THE NATIONAL CARBON CAPTURE CENTER
AT THE POWER SYSTEMS DEVELOPMENT FACILITY

TEST RUN SUMMARY REPORT

TEST RUN R08
JUNE 25, 2012 – SEPTEMBER 18, 2012

DOE COOPERATIVE AGREEMENT
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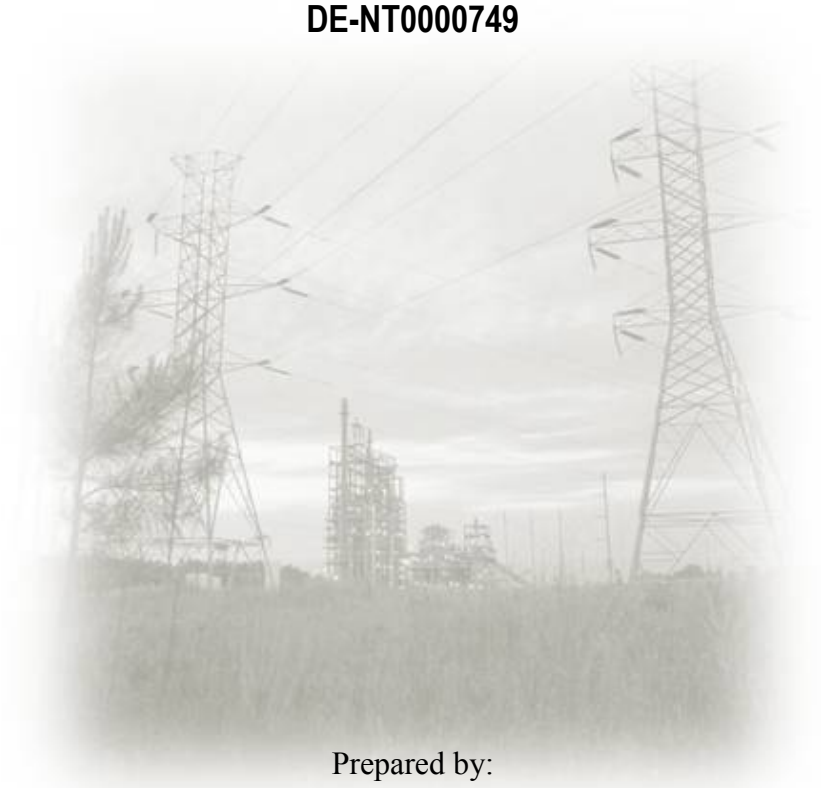

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LIST OF ABBREVIATIONS

CCAD—Continuous Coarse Ash Depressurization
CCAT—Connecticut Center for Advanced Technology
CFAD—Continuous Fine Ash Depressurization
CMS—Carbon Molecular Sieve
DOE—Department of Energy
NCCC—National Carbon Capture Center
MPT—Media & Process Technology
MTR—Membrane Technology & Research
PCD—Particulate Control Device
PDAC—Pressure Decoupled Advanced Coal
PRB—Powder River Basin
PSDF—Power Systems Development Facility
R01 through R10—Tests Runs 1 through 10
SCS—Southern Company Services
SCU—Syngas Conditioning Unit
WGS—Water-Gas Shift
WPI—Worcester Polytechnic Institute

1.0 EXECUTIVE SUMMARY

The Power Systems Development Facility (PSDF) is a key national asset for ensuring continued, cost-effective, environmentally acceptable energy production from coal. Sponsored by the U.S. Department of Energy (DOE), the PSDF is an engineering scale test center located in Wilsonville, Alabama. Since operation began in 1996, the PSDF staff has effectively developed advanced power systems, moving innovative technologies into the marketplace. Building on its previous success, PSDF now hosts the National Carbon Capture Center (NCCC) to address the nation's need for commercially viable CO_2 capture options for flue gas from pulverized coal power plants and syngas from coal gasification power plants.

Test run R08 commenced from June 25 through September 18, 2012, for a total run duration of 722 hours. The run was interrupted for two outages. The first outage occurred from July 3 through July 21 after attempts to resolve a blockage at the coarse ash discharge line resulted in a loss of gasifier solids inventory. The second outage occurred from July 26 through September 2 following a leak from the particulate control device (PCD). Improvements to coal feeder operation and gasifier temperature control were achieved during the run, and a variety of pre-combustion CO_2 capture-related technologies were tested. During the final portion of the run, 219 hours of oxygen-blown gasification testing were conducted with biomass co-feed for the Connecticut Center for Advanced Technology (CCAT).

2.0 COAL AND BIOMASS PREPARATION

The coal for R08 was Powder River Basin (PRB) sub-bituminous coal, which was processed in the mill system to achieve the desired moisture concentration and particle size distribution. A total of 1,600 tons of PRB coal were processed. Table 1 lists the average coal properties as-received and as-fed (after processing in the coal mill).

Table 1. PRB Coal Properties.

Coal Property	Average Value
As-Received Carbon, wt %	52.1
As-Received Hydrogen, wt %	3.5
As-Received Nitrogen, wt %	0.9
As-Received Sulfur, wt %	0.2
As-Received Ash, wt %	6.6
As-Received Oxygen, wt % (by difference)	12.1
As-Received Volatiles, wt %	42.3
As-Received Fixed Carbon, wt %	26.4
As-Received Heating Value, Btu/lb	8,960
As-Received Moisture Concentration, wt%	25
As-Fed Moisture Concentration, wt%	19
Moisture Content Reduction, %	24
As-Fed Mass Median Diameter, micron	302
As-Fed Oversize (>1,180 micron) Content, wt%	6
As-Fed Fine (< 45 micron) Content, wt%	13

In addition to coal, a total of 41 tons each of torrified and raw southern pine biomass pellets were processed. Table 2 lists the average biomass properties as-received and as-fed.

Table 2. Torrified and Raw Biomass Properties.

Biomass Property	Average Value (Raw)	Average Value (Torrified)
As-Received Carbon, wt %	48.5	57.5
As-Received Hydrogen, wt %	5.7	5.3
As-Received Nitrogen, wt %	0.02	0.3
As-Received Sulfur, wt %	0.06	0.01
As-Received Ash, wt %	1.2	1.8
As-Received Oxygen, wt % (by difference)	38.8	30.9
As-Received Volatiles, wt %	72.2	65.3
As-Received Fixed Carbon, wt %	20.3	28.8
As-Received Heating Value, Btu/lb	8,070	9,670
As-Received Moisture Concentration, wt%	6.3	4.2
As-Fed Moisture Concentration, wt%	8.0	7.7
Moisture Content Increase, %	27	83
As-Fed Mass Median Diameter, micron	990	536
As-Fed Oversize (>1,180 micron) Content, wt%	40.8	16.5
As-Fed Fine (< 45 micron) Content, wt%	1.0	7.2

The raw biomass pellets, shown in Figure 1, had been previously operated in the system during both the R03 and R04 test runs. However, this was the first operation utilizing torrified biomass, (see Figure 2). The torrified pellets had mill operational characteristics similar to PRB coal due to the breakdown of the wood fiber structure by the torrification process. The increase in moisture concentration of both forms of biomass after milling was unexpected. Two potential causes are exposure to ambient moisture prior to material processing and lower mill system exhaust gas flow (i.e., higher recycle gas flow) leading to higher moisture levels inside the mill system. However, no definitive conclusion has been reached at the time of this writing.

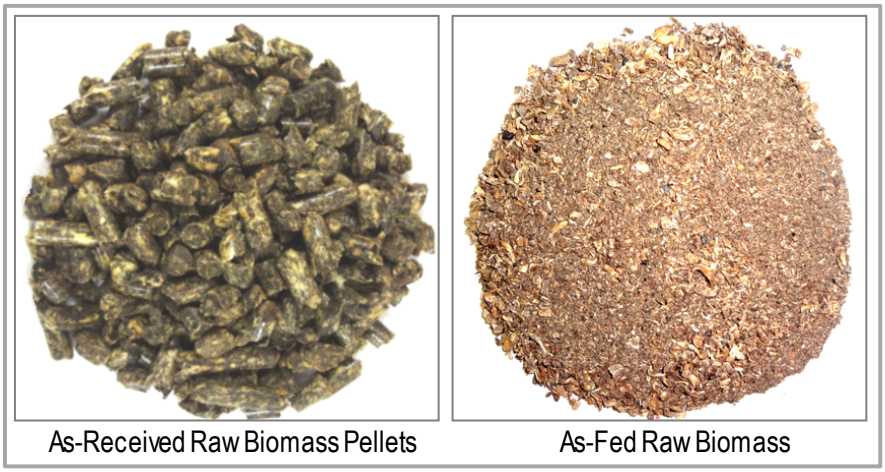

Figure 1. Raw Biomass Pellets for R08 Co-Feeding.

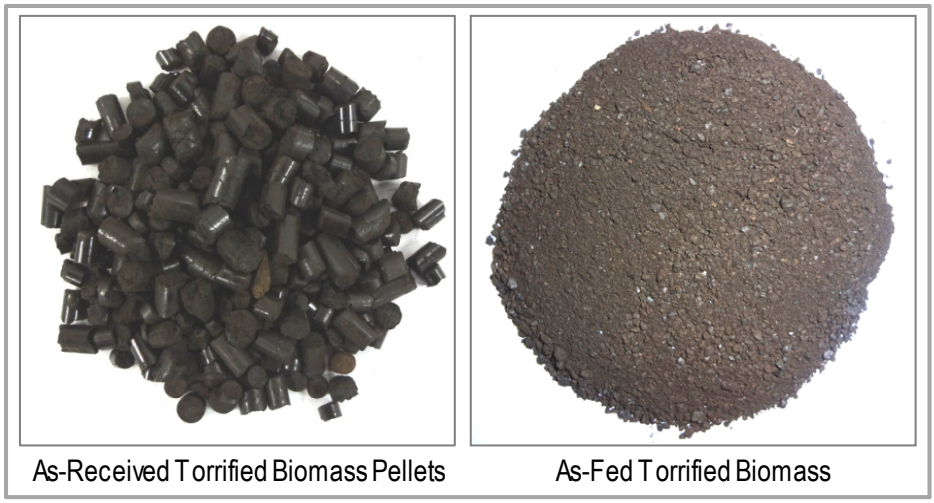

Figure 2. Torrified Biomass Pellets for R08 Co-Feeding.

Figure 3 provides the average particle size distributions for the three feedstocks, with the torrified biomass closely following the normal distribution for PRB coal.

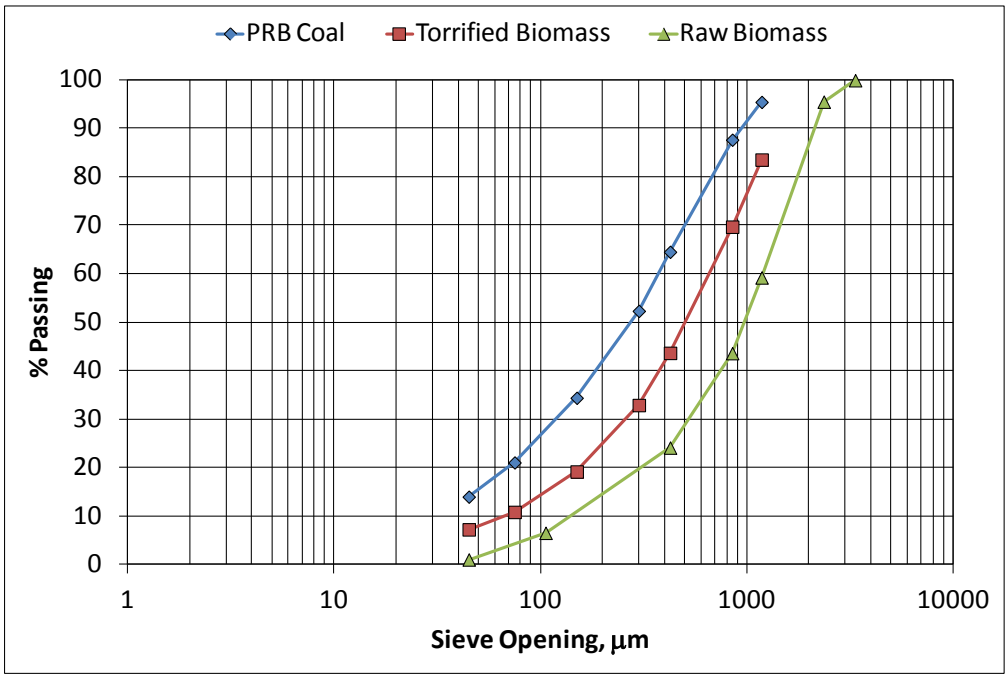

Figure 3. Particle Size Distribution Curves for R08 Gasifier Feedstocks.

3.0 COAL FEED

Both the developmental Pressure Decoupled Advanced Coal (PDAC) feeder and the original coal feeder operated during R08 without any major coal stoppages.

3.1 PDAC FEEDER

The PDAC feeder operated for 667 hours, including independent operations for 98 hours and 215 hours as the sole coal feeder during the oxygen-blown biomass co-feed test. The feeder operated at coal feed rates ranging from 500 to 3,600 lb/hr. Overall feeder performance during the run was stable over the range of coal feed rates tested.

PDAC Control Logic. Testing of previous control logic improvements continued during the R08 run. The coal feed rate trim controller continued to successfully maintain a consistent coal feed rate to the gasifier by changing the nitrogen feed rate to the feeder as necessary. This controller was especially important since the feeder functioned as the sole coal feeder during the biomass co-feed test. This run also marked the first time the PDAC feeder had been utilized during oxygen-blown gasifier operation. The gasifier pressure feedback controller installed previously permitted automatic adjustments to feeder pressure and nitrogen flow as gasifier pressure was reduced for oxygen-blown operation. (The reduction in gasifier operating pressure is necessary due to the supply pressure requirements of the oxygen supply system.) The adjustments made by the controller permitted the pressure differential between the feeder and the gasifier to be maintained at a constant level, keeping the coal feed rate constant as well.

Level Probes. Long-term evaluation of the Dynatrol vibration level probes continued during R08. The level probes were installed in the PDAC feeder dispense vessel and the lock vessel prior to the R02 test run, and have operated for more than 5,420 hours. The probes continued to demonstrate consistent solids level indication.

Evaluation of the Drexelbrook point sensitive level probe also continued during R08. The probe was vertically installed in the top of the PDAC feeder dispense vessel prior to the R04 test run to permit higher level control of the coal inventory in the vessel. Since installation, the probe has continually provided steady solids level control, mitigating the impact of solids level variation on coal feed rate. A total of 4,220 hours of operation has been achieved to date.

Coal Flow Meter. Testing of the DensFlow coal flow meter from SWR Engineering continued during the R08 run with higher coal feed rates being achieved than previous on-line operation due to the sole coal feeder operation. Previous performance of the device during R07 revealed a lower coal feed rate indication when compared to the feed rate calculated from the feeder weigh cells. Since the coal feed rate during that run averaged about 2,500 lb/hr, off-line testing was performed during the outage prior to R08 to see if higher feed rates would result in better agreement between the flow meter and weigh cell-calculated rate. However, during testing at the higher rates, the same discrepancy between the flow meter and the weigh cell calculated rates was observed. This also continued to be the case during the R08 run at higher coal feed rates to the gasifier during the biomass co-feed testing. As a result, data collected during the run will be shared with SWR Engineering personnel to determine what changes are necessary to address the difference.

3.2 ORIGINAL COAL FEEDER

The original rotary coal feeder operated on coal for 495 hours at feed rates varying from 1,000 to 1,575 lb/hr. The feeder was then transitioned to feed biomass for 148 hours at feed rates ranging from 470 to 1,300 lb/hr. Both torrified and raw forms of biomass were fed to the gasifier during testing at approximately 10, 20, and 30 wt% of the total mass feed rate to the gasifier. Biomass feed rate as a function of feeder speed is given in Figure 4. Overall feeder performance during the run was stable over the range of coal feed rates tested.

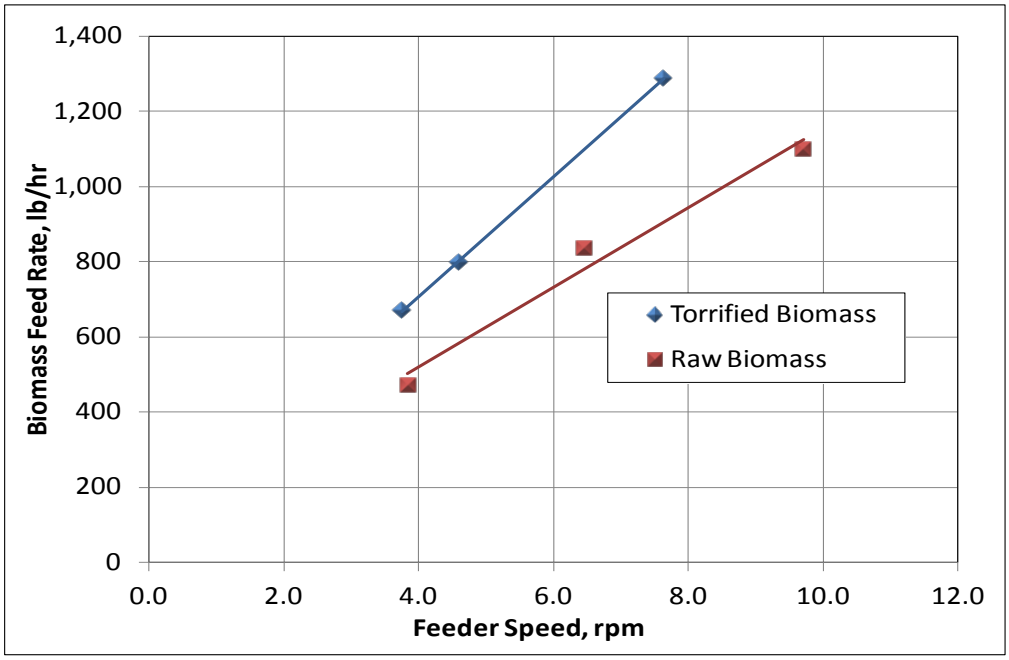

Figure 4. Biomass Feed Rate as a Function of Feeder Speed of Original Coal Feeder.

4.0 TRANSPORT GASIFIER

R08 operation consisted of 47 steady state operating periods, with recycled syngas utilized for gasifier fluidization for 46 of those steady state periods. In addition, a total of 11 steady state periods were achieved during oxygen-blown biomass co-feed testing conducted for CCAT. Gasifier operation during the run yielded high carbon conversions during both coal only and biomass co-feed operation, as shown in Table 3. The historical figures for carbon conversion represent data collected since completion of the 2006 gasifier modifications.

Table 3. Steady-State Carbon Conversion for R08 and Previous PRB Test Runs.

	Maximum	Minimum	Average
R08 PRB Coal Carbon Conversion, %	98.6	98.1	98.4
Historical PRB Coal Carbon Conversion, %	99.6	95.3	98.6
R08 PRB Coal/Biomass Carbon Conversion, %	98.9	97.9	98.3
Previous PRB Coal/Biomass Carbon Conversion, %	99.5	98.9	99.2

Figure 5 plots the maximum gasifier temperature (the mixing zone temperature), the outlet gasifier temperature and pressure, and the primary gas cooler outlet temperature during the steady state periods. The primary gas cooler operated as designed, with an outlet temperature of about 800°F during the run.

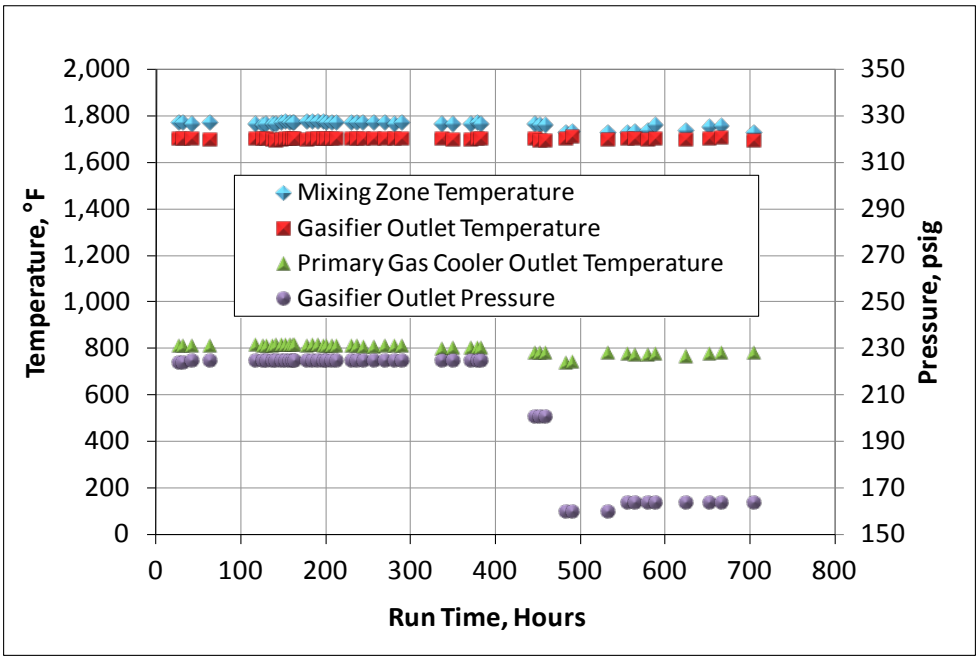

Figure 5. Gasifier Operating Conditions.

Sapphire Thermowell. Testing of the sapphire thermowell from Rosemount continued during R08. The thermocouple failed shortly after R08 began, and a post-run inspection showed that the assembly had broken. The failure will be further analyzed following the R09 run when the assembly can be removed from the gasifier and a new assembly installed.

NCCC staff has also been collaborating with Rosemount for further testing of sapphire thermowell assemblies, and preliminary plans were made to test different design modifications in R10. Test plans will be developed in greater detail after technology collaboration agreements are finalized.

Automated Temperature Control. Gasifier temperature control enhancements utilizing air flow adjustments from the gasifier upper and lower mixing zone continued during R08. The controller was only in service during the period leading up to the oxygen-blown biomass co-feed test for CCAT, but performed well during this period. Figure 6 illustrates the performance achieved by the controller. Gasifier temperature variation during the period was less than 5°F.

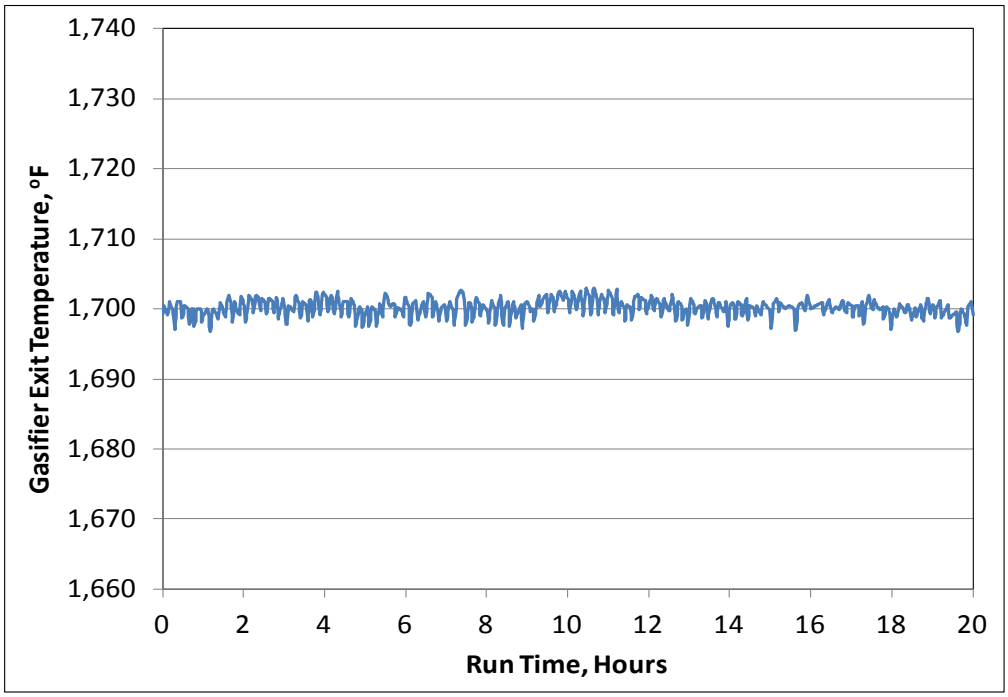

Figure 6. Gasifier Temperature Control Performance.

4.1 GASIFIER REFRACTORY INSPECTIONS

Gasifier system inspections did not reveal any areas of major concern. The new gasifier standpipe installed earlier this year continued to demonstrate excellent refractory performance. Figure 7 shows the condition of the standpipe refractory before and after the final portion of R08 testing during which biomass was used for co-feeding operation.

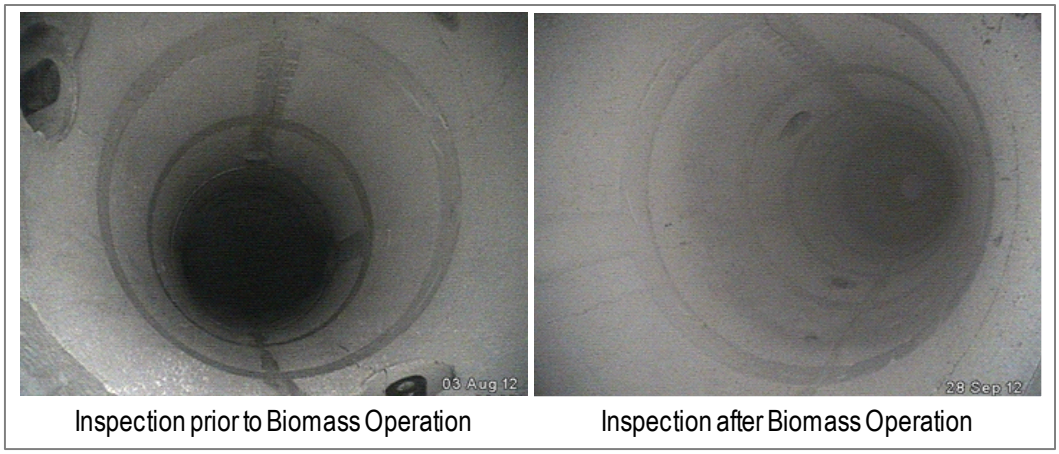

Figure 7. Inspections of Standpipe Refractory.

An area that is being closely monitored for refractory loss is the gasifier mixing zone and J-leg intersection (see Figure 8). Refractory wear in this area has been minimal since its initial

discovery following R07. A skin temperature monitoring system was installed to allow for real-time monitoring of the area during operations.

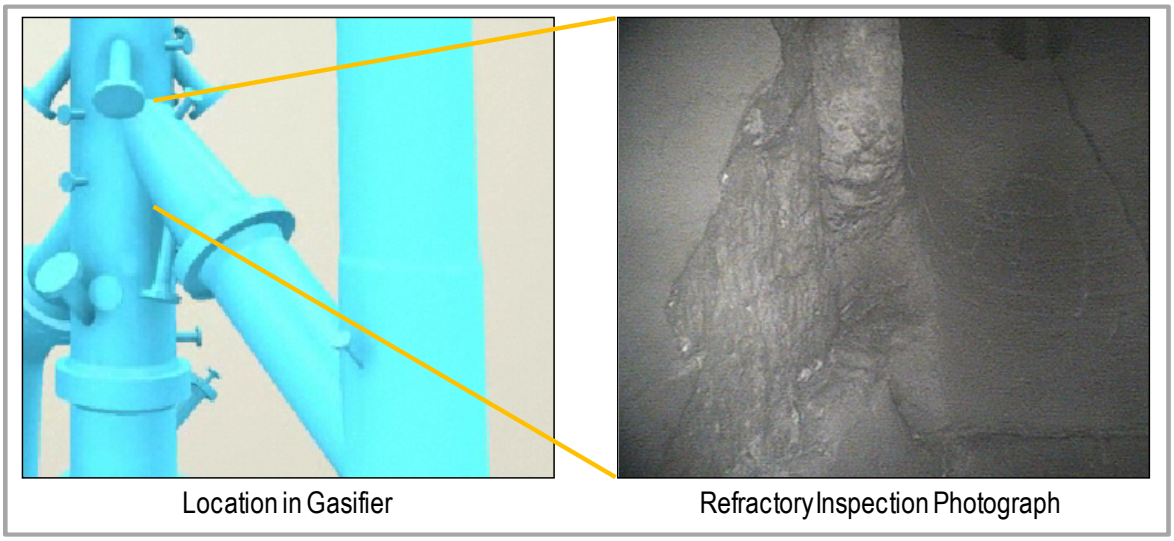

Figure 8. Inspections of Refractory in Mixing Zone and J-Leg Intersection.

5.0 PARTICULATE CONTROL DEVICE

Inspections of the PCD tubesheet were performed in August during the second R08 outage, and a significant crack was found in the tubesheet outer-ring to outer-cone weld, as shown in Figure 9. This is a structural weld that supports the weight of the tubesheet and plenum assemblies. Working with the original design engineer (Siemens Westinghouse), it was determined that the weld could be repaired. Construction and maintenance personnel made the repairs and reinstalled the PCD tubesheet at the end of August.

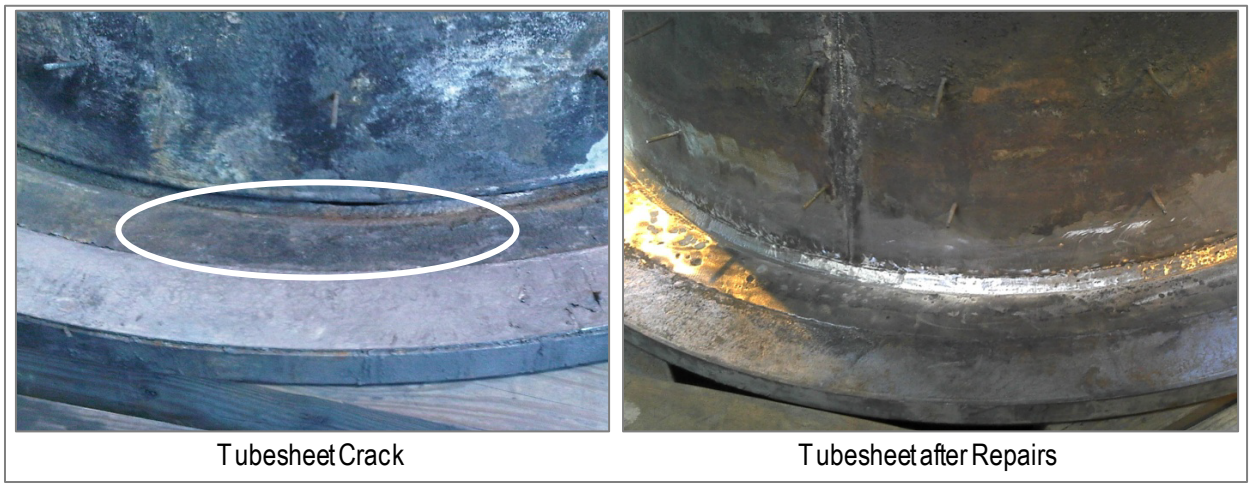

Figure 9. Inspections of PCD Tubesheet.

The PCD operated with a high collection efficiency and stable pressure drop following the tubesheet weld repair with particulate outlet loading typically less than 0.1 ppmw. Due to the compressed timeframe of the repair, the PCD plenums were re-installed using spare filter elements from the on-site inventory. The spare filter elements consisted of both new and used Iron Aluminide and HR160 elements from Pall and used sintered-fiber elements with an inert coating from Porvair. After completion of the R09 test, the filter elements installed in the PCD prior to the tubesheet failure, that have the most hours of run time, will be re-installed in order to continue long-term material evaluation. Most of the failsafes were cleaned and re-installed including Pall Dynalloy devices constructed of forward (supporting screen on the inner surface of the failsafe) and reverse structures (supporting screen on the outer surface), as well as PSDF-designed devices constructed of HR-160 material.

6.0 ASH REMOVAL SYSTEMS

Both the Continuous Coarse Ash Depressurization (CCAD) and Continuous Fine Ash Depressurization (CFAD) systems operated well during R08. The change in piping configuration to eliminate intermediate transport equipment for the CFAD system, installed prior to R03, continued to maintain the high reliability that has historically been demonstrated by the system. Following the discharge blockage that occurred in the CCAD system resulting in an outage early in the run, a modification is currently being developed to create greater operational flexibility and safety during runs and to eliminate intermediate transport equipment as was previously completed for the CFAD system. The ash removal systems operated over a range of particle size distributions during both the coal only and coal/biomass feed periods as shown in Figure 10.

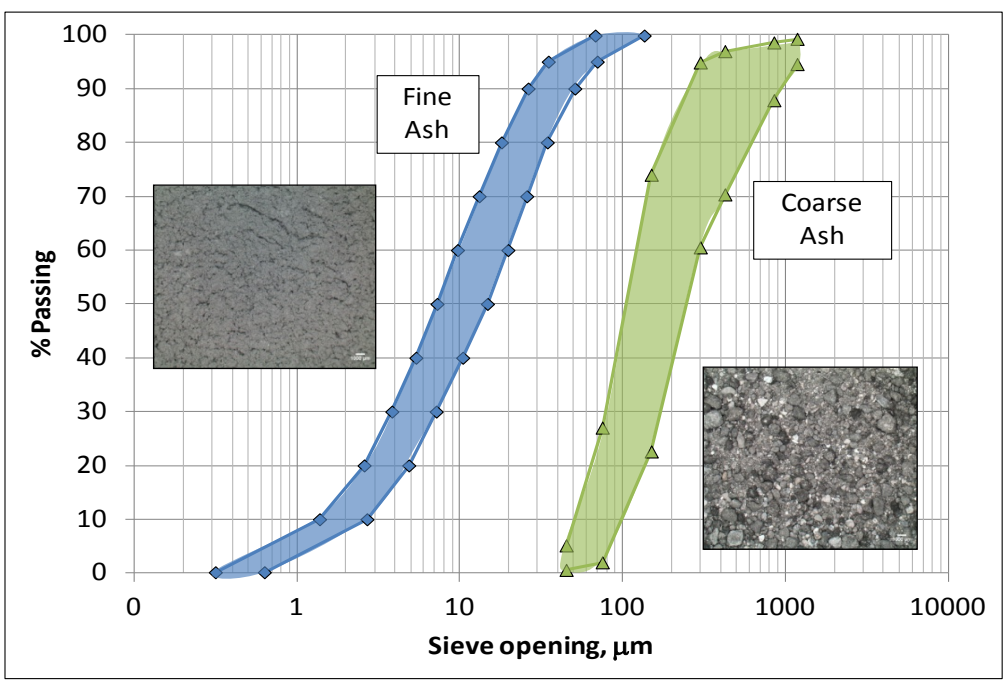

Figure 10. Coarse and Fine Ash Particle Size Distribution Curves.

7.0 SYNGAS CONDITIONING UNIT

7.1 WATER-GAS SHIFT CATALYST

Testing of the water-gas shift (WGS) catalyst previously tested in R07 was conducted in R08 at steady conditions for a total of 292 hours to evaluate long-term durability. The reactor inlet temperature was 480°F, and the syngas flow rate was 50 lb/hr with no steam addition. The moisture content of the inlet and outlet gas was determined by the method of condensation. At the end of the run, the catalyst was blanketed with nitrogen to inhibit oxidation until testing resumes in R09. R08 test results are plotted in Figure 11.

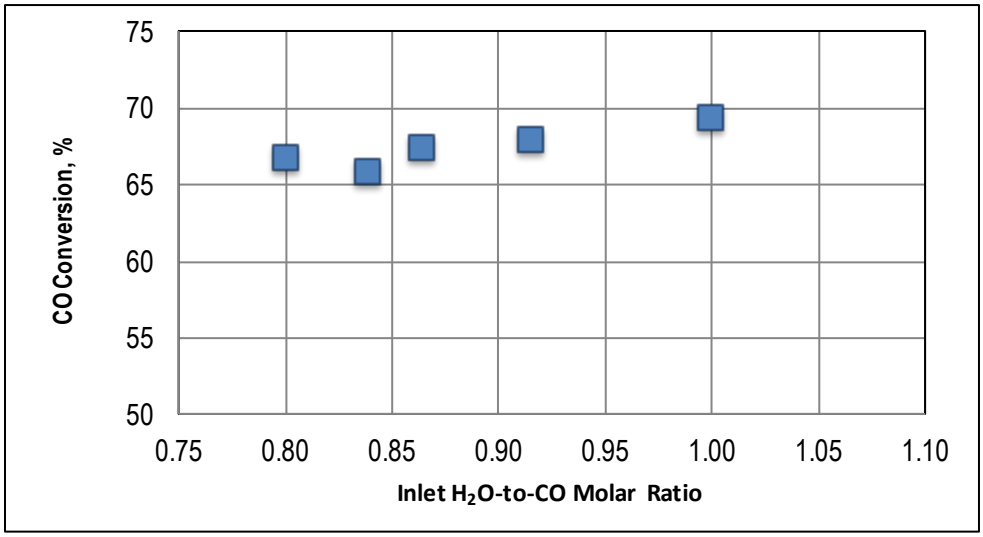

Figure 11. Water-Gas Shift Catalyst Test Results.

7.2 WORCESTER POLYTECHNIC INSTITUTE MEMBRANES

During R08, Worcester Polytechnic Institute (WPI) tested a palladium-based hydrogen membrane with a thin layer of gold-platinum coating in a nitrogen/hydrogen mixture for 295 hours and in syngas with hydrogen augmentation for 116 hours, for a combined 411 hours of testing. The exposure time was achieved in two test periods, which are described below.

- June 23 to July 11—Initially, about 85 hours in a mixture of 26 vol% hydrogen in nitrogen followed by 60 hours in syngas augmented to 36 vol% hydrogen. Finally, 170 hours in nitrogen/hydrogen mixture varying the hydrogen content from 10 vol% to 50 vol% to investigate hydrogen permeance. During the parametric tests, over 99.9 percent pure hydrogen was produced.
- July 22 to July 26—Initially, about 40 hours in a mixture of 26 vol% hydrogen in nitrogen followed by 56 hours in syngas augmented to 36 vol% hydrogen.

Hydrogen permeance was about 57 percent of the permeance measured at WPI's lab when the membrane was first exposed to hydrogen/nitrogen. The permeance gradually increased to 80 percent of the lab value in the next 50 hours. Slightly lower permeance was observed when

syngas/hydrogen was introduced, but remained stable in syngas environment. Test results showed hydrogen purity increased with hydrogen concentration in the feed gas. A purity as high as 99.9 percent was achieved at 40 vol% hydrogen in feed. This relationship is illustrated in Figure 12, which shows hydrogen purity as function of hydrogen concentration for several membranes tested at the NCCC.

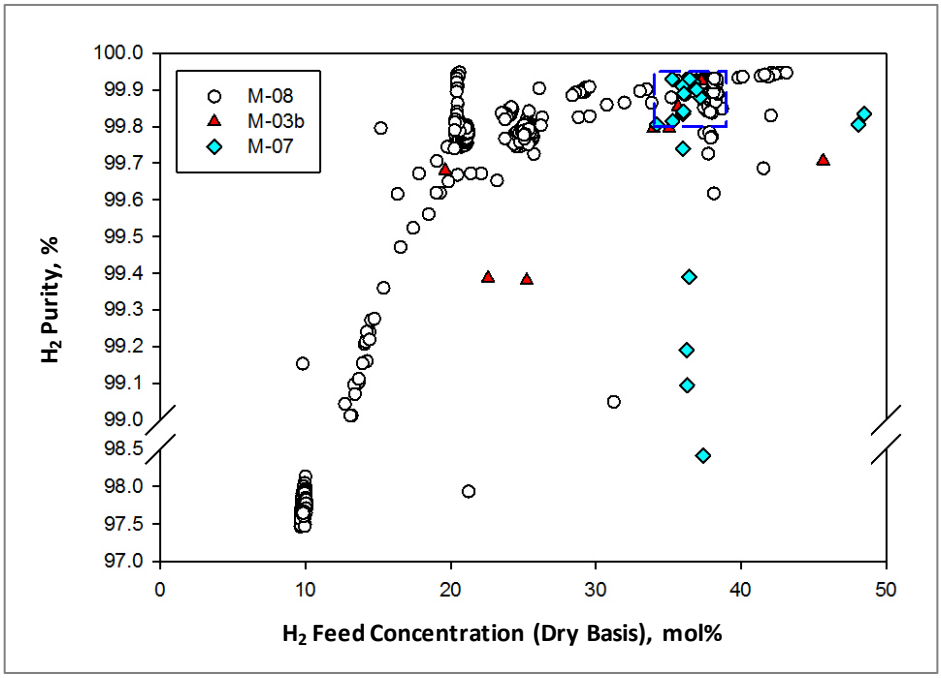

Figure 12. Hydrogen Product Purity as a Function of Hydrogen Feed Concentration for Several WPI Membranes Tested at the NCCC.

Throughout both test periods, the membrane operated stably. Overall, this test confirmed the robustness of WPI's hydrogen membranes in coal-derived syngas as demonstrated previously in runs R06 and R07. Post-test inspections showed the membrane surface to be clean with no discoloration, unlike the condition following previous runs. This could be attributed to a combination of the shorter exposure time to syngas and a beneficial effect of the platinum coating.

7.3 MEMBRANE TECHNOLOGY & RESEARCH MEMBRANES

MTR continued to test the Polaris™ CO_2 and Proteus™ hydrogen membranes in R08 with optimized configurations for better separation performance. Membranes achieved a total of 288 hours of operation in syngas. For CO_2-selective membranes, two modules in series (shown in Figure 13) were tested, which enriched CO_2 content four- to fivefold, from an average of about 10 percent in the feed to 35 to 50 percent in the permeate. For hydrogen-selective membranes, two membrane stamps were tested, which enriched hydrogen content from about 10 percent to 50 percent.

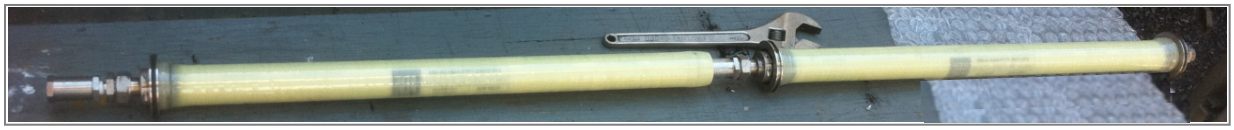

Figure 13. MTR CO_2 Membrane Modules Connected in Series.

Both the CO_2 and hydrogen membranes have performed very well using coal-derived syngas. The results are consistent with that from bench scale test at MTR facilities under simulated mixed gas conditions. Stable membrane performances observed during the past three test runs under real world conditions are encouraging for further development in polymeric membrane technologies for CO_2 and hydrogen separation.

7.4 MEDIA & PROCESS TECHNOLOGY MEMBRANE

During R08, testing of the Media & Process Technology (MPT) Carbon Molecular Sieve (CMS) hydrogen membrane was conducted using its full-scale 86-tube bundle, which is shown in Figure 14. The tube-bundle was first tested in R07, a significant scale-up from the single tubes and a pilot bundle containing 14 tubes tested previously. To overcome poor gas distribution in R07 (which prevented agreement of the mixed gas permeance of the CMS bundle for hydrogen versus the pure component value), MPT added reinforced internal baffles. This baffle arrangement was first tested in off-line tests at the NCCC prior to R08. MPT's primary goal in R08 testing was to demonstrate good agreement between the mixed gas and pure component hydrogen permeance using syngas, and thus validate the baffle design.

Figure 14. MPT Full-Scale CMS Bundle.

Test data confirmed the results obtained from off-line testing, as the hydrogen permeance was within 85 to 90 percent of the pure component value. Further, the product hydrogen purity was in the range of 50 to 55 percent from raw syngas containing about 8 percent hydrogen, far exceeding the 35 to 40 percent hydrogen purity results obtained in earlier tests at NCCC. Overall, it appeared that the redesigned baffle was able to successfully overcome the feed flow distribution problem experienced during R07 test campaign.

During the final portion of R08, conducted with oxygen-blown gasifier operation, MPT conducted an additional field test to further verify the performance of the improved module. Over 100 hours of testing were completed. Although the membrane performed well, enriching

the hydrogen to about 90 percent, significant steam present in the syngas (estimated at 30 vol% or more) during this test made quantitative data analysis difficult. Modifications are being implemented to improve the steam determination for the next test so more rigorous data analysis can be performed.

7.5 MEMBRANE COUPON TESTING

Additional membrane materials testing during R08 included a series of test coupons of metal alloys being investigated for hydrogen separation membranes. The coupons, supplied by DOE and United Technologies Research Center, were placed downstream of the PCD filter elements where they were exposed to particulate free raw syngas in order to assess their resistance to degradation arising from syngas stream impurities, such as hydrogen sulfide. Preliminary analysis shows that the varied nature of syngas impurities produced significant differences compared to controlled laboratory conditions.

7.6 CO_2 CAPTURE SOLVENT TESTING IN BATCH REACTOR

The NCCC continued its test program for evaluating physical and chemical CO_2 solvents. For R08, syngas was bubbled through dimethyl ether of polyethylene glycol in the SCU CO_2 capture batch reactor to identify any contaminants accumulating in the solvent. This work was prompted by results from the tests previously conducted on monoethanol amine in the Pilot Solvent Test Unit. Very little metal was accumulated, and it is considered that the metals and other contaminants were removed in the sample preparation stage. Tests will be conducted in R09 on collected samples to give a better indication of the metals that could potentially be removed by the solvent.