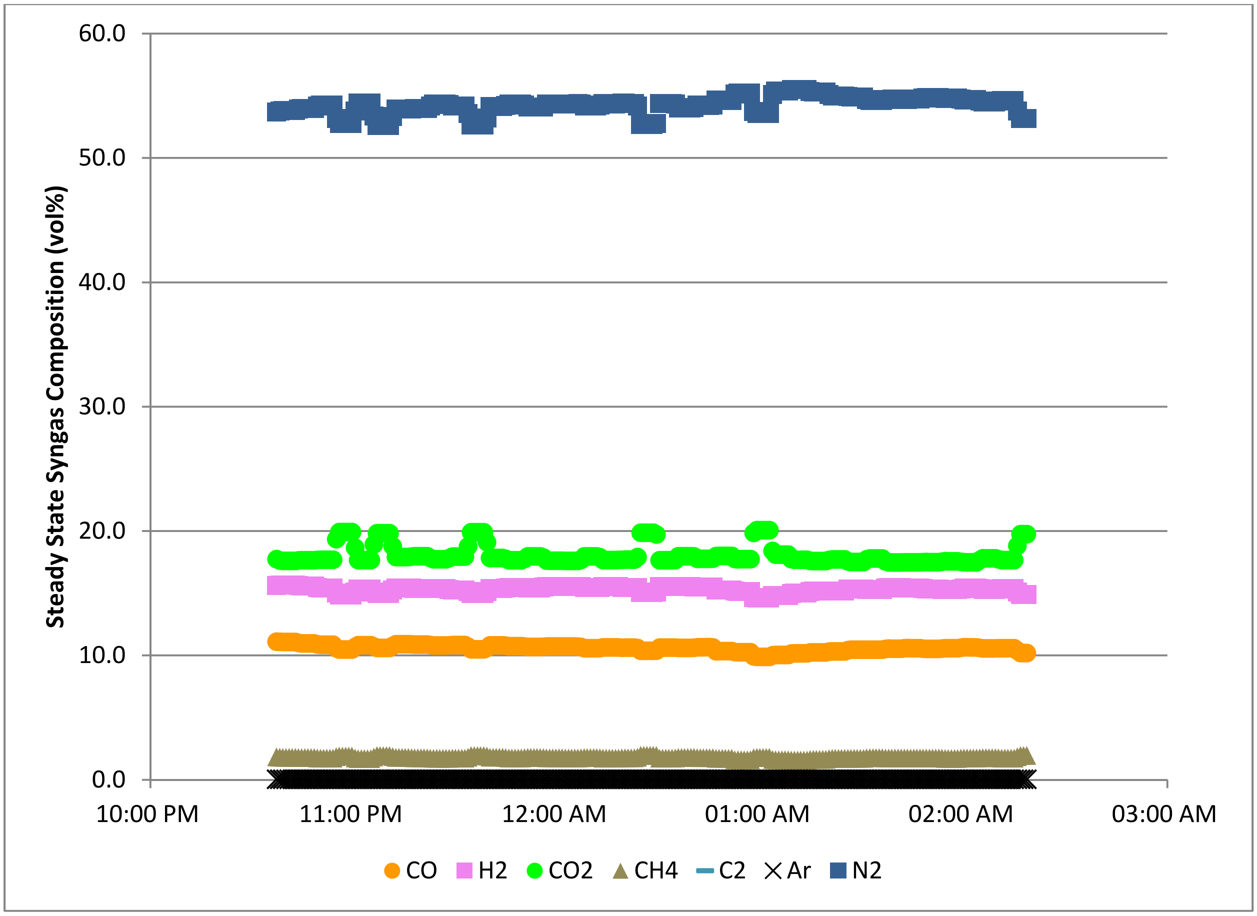

Figure G-12: SS Period 44 (NCCC-TRIG-20120913A) for Exiting Gas Composition

10% Tor

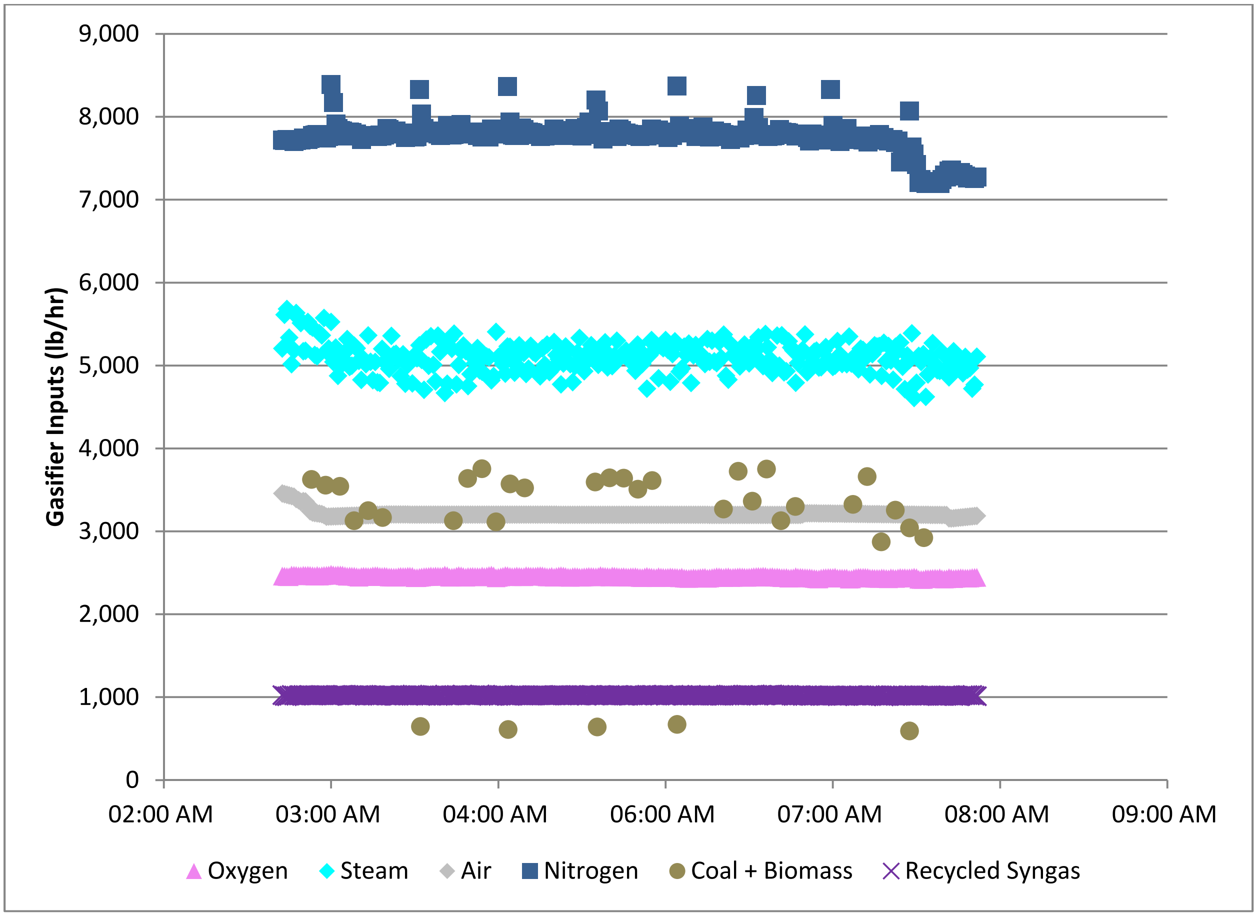

Figure G-13: SS Period 39 (NCCC-TRIG-20120910A) for Gasifier Inputs

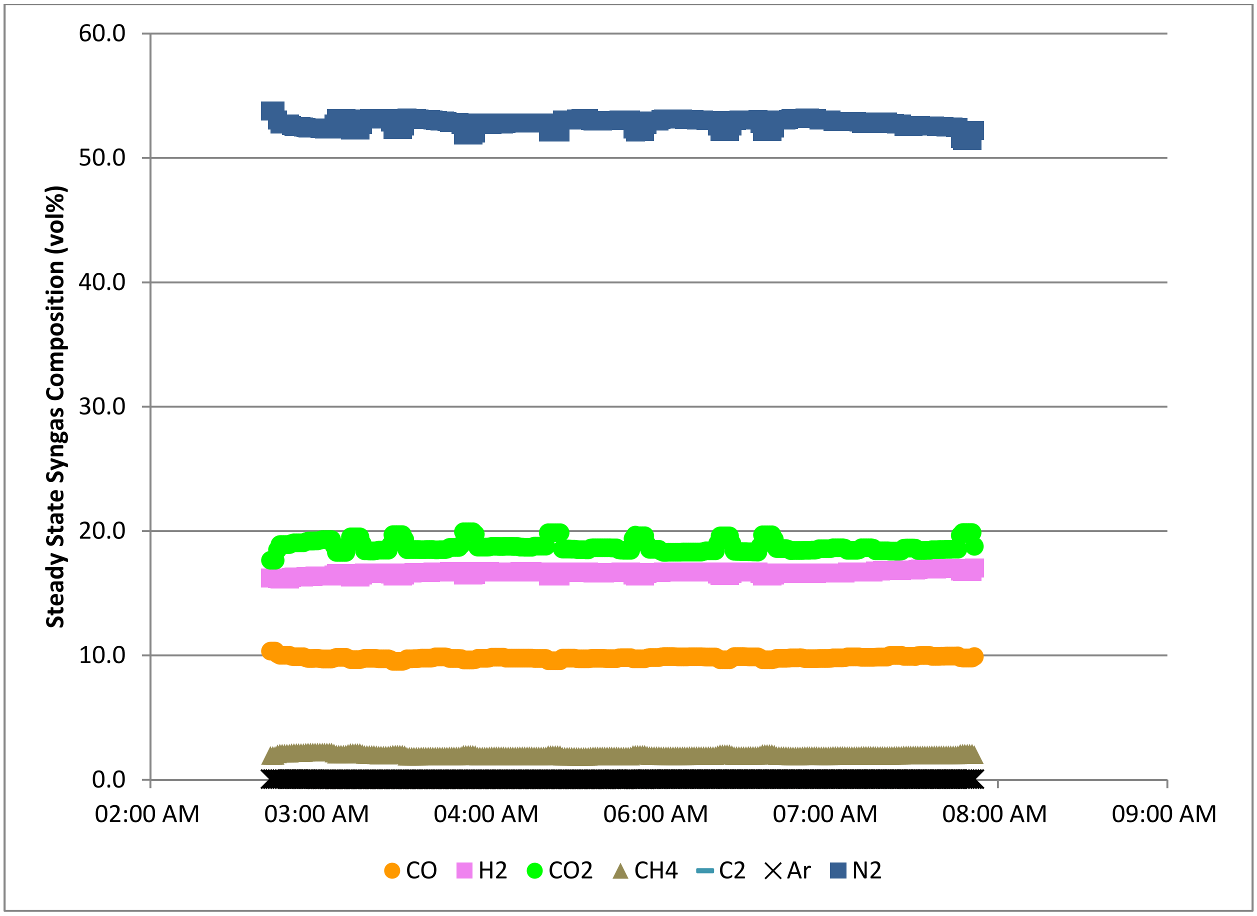

Figure G-14: SS Period 39 (NCCC-TRIG-20120910A) for Exiting Gas Composition

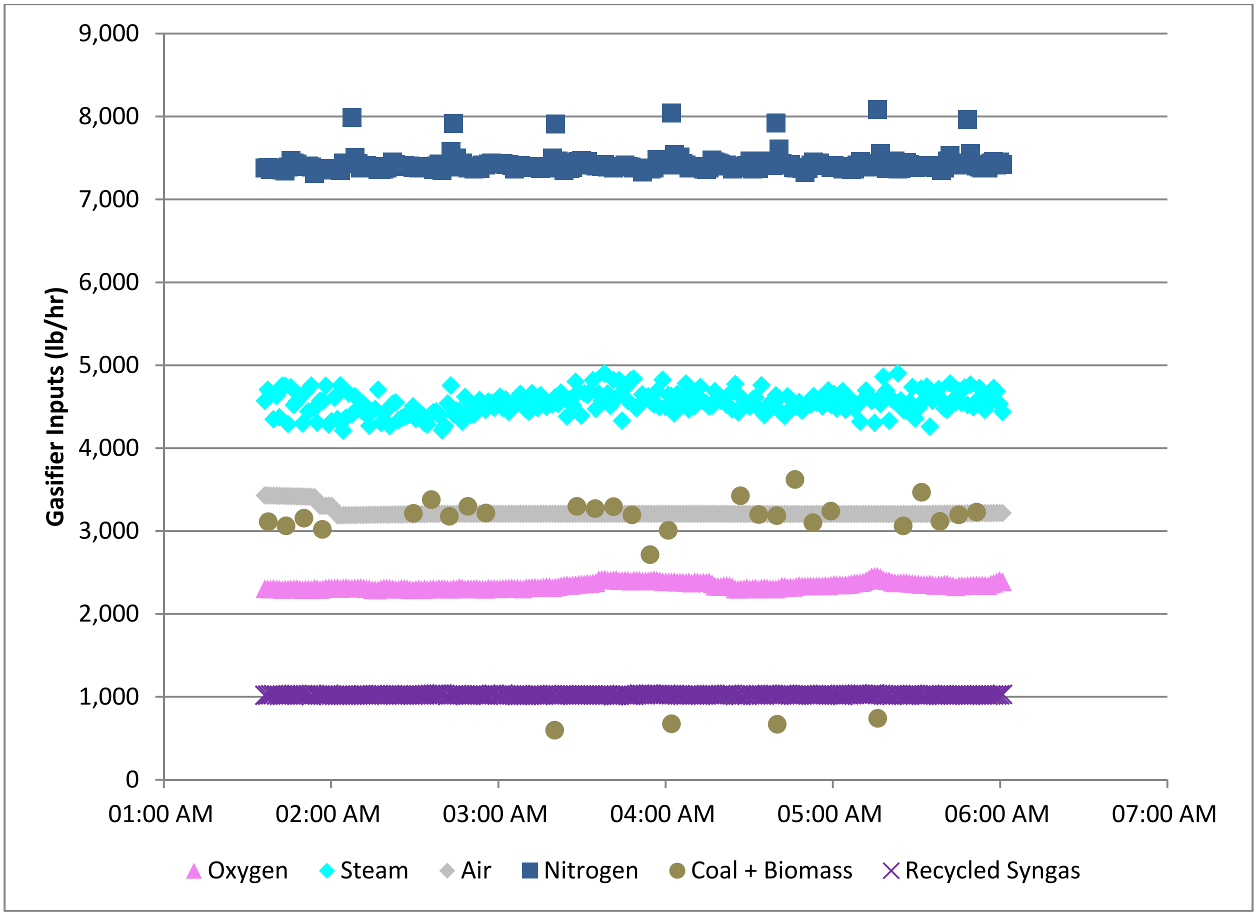

Figure G-15: SS Period 40 (NCCC-TRIG-20120911A) for Gasifier Inputs

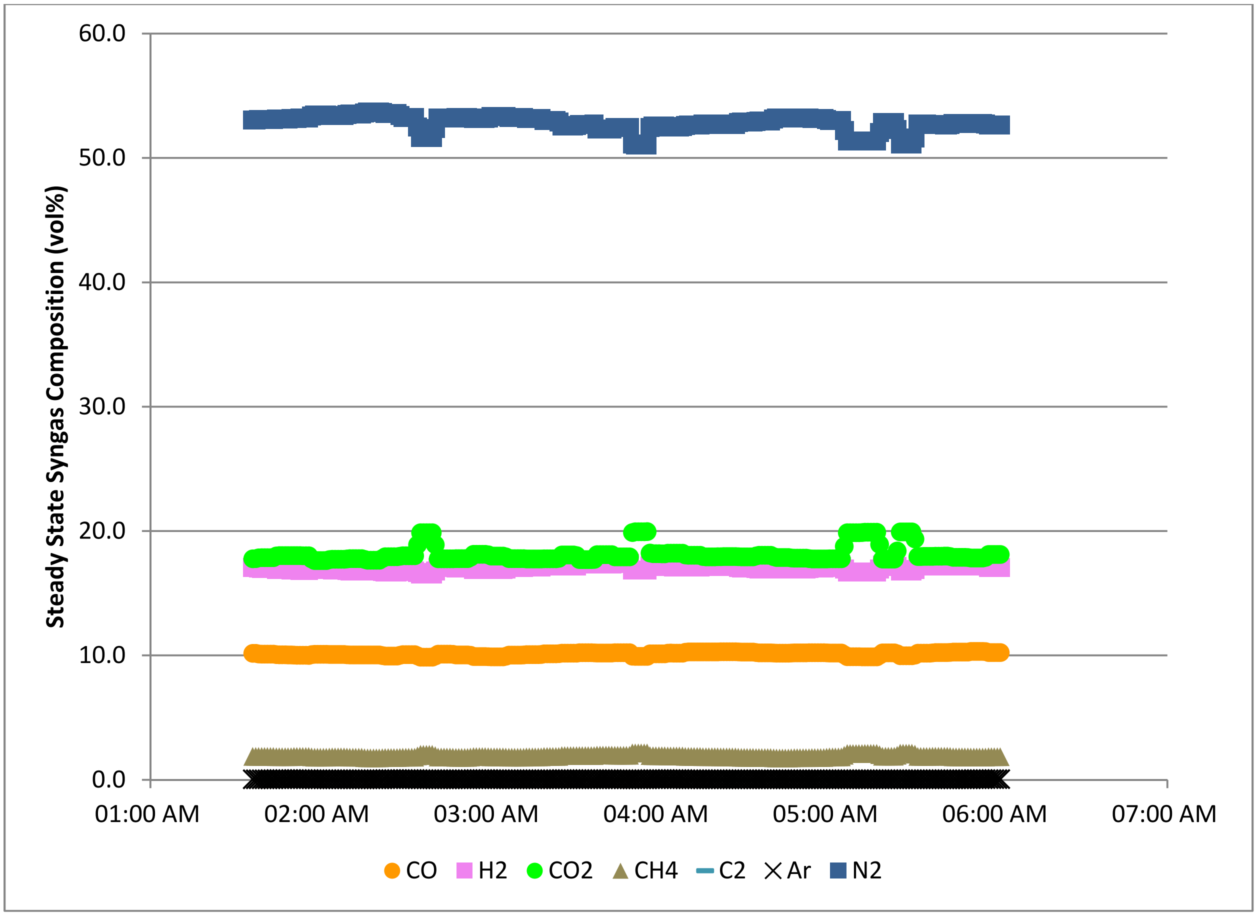

Figure G-16: SS Period 40 (NCCC-TRIG-20120911A) for Exiting Gas Composition

20% Tor

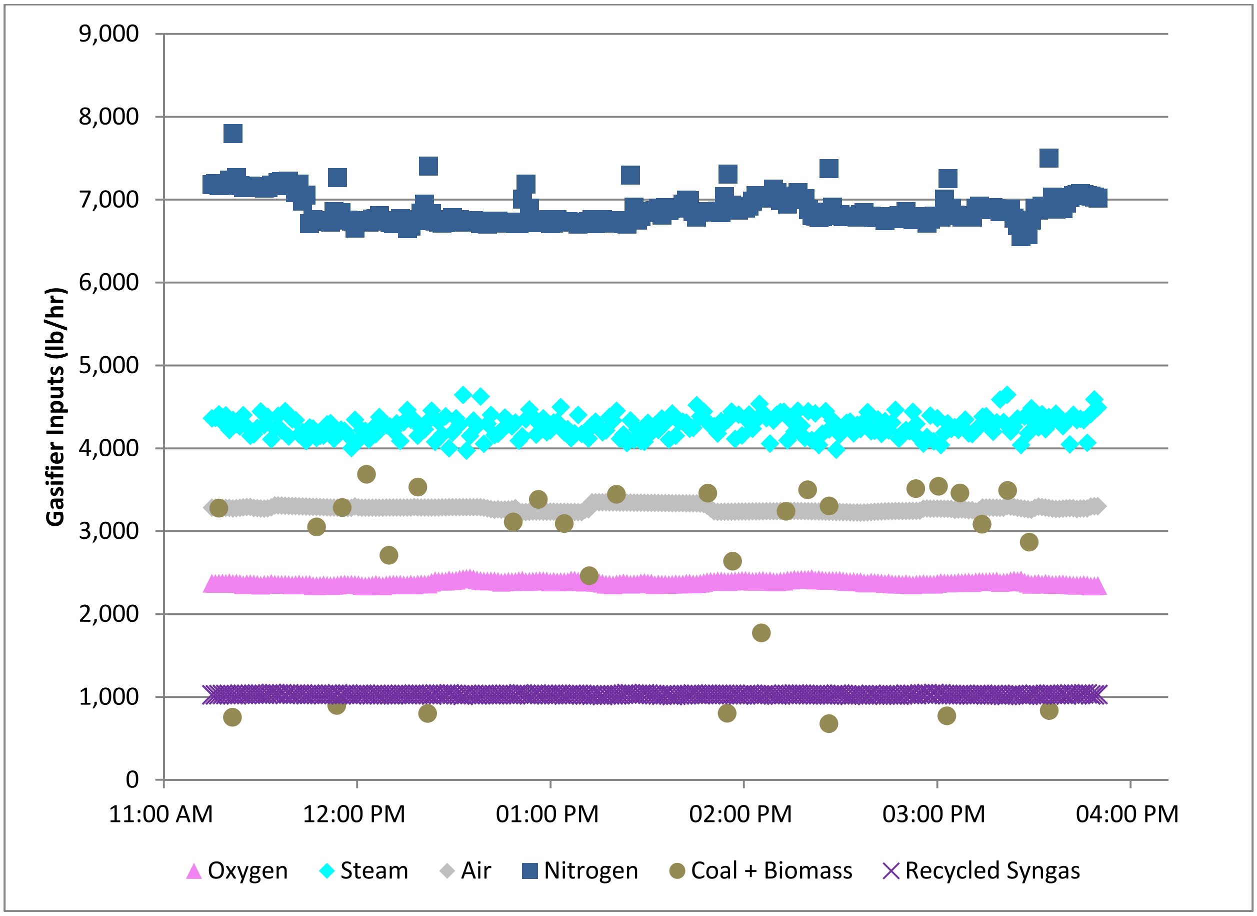

Figure G-17: SS Period 41 (NCCC-TRIG-20120911B) for Gasifier Inputs

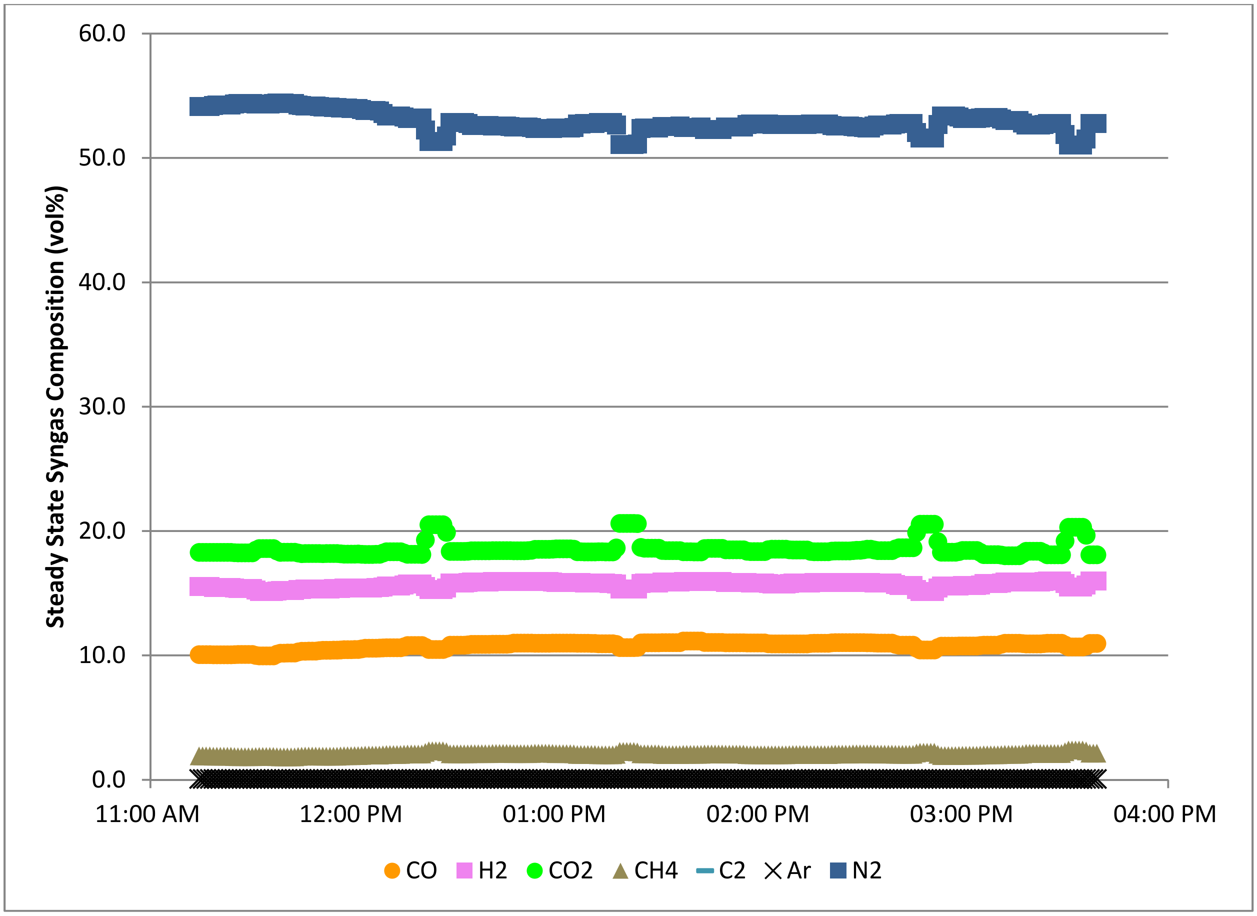

Figure G-18: SS Period 41 (NCCC-TRIG-20120911B) for Exiting Gas Composition

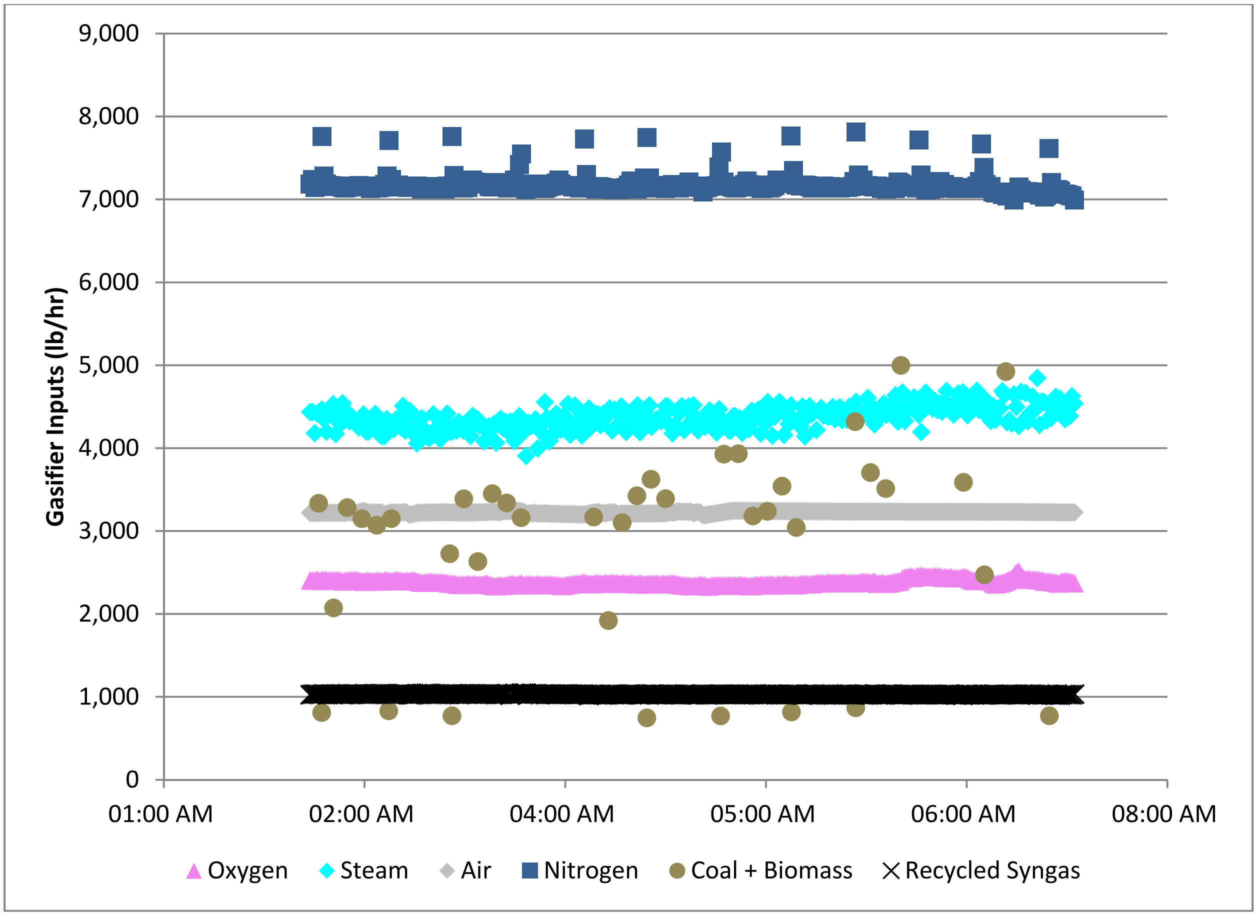

Figure G-19: SS Period 42 (NCCC-TRIG-20120912A) for Gasifier Inputs

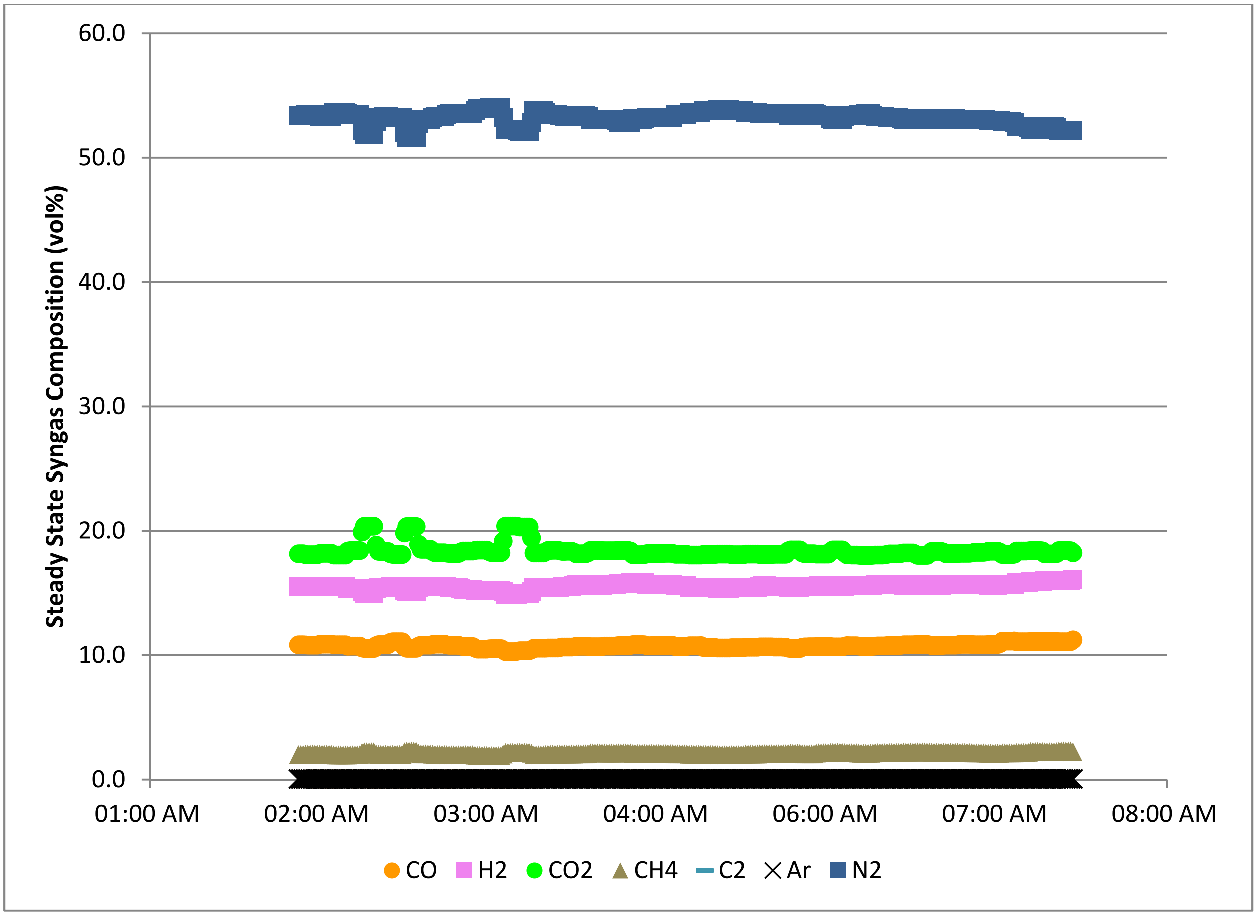

Figure G-20: SS Period 42 (NCCC-TRIG-20120912A) for Exiting Gas Composition

30% Tor

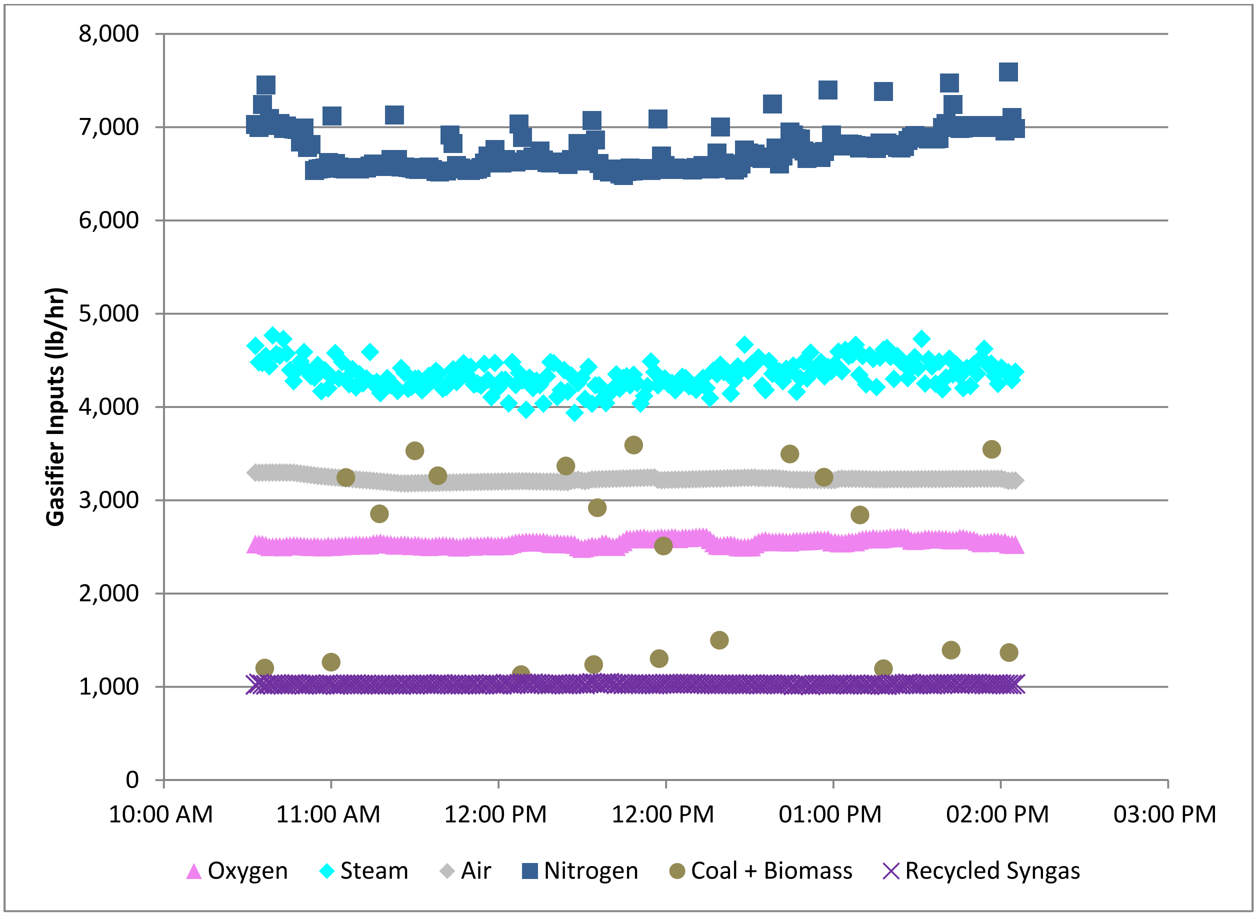

Figure G-21: SS Period 43 (NCCC-TRIG-20120912B) for Gasifier Inputs

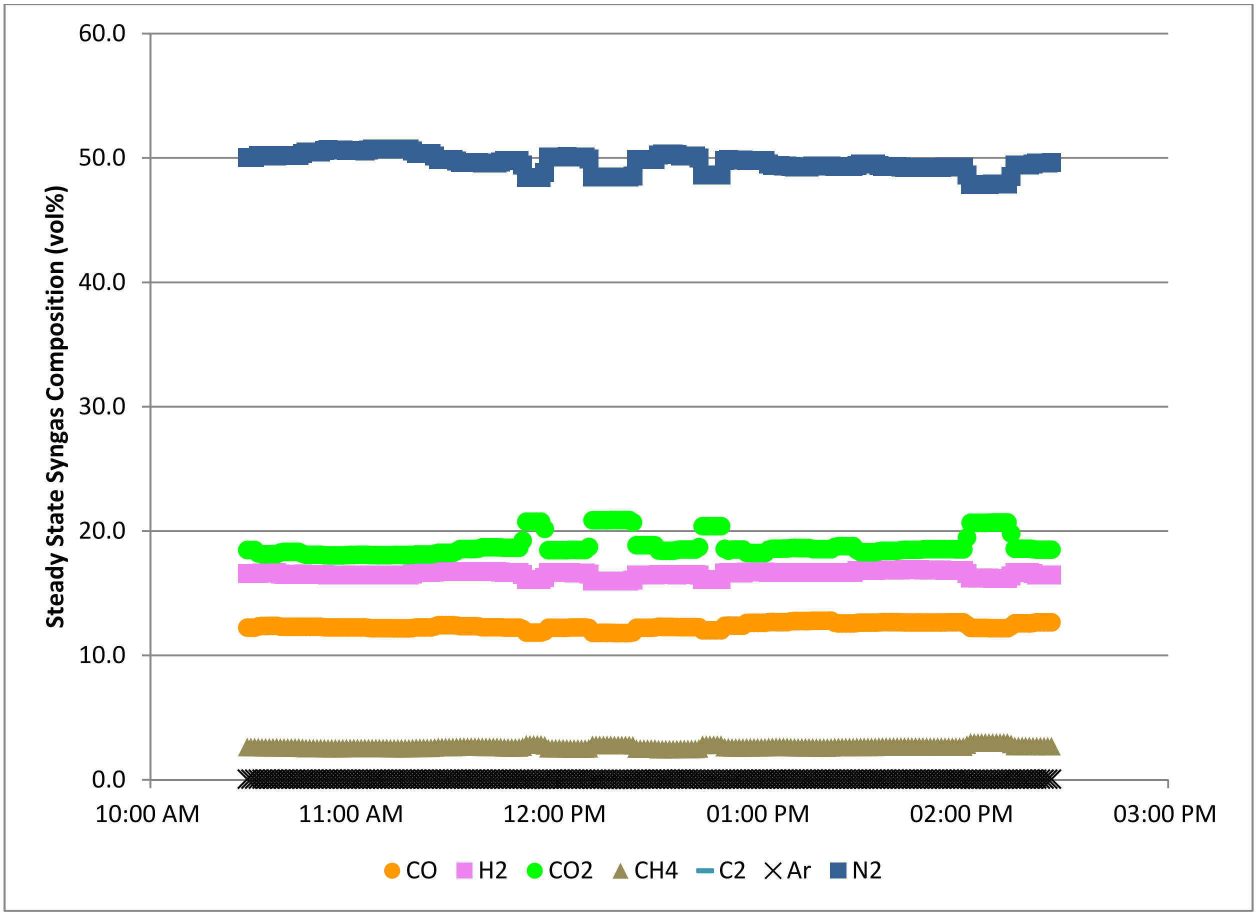

Figure G-22: SS Period 43 (NCCC-TRIG-20120912B) for Exiting Gas Composition

10% Raw

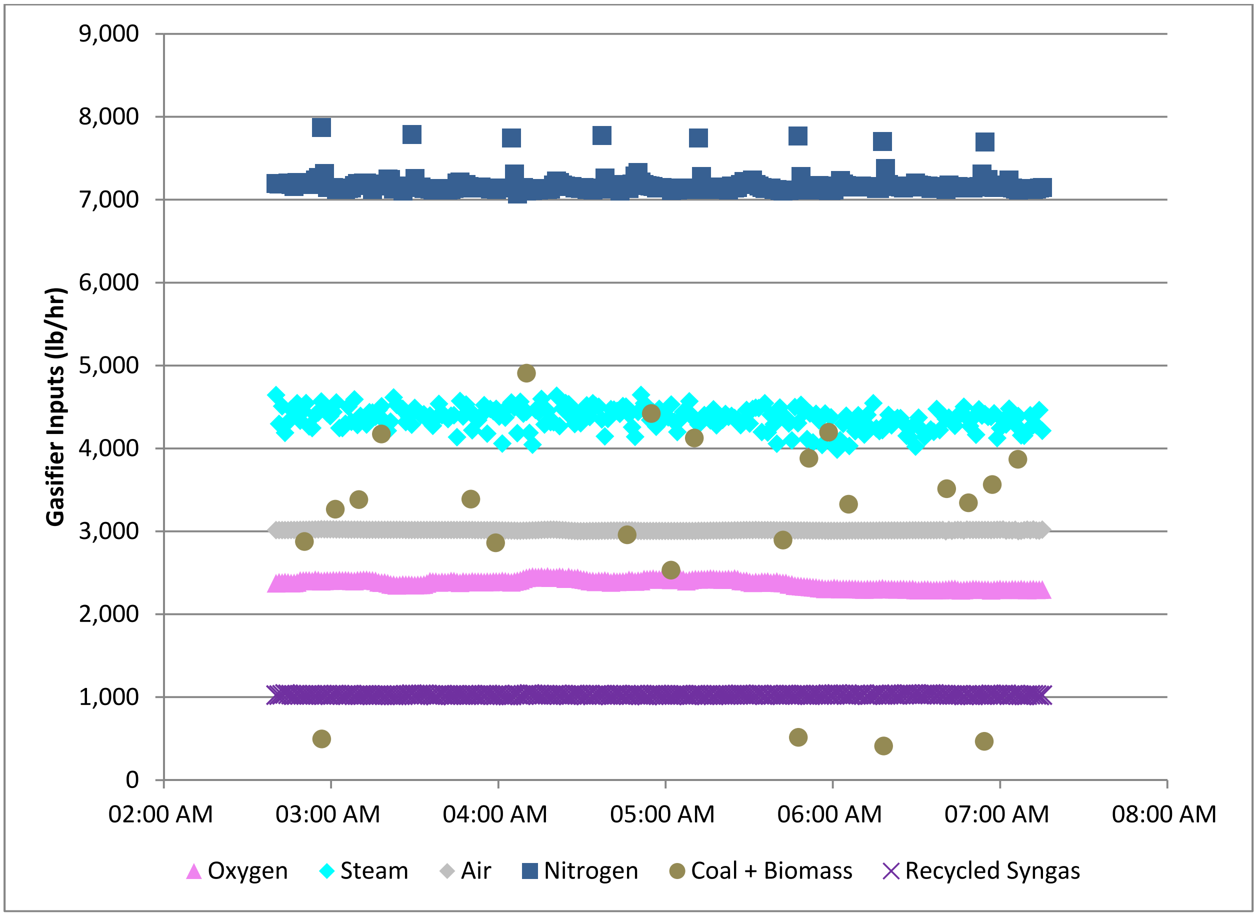

Figure G-23: SS Period 45 (NCCC-TRIG-20120915A) for Gasifier Inputs

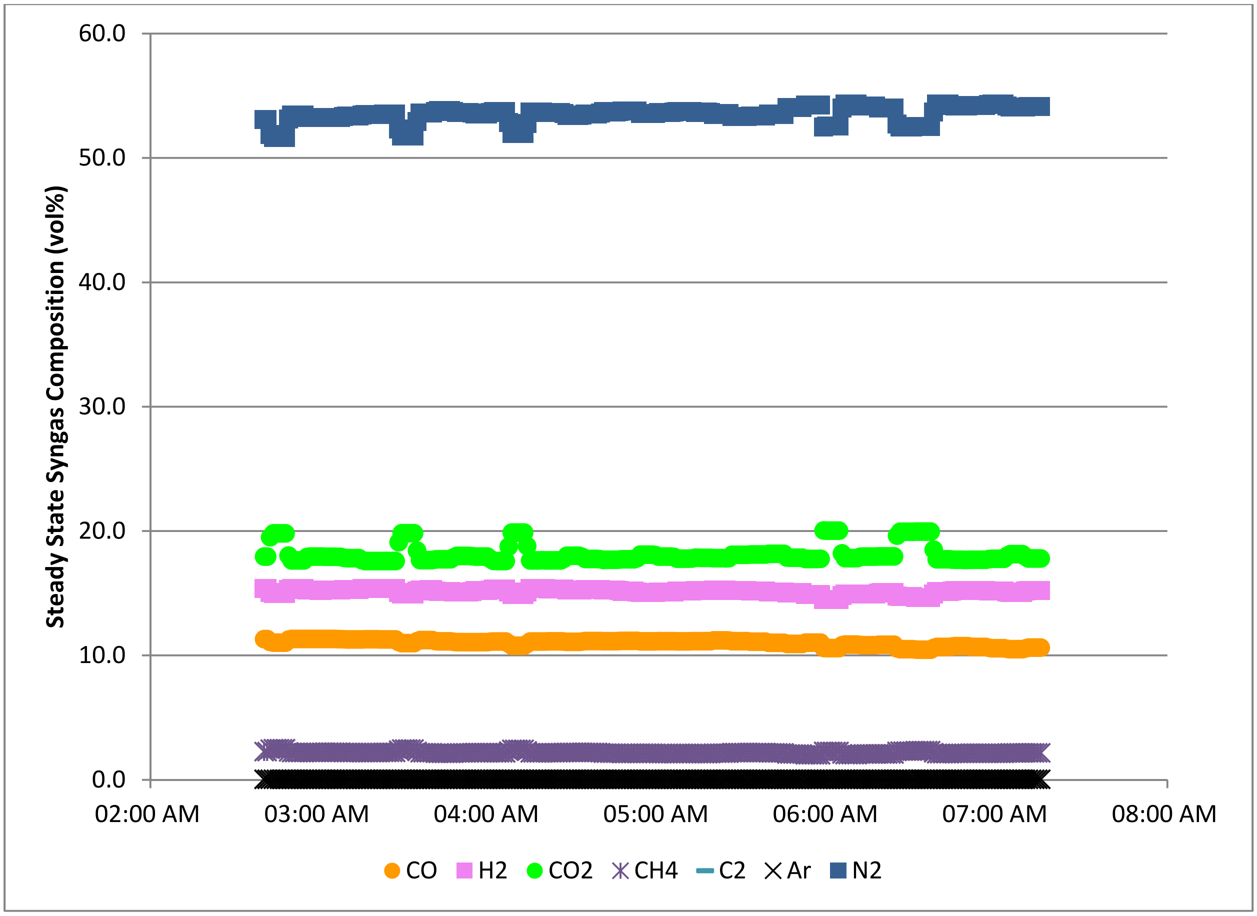

Figure G-24: SS Period 45 (NCCC-TRIG-20120915A) for Exiting Gas Composition

20% Raw

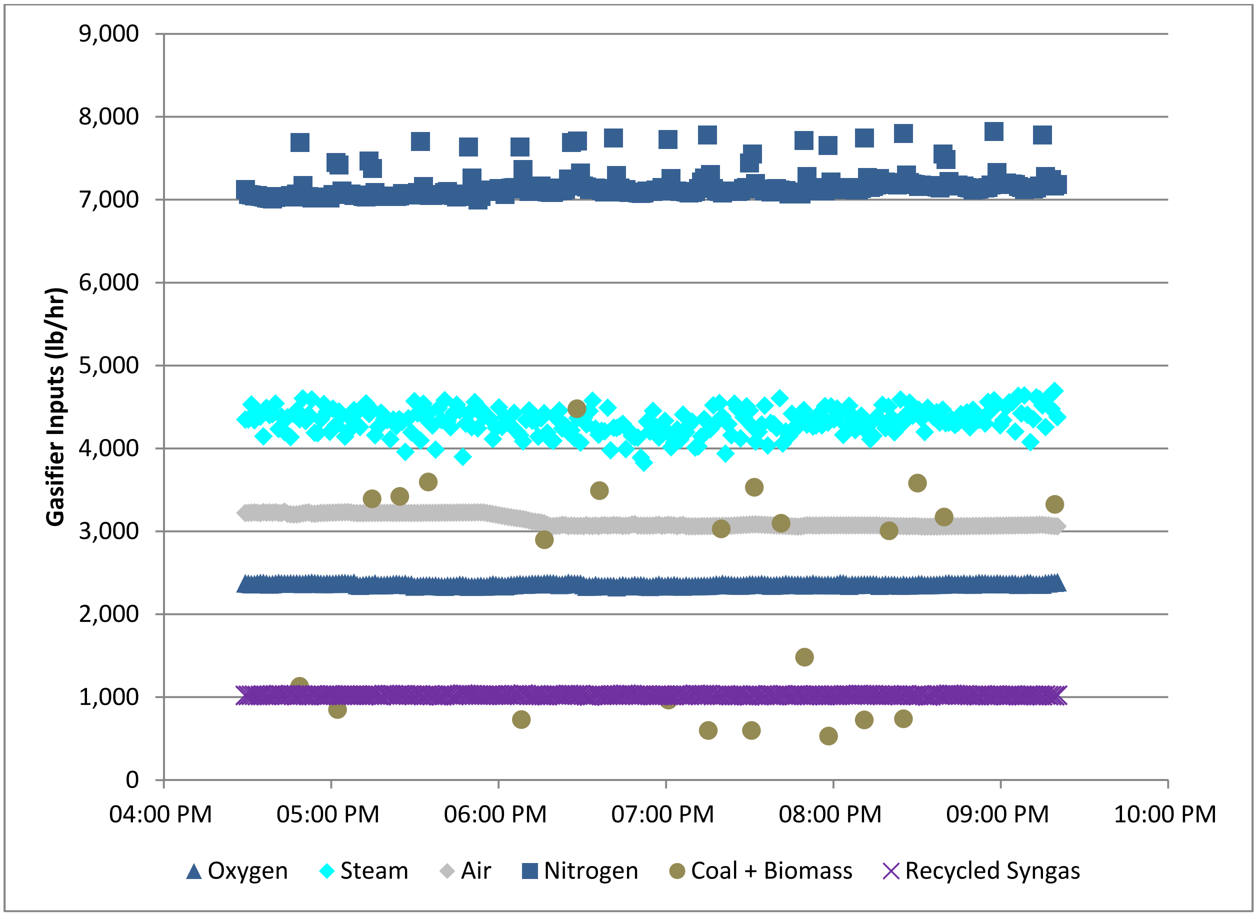

Figure G-25: SS Period 46 (NCCC-TRIG-20120915B) for Gasifier Inputs

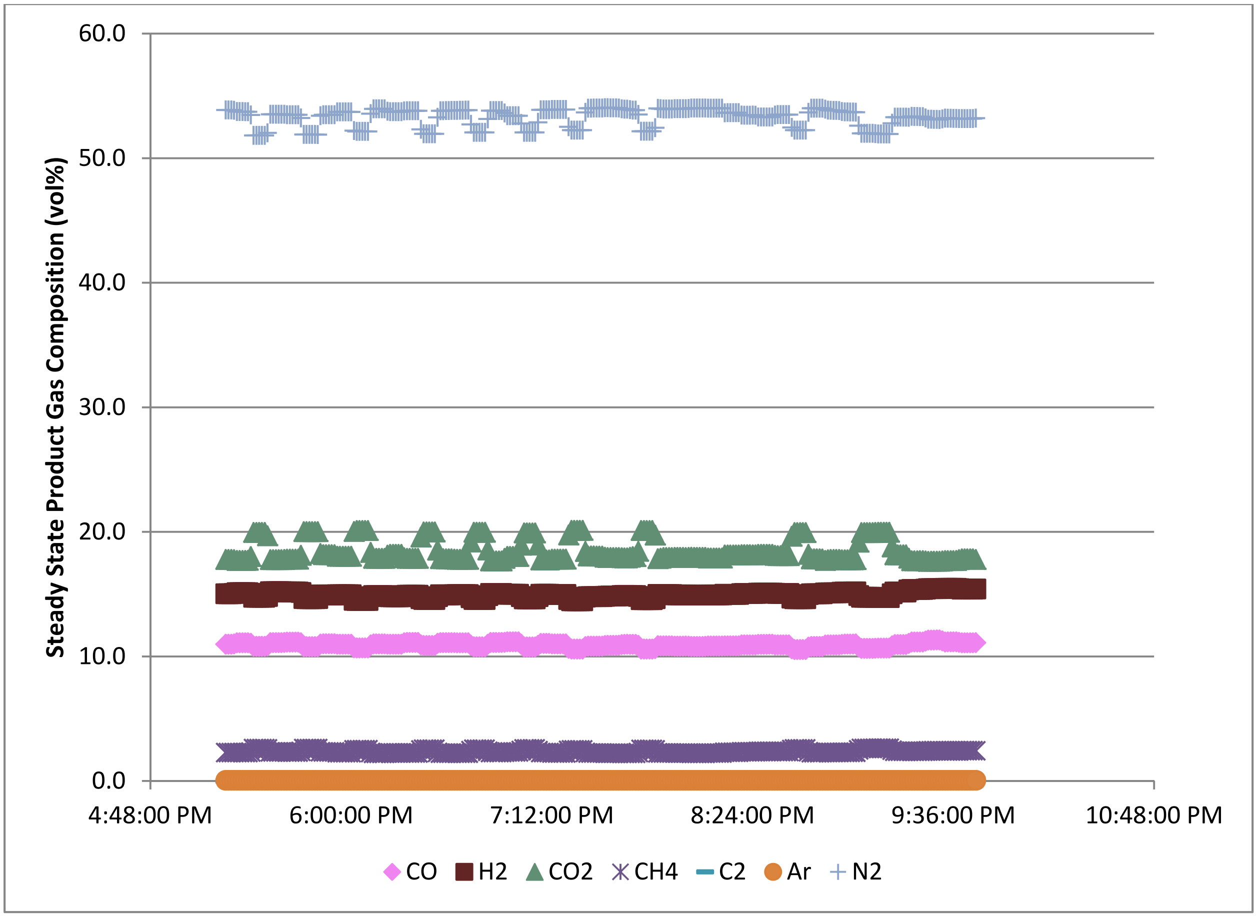

Figure G-26: SS Period 46 (NCCC-TRIG-20120915B) for Exiting Gas Composition

30% Raw

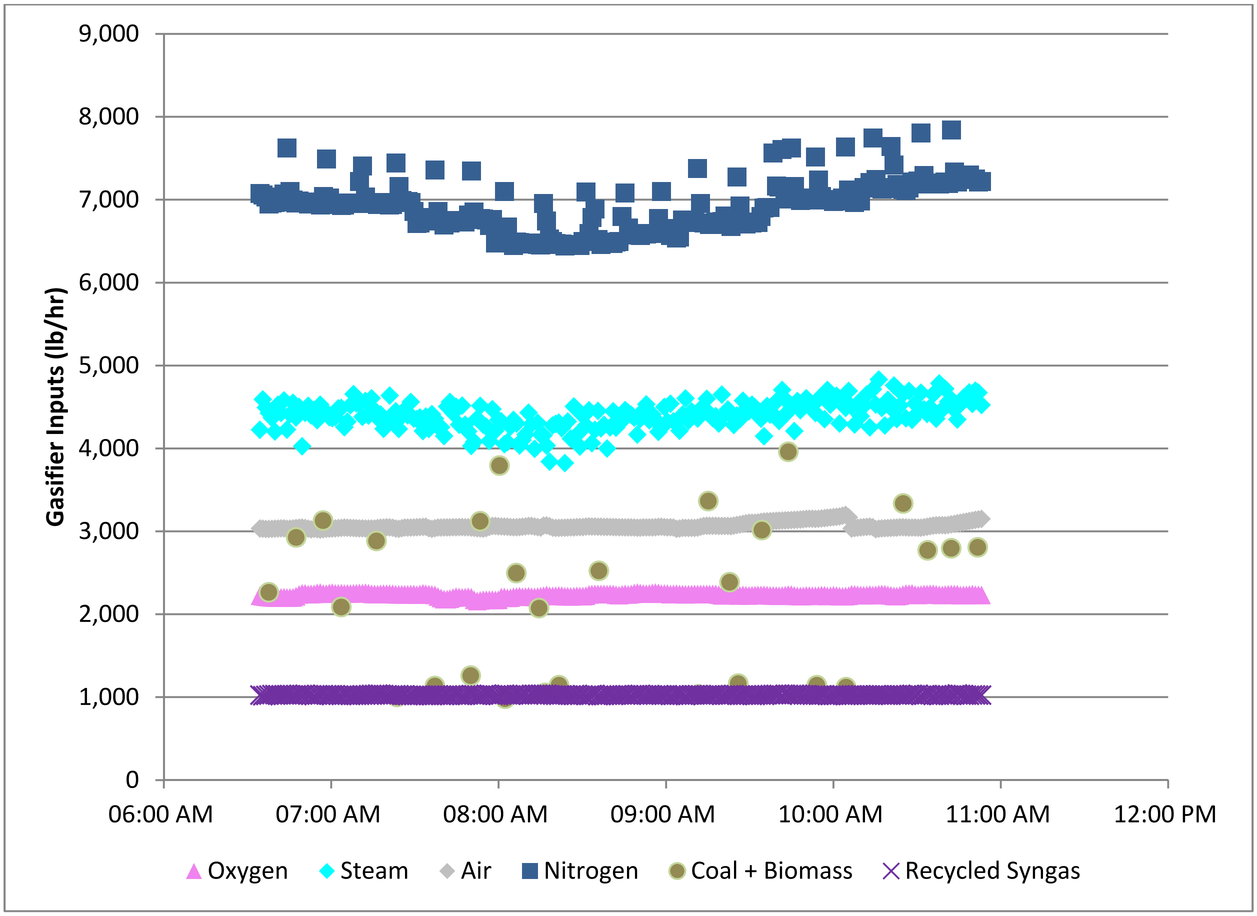

Figure G-27: SS Period 47 (NCCC-TRIG-20120917A) for Gasifier Inputs

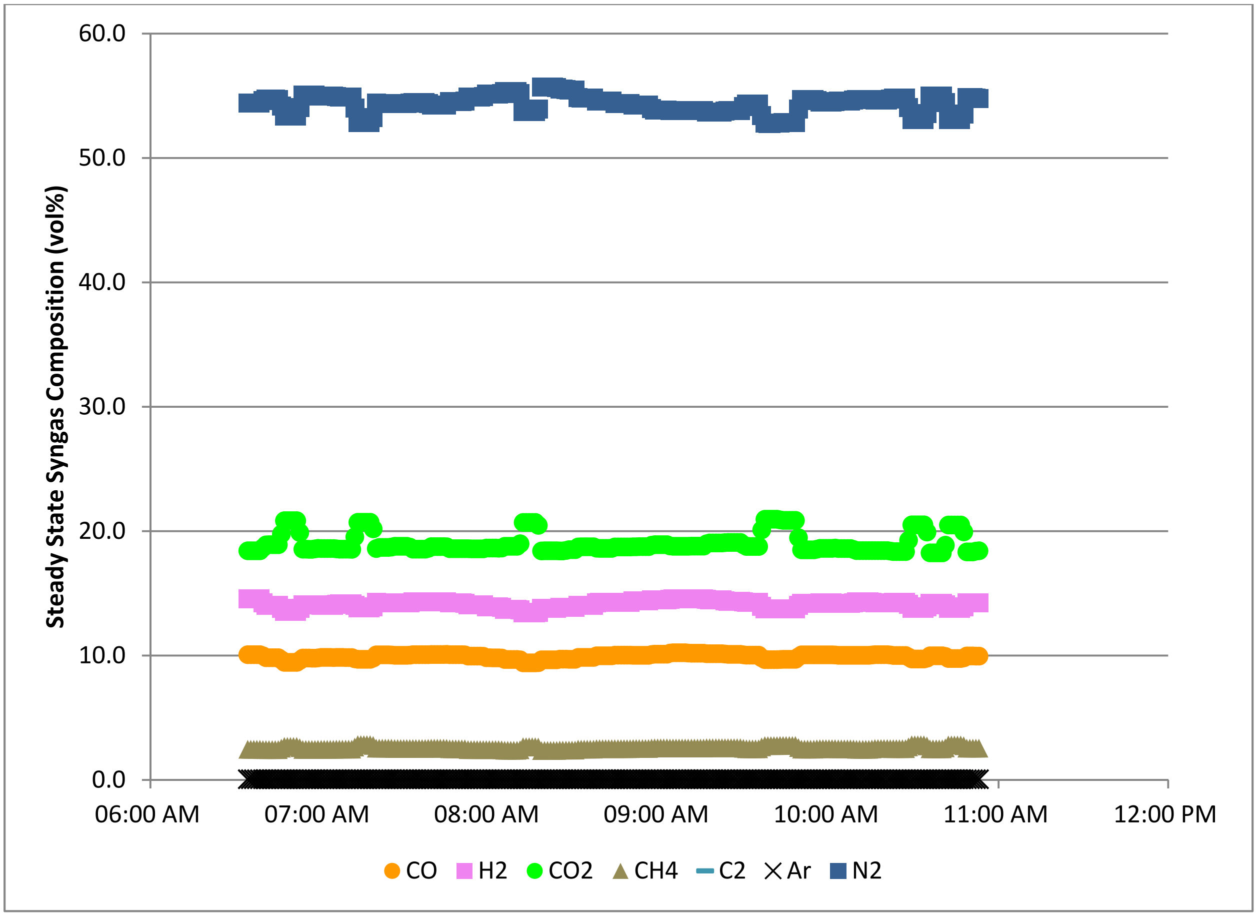

Figure G-28: SS Period 47 (NCCC-TRIG-20120917A) for Exiting Gas Composition

Appendix H: Gasifier Operation

As was done in **Error! Reference source not found.**, below are the summaries for the gasifier operation. These cases were not part of the main CCAT data set and as such were not reported in the body of the report. They have however, been reported here for completeness.

Table H-1: SS Period 34 (NCCC-TRIG-20120905A) average operational parameters for 100% coal air-blown test (pre-CCAT test)

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	62.0	27,219	13,756	0.0	8,097	201	1700.
Allowable Range	55.8 – 68.2	24,498 – 29,941	12,381 – 15,132	n/a	7,287 – 8,907	197 – 205	1649 – 1751
Observed Range	59.8 – 63.6	25,276 – 29,953	13,539 – 14,056	n/a	7,440. – 9,777	200 - 202	1681 - 1727

Table H-2: SS Period 35 (NCCC-TRIG-20120906A) average operational parameters for 100% coal air-blown test (pre-CCAT test)

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	64.1	26,703	13,744	0.0	7,573	201	1,691
Allowable Range	57.7 – 70.5	24,033 – 29,373	12,369 – 15,118	n/a	6,816 – 8,330	197 – 205	1,640. – 1,742
Observed Range	63.1 – 65.3	25,414 – 27,750.	13,642 – 13,871	n/a	7,435 – 8,243	200 – 202	1,674 – 1,708

Table H-3: SS Period 36 (NCCC-TRIG-20120906B) average operational parameters for 100% coal air-blown test (pre-CCAT test)

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	63.4	26,498	13,622	0.0	7,520	201	1,694
Allowable Range	57.0 – 69.7	23,849 – 29,148	12,259 – 14,984	n/a	6,768 – 8,272	197 - 205	1,643 – 1,745
Observed Range	62.4 – 64.2	24,840. – 27,691	13,561 – 13,765	n/a	7,389 – 8,201	200 - 202	1,684 – 1,708

Table H-4: SS Period 37 (NCCC-TRIG-20120907A) average operational parameters for 100% coal oxygen-blown test

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	114	17,539	2,974	2,258	6,642	160	1,702
Allowable Range	102 -125	15,785 – 19,293	2,676 – 3,271	2,032- 2,484	5,977 – 7,306	157 – 163	1,651 – 1,753
Observed Range	111 – 117	16,207 – 18,938	2,941 – 3,020.	2,050. -2,325	5,707 – 7,866	159 – 161	1,673 – 1,720.

Table H-5: SS Period 38 (NCCC-TRIG-20120907B) average operational parameters for 100% coal oxygen-blown test

	Dry Product Gas LHV	Gasifier Product Gas Flow Rate	Gasifier Air Flow Rate	Gasifier O_2 Flow Rate	Gasifier N_2 Flow Rate	Gasifier Outlet Pressure	Gasifier Exit Temperature
	Btu/SCF	*lb/hr*	*lb/hr*	*lb/hr*	*lb/hr*	*psig*	*°F*
Average	113	17,428	2,989	2,263	5,818	160	1,711
Allowable Range	102 - 124	15,685 – 19,170.	2,690. – 3,288	2,036 – 2,489	5,236 – 6,400.	157 - 163	1,660. – 1,762
Observed Range	112 - 114	16,410. – 18,430.	2,973 – 3,027	2,235 – 2,315	5,752 – 5,917	159 - 161	1,691 – 1,734