# POWER SYSTEMS DEVELOPMENT FACILITY

# TOPICAL REPORT

# GASIFICATION TEST CAMPAIGN TC21

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## DISCLAIMER

## ABSTRACT

In support of technology development to utilize coal for efficient, affordable, and environmentally clean power generation, the Power Systems Development Facility (PSDF), located in Wilsonville, Alabama, routinely demonstrates gasification technologies using various types of coal. The PSDF is an engineering scale demonstration of key features of advanced coal-fired power systems, including a Transport Gasifier, a hot gas particulate control device (PCD), advanced syngas cleanup systems, and high-pressure solids handling systems.

This report summarizes the results of the first demonstration of gasification operation with lignite coal following the 2006 gasifier configuration modifications. This demonstration took place during test campaign TC21, occurring from November 7, 2006, through January 26, 2007. The test campaign began with low sodium lignite fuel, and after 304 hours of operation, the fuel was changed to high sodium lignite, for 34 additional hours of operation. Both fuels were from the North Dakota Freedom mine. Stable operation with low sodium lignite was maintained for extended periods, although operation with high sodium lignite was problematic due to agglomeration formation in the gasifier restricting solids circulation.

ACKNOWLEDGEMENT

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# 1.0 EXECUTIVE SUMMARY

Test campaign TC21 was the first demonstration of the Power Systems Development Facility (PSDF) gasification process with lignite coal in the newly modified gasifier. TC21 occurred from November 7, 2006, to January 26, 2007. The Transport Gasifier operated with low sodium lignite coal for 304 hours and with high sodium lignite for 34 hours. In addition to characterizing operation of the modified gasifier with lignite, objectives for the test campaign included further testing of hot gas filter components, coal feeder development, continued testing of instrumentation enhancements, and evaluation of advanced syngas cleanup sorbents and catalysts. In addition, the PSDF provided a testing site for outside researchers to evaluate high frequency pressure measurements, advanced flue gas analyzers, and trace metals removal from syngas.

## 1.1 PSDF Overview

The PSDF, located near Wilsonville, Alabama, was established to support the U.S. Department of Energy's effort to develop cost-competitive and environmentally acceptable coal-based power generation technologies. This effort promotes fuel diversity—a key component in maintaining national security—while meeting the highest environmental standards. The PSDF is developing environmentally friendly technologies that will allow the continued use of coal, the United States' most abundant and least expensive fuel source.

The PSDF is operated by Southern Company Services. Other project participants currently include the Electric Power Research Institute, KBR (formerly Kellogg Brown & Root), the Lignite Energy Council, and Peabody Energy. The facility is a highly flexible test center where researchers can evaluate innovative power system components on a semi-commercial scale at a low cost. Development of advanced power systems at the PSDF is focused specifically on identifying ways to reduce capital cost, enhance equipment reliability, and increase efficiency while meeting strict environmental standards. Current testing involves pressurized feed systems, gasifier optimization using a variety of fuels, sensor development, hot gas particulate removal, and advanced syngas cleanup.

## 1.2 Process Description

The PSDF gasification process, shown in Figure 1-1, features key components of an integrated gasification combined cycle (IGCC) plant. These include high pressure solids feed systems; a KBR Transport Gasifier; syngas coolers; a hot gas filter vessel, the particulate control device (PCD); continuous ash depressurization systems developed at the PSDF for ash cooling and removal; a novel piloted syngas burner; a slipstream syngas cleanup unit to test various pollutant control technologies; and a recycle syngas compressor.

The coal used as the gasifier feedstock is processed on site, first crushed and then pulverized to a nominal particle diameter between 250 and 400 microns. Coal may be fed to the gasifier using two systems, the original coal feed system and a secondary coal feed system. The original coal feed system is a lock hopper, horizontal pocket feeder design with a "rotofeed" dispenser. It consists of two pressure vessels, with the coal pressurized in an 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 the rotofeed dispenser, which is driven by a variable speed electric motor and delivers the material into the discharge line where it is conveyed by air or nitrogen into the gasifier. The secondary coal feeder is a developmental test unit designed to evaluate different feeder mechanisms. Types of mechanisms that can be tested with this system include auger-style, fluid bed, and a higher pressure rotary feeder. Coal is fed at a nominal rate of 4,000 lb/hr.

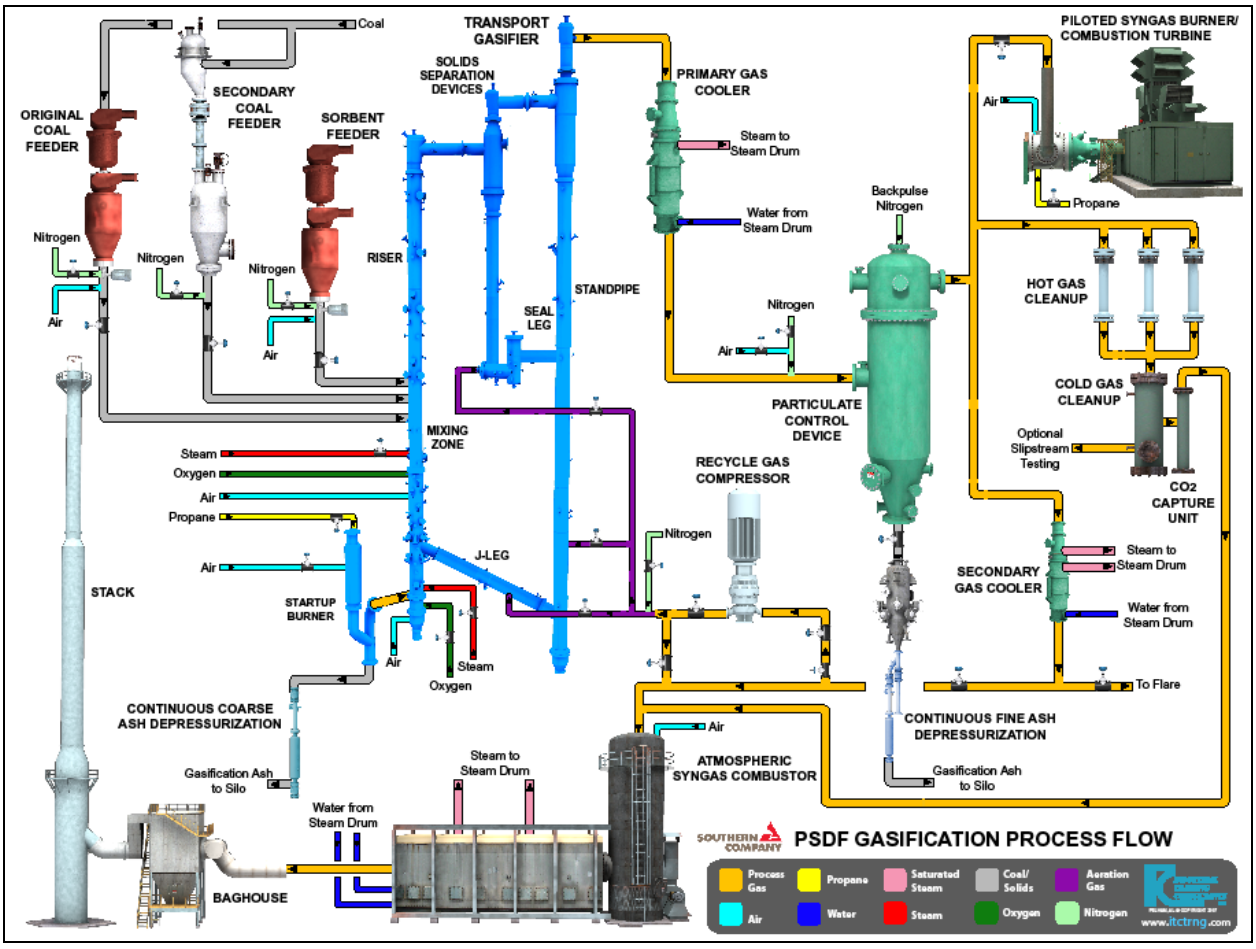


Figure 1-1. PSDF Gasification Process Flow Diagram.

A sorbent feeder is available to feed material into the gasifier for in-situ sulfur capture or to address ash chemistry issues. For sulfur capture, either limestone or dolomite is fed after being crushed and pulverized to a nominal particle diameter of 10 to 100 microns. The sorbent feeder utilizes the same design as the original coal feeder, but for a lower feed rate of nominally 100 lb/hr.

The start-up burner is a direct propane-fired burner operated to heat the gasifier to about 1,200°F. The burner is typically started at a system pressure of 60 psig, and can operate at pressures up to 135 psig.

The Transport Gasifier, a pressurized, advanced circulating fluidized bed reactor, consists of a mixing zone, riser, solids separation unit, seal leg, standpipe, and J-leg. The gasifier is equally

capable of using air or oxygen as the gasification oxidant. Steam and either air or oxygen are mixed together and fed into the mixing zone at different elevations and orientations to evenly distribute heat generated from the partial combustion of the circulating solids. The oxygen from the air or pure oxygen feed is completely consumed in this section of the gasifier. The coal and sorbent are fed at a higher elevation in the mixing zone where the atmosphere is reducing, or oxygen-free.

As the coal devolatilizes and chemical reactions occur to generate syngas, the gas and solids move up the riser and enter the solids separation unit. This unit contains two solids separation devices, which use cyclonic action to remove particles. Between the first and second solids separation devices is the seal leg, which prevents backflow of solids. The solids collected by the solids separation unit are recycled back to the gasifier mixing zone through the standpipe and J-leg. The gasifier solids inventory is controlled by removing gasification ash through the continuous course ash depressurization (CCAD) system, which cools and depressurizes the solids. The nominal gasifier operating temperature is 1,800°F, and the gasifier system was designed to have a maximum operating pressure of 294 psig with a thermal capacity of about 41 MMBtu/hr.

The syngas exits the Transport Gasifier, passes through the primary gas cooler where the gas temperature is reduced to about 750°F, and enters the PCD for final particulate removal. The metal or ceramic filter elements used in the PCD remove essentially all the particulate from the gas stream. The PCD utilizes a tube sheet holding up to 91 filter elements, which are attached to one of two plenums. Process gas flows into the PCD through a tangential entrance, around a shroud, and through the filter elements into the plenums. Failsafe devices are located downstream of the filter elements to stop solids leakage by plugging in the event of element failures. High pressure nitrogen back-pulsing, typically lasting 0.2 seconds, is used to clean the filters periodically to remove the accumulated gasification ash and control the pressure drop across the tube sheet. The solids fall to the bottom of the PCD and are cooled and removed through the continuous fine ash depressurization (CFAD) system.

After exiting the PCD, a small portion of the syngas, up to 100 lb/hr, can be directed to an advanced syngas cleanup system downstream of the PCD. The syngas cleanup system is a specialized, flexible unit, capable of operating at a range of temperatures, pressures, and flow rates, and provides a means to test various pollutant control technologies, including removal of sulfur, nitrogen, chlorine, and mercury compounds. The syngas cleanup slipstream can also be used to test other power generation technologies such as fuel cells.

A portion of the syngas can also be directed to the piloted syngas burner (PSB), a gas turbine combustor designed to burn coal-derived syngas with a lower heating value below 100 Btu/SCF. After syngas combustion in the burner, the flue gas passes through a 4 MWe turbine before exiting the turbine stack. An associated generator can supply power from the turbine to the electric transmission grid.

The main stream of syngas is then cooled in a secondary gas cooler, which reduces the temperature to about 450°F. Some of this gas may be compressed and sent to the gasifier for aeration to aid in solids circulation. The recycle gas compressor is a vertically mounted

centrifugal compressor which operates at high temperature, nominally 500 to 600°F, and was designed for a throughput of about 2,000 to 3,000 lb/hr.

The remaining syngas is reduced to near atmospheric pressure through a pressure control valve. The gas is then sent to the atmospheric syngas combustor which burns the syngas components. The flue gas from the atmospheric syngas combustor flows to a heat recovery boiler, through a baghouse, and then is discharged out a stack. A flare is available to combust the syngas in the event of a system trip when the atmospheric syngas combustor is offline.

A brief description of the PSDF gasification testing history can be found in Appendix A.

### 1.3 Major Test Objectives

*Lignite Operation*. The major test objective for TC21 was the characterization of gasifier operation and performance with both low and high sodium lignite in the recently modified gasifier. As discussed in the TC20 Topical Report, one of the goals of the gasifier modifications was to improve gasifier performance using fuels with inherent ash chemistry issues such as high sodium lignite, which require lower gasifier operating temperatures. Since lower operating temperatures may result in lower carbon conversions, the gasifier modifications were focused on increasing the residence time in the gasifier and improving the gasifier solids collection efficiency.

For the first portion of TC21, during which low sodium lignite was fed, the gasifier operated well, and several parametric studies were performed. However, after the transition to high sodium lignite, agglomerations began forming, restricting solids circulation and limiting the operating duration. After removing these deposits, a second attempt to operate with the high sodium lignite was made, and also resulted in agglomerations in the gasifier. Although previous operation (test campaign TC16) with the Freedom mine high sodium lignite had shown that with low gasifier temperatures (1,700°F) and sorbent addition, agglomerations of sodium silicates could be avoided, the lignite coal used in TC21 had a higher sodium content. (The average $Na_2O$ content in the coal ash was 8.2 in TC21 as compared to an average of 4.9 weight percent in TC16.) The gasifier solids readily formed agglomerates despite operating at low temperatures, with high steam flow rates, and with dolomite fed directly to the gasifier.

*Recycle Syngas Use.* Recycled syngas was used for gasifier aeration during the majority of operating periods to achieve the highest possible syngas heating value. This was the first use of recycle syngas use in the modified gasifier, since the use of recycle syngas was deferred until after TC20 (the first test campaign following the modifications) to simplify analysis of the modified gasifier performance. The use of recycle syngas in TC21 resulted in an approximately 8 percent increase in the syngas heating.

*Particulate Control Device*. An objective related to PCD operation was the performance assessment of Dynalloy HR-160 filter elements. The HR-160 metal fiber filter elements replaced most of the previously tested iron aluminide (FEAL) sintered metal powder elements, which have shown progressive corrosion and subsequent increasing pressure drop across the filter media with time. The HR-160 elements used in TC21 were able to consistently maintain outlet loadings near the lower limit of resolution (~0.1 ppmw), and inspections of the filter elements did not indicate corrosion at this point in operation.

## 1.4 Secondary Test Objectives

***Transport Air Evaluation***. Air was used as the coal conveying gas, in lieu of the nitrogen typically used, for about 40 percent of the test campaign. Transitioning from nitrogen to air was achieved smoothly, and the use of transport air resulted in a syngas heating value increase of typically 20 percent.

***Sensor Development.*** Development of real-time particulate monitors continued with the evaluation of modifications made to the Process Metrix Process Particle Counter. The retrofit with coolant and purge gas heaters prior to TC21 were effective in resolving the instrument window contamination problems experienced in previous test campaigns, and the system operated reliably throughout TC21.

Evaluation of ceramic-tipped pressure differential indicators (PDIs) was continued, as well as testing of thermowell material for improved gasifier thermocouple longevity. The PDIs fitted with the higher differential pressure design ceramic tips became plugged, while the PDI fitted with the lower differential pressure design operated well and compared well with standard PDI measurements. Three HR-160 thermowells which were located near an area in which agglomerations occurred showed significant wear from corrosion, although the associated thermocouples functioned throughout the test campaign. The corrosion on these thermowells may have been accelerated by high localized velocity from channeling around the deposit.

To obtain a direct velocity measurement in the gasifier, six Promecon velocity probes were fitted with ceramic tips and pressure resistant seals and installed at varying lengths in the riser. The probes ceased to give output early in operation, and subsequent inspections showed that the ceramic tips had been severely damaged.

Sensor development conducted by outside researchers included the testing of high frequency pressure sensors by Babcock & Wilcox and semi-conducting metal oxide gas sensors by Sensor Research and Development. Initial testing of both types of sensors was completed, and further testing was planned for a subsequent test campaign.

***Advanced Syngas Cleanup.*** Testing of syngas cleanup included carbonyl sulfide (COS) hydrolysis with the previously tested Alcoa 200 catalyst. Conversions up to about 95 percent were measured. The hydrolyzed syngas was then processed through two Synetix sulfur sorbents, and the treated gas was delivered to the TDA Research trace metals removal test unit. The initial testing of the TDA Research test unit was performed, with additional testing planned during future gasifier operation.

## 1.5 Report Structure

The following report presents the operational data and results of gasification technology development at the PSDF during TC21, compiled in the sections listed below.

Section 2 Coal Feed — Presents analysis of the two types of Freedom mine lignite used during TC21. Discusses coal feeder , and presents coal moisture values and particle sizes and their effects on coal feeder performance.

Section 3 Transport Gasifier — Details operation of the newly modified gasifier with low and high sodium lignite. Includes the major gasifier operating parameters and the gasifier performance as indicated by solids and gas analyses. Also includes the inspection results for the gasifier, gasifier deposits, and related equipment.

Section 4 Sensor Development — Discusses recent operation of real-time particulate monitors, results of gasifier instrumentation improvements, and sensor testing by outside researchers.

Section 5 Particulate Control Device — Describes the hot gas filter particulate characteristics, PCD performance, and filter element testing.

Section 6 Advanced Syngas Cleanup — Discusses testing of COS hydrolysis and sulfur removal and use of the syngas cleanup slipstream for testing by an outside research group.

Section 7 Conclusions — Lists the major conclusions and lessons learned from TC21 operation.

Appendix A gives a brief history of gasification operation at the PSDF. Appendix B shows the steady state operating periods and the major system operating conditions for each period. Material and energy balances are shown in Appendix C, and Appendix D lists the abbreviations and units used in this report.

# 2.0 COAL FEED

Operation during TC21 was achieved with low and high sodium lignite coals from the Freedom mine in North Dakota. Coal feeder technology development continued with vent line modifications and with the continued characterization of the coal feeder operating envelope.

## 2.1 Coal Characteristics

The composition and heating value of the low sodium lignite and of the high sodium lignite as sampled from the coal feeders are given in Table 2-1 and Table 2-2, respectively. Hydrogen from the coal was reported separately from hydrogen in the moisture. The as-received moisture content for both the low sodium and high sodium lignite coals were about 37 weight percent.

Table 2-1. Low Sodium Lignite As-Fed Characteristics.

| | Average | Standard Deviation | Minimum | Maximum |
|---|---|---|---|---|
| Moisture, wt% | 21.9 | 1.3 | 18.6 | 24.4 |
| Carbon, wt% | 48.8 | 1.1 | 47.3 | 51.6 |
| Nitrogen, wt% | 0.7 | 0.04 | 0.6 | 0.8 |
| Oxygen, wt% | 15.1 | 0.7 | 13.6 | 16.9 |
| Sulfur, wt% | 0.8 | 0.2 | 0.6 | 1.4 |
| Ash, wt% | 9.8 | 0.8 | 8.4 | 11.6 |
| Volatiles, wt% | 31.3 | 4.4 | 19.1 | 41.1 |
| Fixed Carbon, wt% | 37.0 | 4.5 | 26.9 | 49.5 |
| As-Received Heating Value, Btu/lb | 8,080 | 350 | 6,670 | 8,510 |
| CaO, wt % in ash | 19.8 | 1.3 | 17.4 | 22.9 |
| $SiO_2$, wt % in ash | 30.5 | 2.1 | 25.6 | 34.7 |
| $Al_2O_3$, wt % in ash | 11.9 | 0.6 | 10.9 | 13.2 |
| MgO, wt % in ash | 6.6 | 0.3 | 6.1 | 7.3 |
| $Na_2O$, wt % in ash | 1.3 | 0.2 | 1.0 | 1.8 |
| Ca/S, mole/mole | 1.5 | 0.3 | 0.8 | 2.0 |

Table 2-2. High Sodium Lignite As-Fed Characteristics.

| | Average | Standard Deviation | Minimum | Maximum |
|---|---|---|---|---|
| Moisture, wt% | 20.4 | 3.1 | 15.0 | 25.3 |
| Carbon, wt% | 52.1 | 2.8 | 48.6 | 58.1 |
| Nitrogen, wt% | 0.8 | 0.1 | 0.7 | 0.9 |
| Oxygen, wt% | 14.2 | 0.9 | 12.5 | 15.6 |
| Sulfur, wt% | 0.7 | 0.1 | 0.6 | 0.9 |
| Ash, wt% | 8.9 | 0.5 | 7.7 | 9.4 |
| Volatiles, wt% | 30.9 | 2.8 | 28.2 | 37.7 |
| Fixed Carbon, wt% | 39.8 | 3.0 | 34.1 | 45.6 |
| As-Received Heating Value, Btu/lb | 8,590 | 530 | 7,950 | 9,730 |
| CaO, wt % in ash | 19.7 | 1.2 | 16.8 | 20.9 |
| $SiO_2$, wt % in ash | 22.9 | 1.2 | 21.6 | 24.9 |
| $Al_2O_3$, wt % in ash | 11.6 | 1.0 | 10.2 | 13.8 |
| MgO, wt % in ash | 6.1 | 0.5 | 5.2 | 6.8 |
| $Na_2O$, wt % in ash | 8.2 | 0.9 | 6.8 | 9.6 |
| Ca/S, mole/mole | 1.5 | 0.2 | 1.0 | 1.8 |

The mass median diameter (MMD) particle sizes of the coal sampled from the coal feeders are shown in Figure 2-1. The coal particle size averaged 374 microns and had a standard deviation of 90 microns.

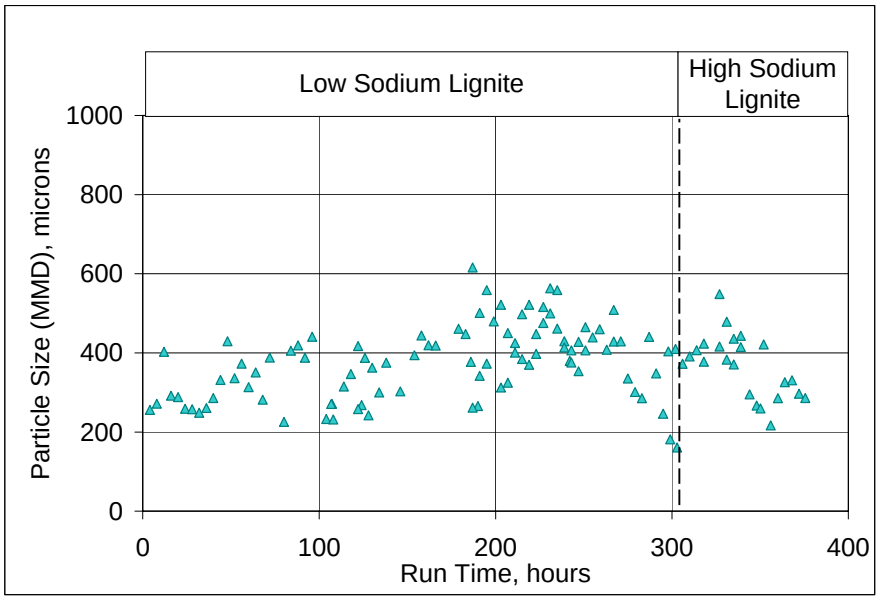


Figure 2-1. Coal Particle Sizes.

Figure 2-2 shows the percentage of fine coal, that below 45 microns, and the percentage above 1,180 microns, considered oversize coal. The fines and oversize contents were typically below 20 weight percent.

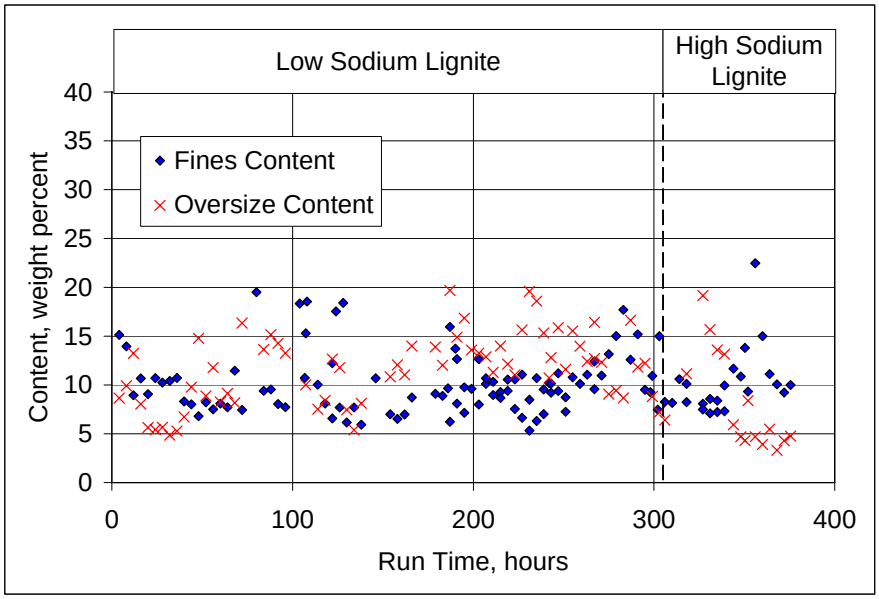


Figure 2-2. Coal Fines and Oversize Particles.

## 2.2 Coal Feeder Operation

During TC21, both the original feeder and the developmental feeder were operated. The balance line installed from the dispense vessel to the transport gas supply line of the original coal feeder successfully eliminated the occurrence of vent line plugging in this coal feeder during 367 hours of operation. The balance line installed in developmental coal feeder system was also successful in eliminating vent line plugging during its 190 hours of operation.

*Coal Feeder Operating Envelope.* Based on TC21 operation, the original coal feed system operating range for coal moisture content and particle size was evaluated. Figure 2-6 shows the variation in particle size and coal moisture contents, and the ranges of which were conducive to acceptable feeder operation. Coal feeder operations were problematic when the particle size was less than about 300 microns at moisture contents of 20 percent or greater.

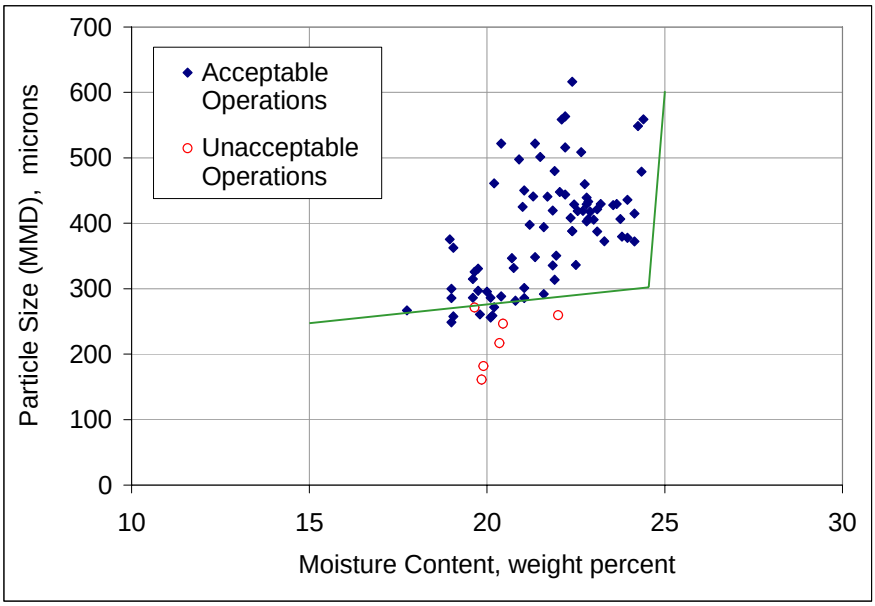


Figure 2-6. Coal Feeder Operating Envelope.

## 3.0 TRANSPORT GASIFIER

A major test objective for TC21 was the characterization of gasifier operation and performance with both low and high sodium lignite in the recently modified gasifier. As discussed in the TC20 Topical Report, one of the goals of the gasifier modifications was improved gasifier performance using fuels with inherent ash chemistry issues such as high sodium lignite, which require lower gasifier operating temperatures. Since lower operating temperatures may result in lower carbon conversions, the gasifier modifications were focused on increasing the residence time in the gasifier and improving the gasifier solids collection efficiency.

In this section, TC21 operations and analysis are described as Part A and B. The delineation was made due to the 52-day outage that occurred at Hour 342. TC21 Part A started on November 7, 2006, and ended on December 4, 2006, and TC21 Part B started on January 25, 2007, and ended on January 26, 2007. Both low and high sodium lignite were fed to the gasifier during TC21 Part A, but only high sodium lignite was fed to the gasifier during TC21 Part B.

During TC21 Part A, the gasifier operated well with low sodium lignite; however, gasifier operations were more challenging after the transition to high sodium lignite was made at Hour 304. Agglomeration started in the lower mixing zone (LMZ) and progressed into the upper mixing zone (UMZ) which restricted solids circulation and necessitated a system shutdown at Hour 342. The agglomerated material was removed during the outage and the system was restarted. Several operating changes were made such as increasing the steam flow rate and adding dolomite directly to the gasifier. Unfortunately, agglomeration occurred again during TC21 Part B operation, and the system was shut down after 34 hours of high sodium lignite feed. Although agglomerations had been prevented in TC16 operation with the Freedom mine high sodium lignite by operating with lower temperatures and by adding dolomite sorbent, the higher sodium content in the TC21 lignite (TC21averaged 8.2 weight percent $Na_2O$ in the coal ash as compared to an average of 4.9 weight percent in TC16) proved to more readily form sodium silicates, leading to large agglomerations.

### 3.1 Gasifier Operating Parameters

TC21 Part A consisted of 20 steady state operating periods, 18 periods during low sodium lignite gasification, and 2 periods with high sodium lignite, and TC21 Part B had 3 steady state operating periods with high sodium lignite. All of the steady state periods were in air-blown gasification mode. Recycle syngas was used for gasifier aeration during 15 of the low sodium lignite operating periods and during one of the high sodium lignite periods. The steady state periods are defined based on maintaining gasifier operating conditions within defined ranges. The steady state operating periods and major operating parameters are shown in Appendix B. Gasifier performance was evaluated through extensive gas and solids sampling and analyses.

Figure 3-1 gives the gasifier temperatures and pressures for the TC21 steady state periods. While operating with low sodium lignite, the mixing zone temperature varied between 1,610 and 1,740°F, and the outlet temperature was between about 1,540 and 1,620°F. With high sodium lignite, the temperatures maintained were much lower, with the mixing zone temperature between 1,450 and 1,490°F, and the outlet temperature ranging from 1,420 to 1,460°F. The

gasifier outlet pressure was typically 200 to 214 psig, with three periods at 174 psig during low sodium testing for parametric testing and three periods at 134 psig during high sodium testing to improve solids circulation.

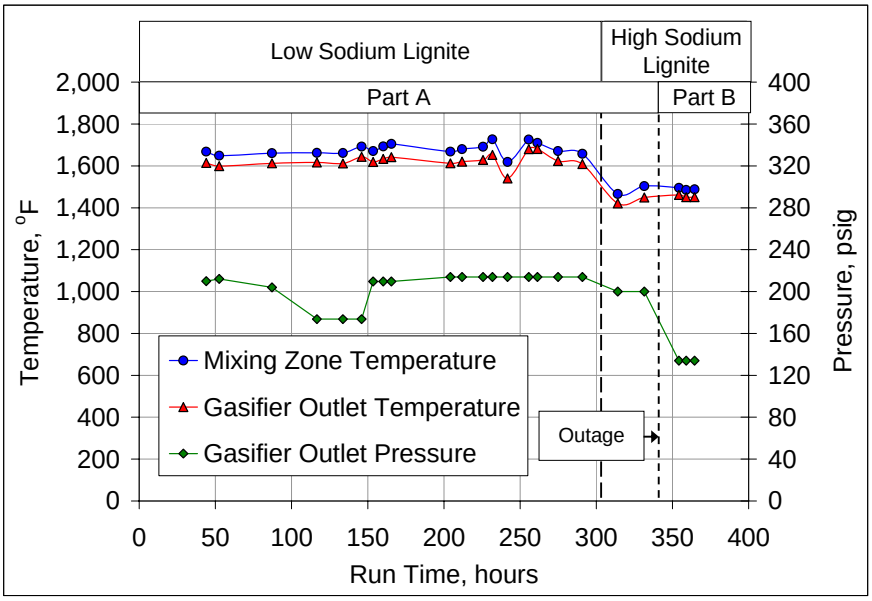


Figure 3-1. Gasifier Operating Temperature and Pressure.

Flow rates of the feed streams to the gasifier during TC21 are shown in Figure 3-2. The coal and dolomite feed rates were calculated from the feeder weigh cells, and the air, nitrogen, and recycle gas flow rates were taken from flow indicators. The steam flow rates were derived from either the system hydrogen balance or a steam flow indicator.

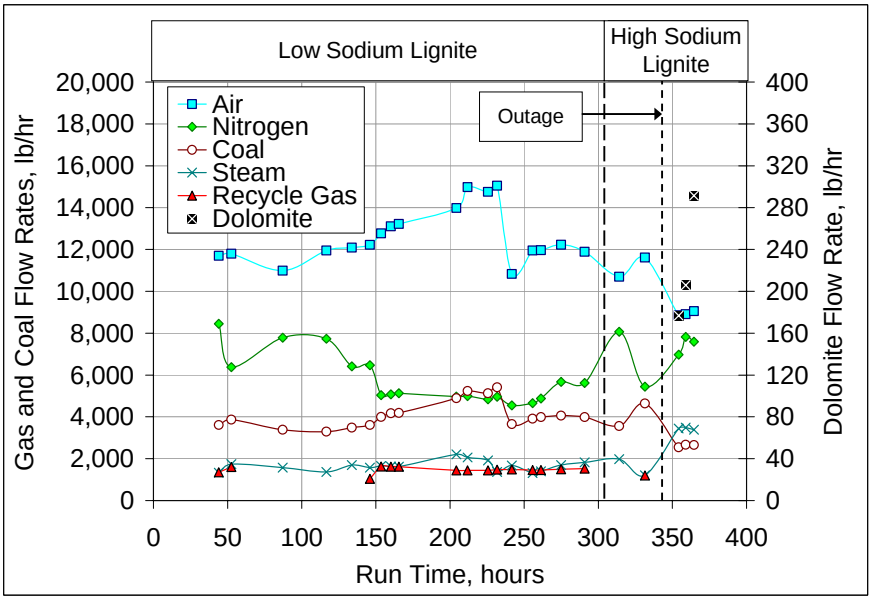


Figure 3-2. Gasifier Feed Stream Flow Rates.

The standpipe levels (measured as differential pressures) and the riser differential pressures are plotted in Figure 3-3. The riser differential pressure tracked the standpipe level during most of TC21. The standpipe level increased from approximately 150 to 200 in$H_2O$ during TC21 Part B due to difficulty establishing solids flow from the mixing zone to the CCAD inlet.

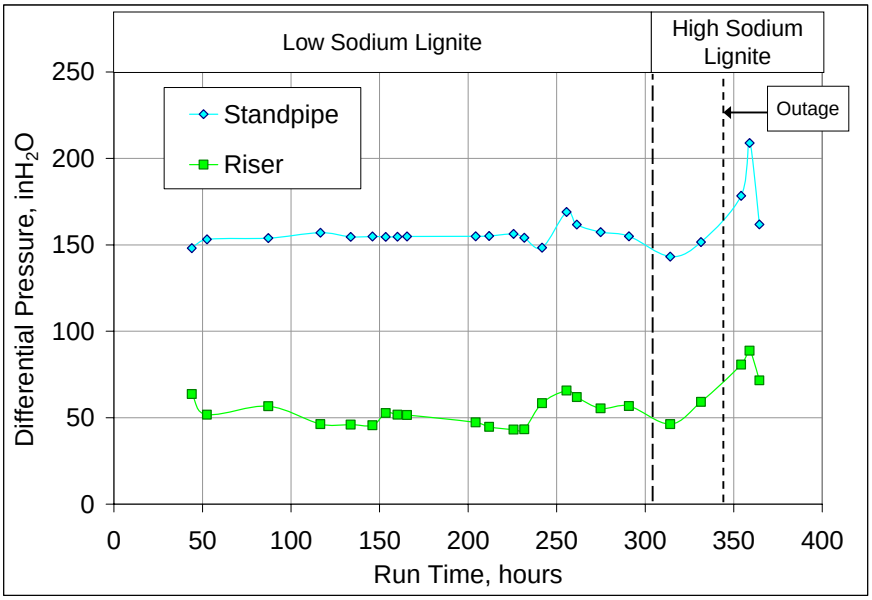


Figure 3-3. Standpipe and Riser Differential Pressures.

## 3.2 Gasifier Performance, Solids Analysis

The gasifier solids chemical composition and particle size analyses presented in the following sections represent both the circulating gasifier solids sampled from the gasifier standpipe and the solids exiting the gasifier, filtered in the PCD, and sampled from the CFAD ash removal system.

***Solids Chemical Analyses***. The solids chemical analyses were used to monitor transition of the solids inventory from the start-up sand bed material to gasification ash and to characterize operation of the gasifier solids separation devices. The chemical analyses, including the as-received heating value of the gasifier circulating solids and the PCD solids during low sodium operations, are presented in Tables 3-1 and 3-2, respectively. After the start-up sand was replaced with gasification ash, there was little variation in the solids composition during low sodium operation in TC21 Part A.

During high sodium operation in TC21 Part A, the composition changed due to the higher sodium content in the feed material as well as reactions of the sodium with other ash components. The composition changed again during TC21 Part B due to the addition of dolomite.

Table 3-1. Gasifier Circulating Solids Analysis During Low Sodium Lignite Operation.

| | Average | Standard Deviation | Minimum Value | Maximum Value |
|---|---|---|---|---|
| $SiO_2$, wt% | 36.1 | 1.8 | 33.5 | 40.4 |
| $Al_2O_3$, wt% | 12.6 | 0.5 | 11.3 | 13.3 |
| $Fe_2O_3$, wt% | 11.6 | 0.8 | 10.7 | 12.4 |
| $Na_2O$, wt% | 1.5 | 0.4 | 1.0 | 2.5 |
| Other Inerts ($P_2O_5$, $K_2O$, BaO & $TiO_2$), wt% | 2.9 | 0.3 | 2.4 | 3.4 |
| $CaCO_3$, wt% | 0.3 | 0.1 | 0.1 | 0.4 |
| CaS, wt% | 0.6 | 0.3 | 0.1 | 1.0 |
| CaO, wt% | 23.4 | 1.4 | 20.5 | 25.7 |
| MgO, wt% | 7.7 | 0.6 | 6.0 | 8.3 |
| Organic Carbon, wt% | 1.6 | 1.5 | 0.4 | 5.0 |
| Heating Value, As Received, Btu/lb | <100 | <100 | <100 | <100 |

Table 3-2. PCD Solids Analysis During Low Sodium Lignite Operation.

| | Average | Standard Deviation | Minimum Value | Maximum Value |
|---|---|---|---|---|
| $SiO_2$, wt% | 31.5 | 2.4 | 27.4 | 35.2 |
| $Al_2O_3$, wt% | 12.6 | 0.9 | 11.1 | 14.4 |
| $Fe_2O_3$, wt% | 7.8 | 0.7 | 6.5 | 8.8 |
| $Na_2O$, wt% | 2.1 | 0.4 | 1.6 | 3.1 |
| Other Inerts ($P_2O_5$, $K_2O$, BaO & $TiO_2$), wt% | 3.3 | 0.2 | 2.8 | 3.6 |
| $CaCO_3$, wt% | 2.2 | 0.5 | 1.5 | 3.2 |
| CaS, wt% | 2.5 | 0.9 | 1.4 | 3.9 |
| CaO, wt% | 14.7 | 1.4 | 12.1 | 16.5 |
| MgO, wt% | 6.2 | 0.4 | 5.6 | 7.3 |
| Organic Carbon, wt% | 15.6 | 3.6 | 9.3 | 23.0 |
| Heating Value, As Received, Btu/lb | 2,413 | 578 | 1,426 | 3,584 |

The silicon dioxide ($SiO_2$), aluminum oxide ($Al_2O_3$), calcium oxide (CaO), iron oxide ($Fe_2O_3$), and magnesium oxide (MgO) concentrations of the gasifier circulating solids ash and the PCD solids sampled for the last 67 hours of Part A for the entirety of Part B of TC21 are plotted in Figure 3-4 and 3-5, respectively . For both the gasifier and PCD solids, the concentrations were fairly constant during Part A but then changed after the outage at Hour 342. During TC21 Part B, which followed the outage, dolomite was added to the gasifier to prevent agglomeration. The CaO and MgO increased as a result, while the other components, $SiO_2$, $Al_2O_3$, and $Fe_2O_3$, decreased. The calcium carbonate ($CaCO_3$) and calcium sulfide (CaS) concentrations are not shown, as the concentrations were negligible in the gasifier and PCD solids for most of the samples.

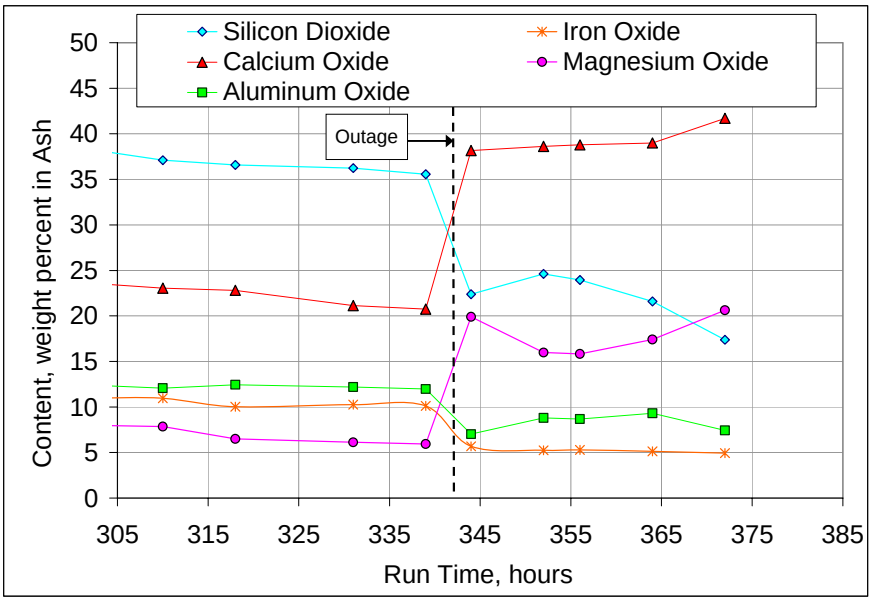


Figure 3-4. Concentrations of Major Constituents of Gasifier Circulating Solids Ash.

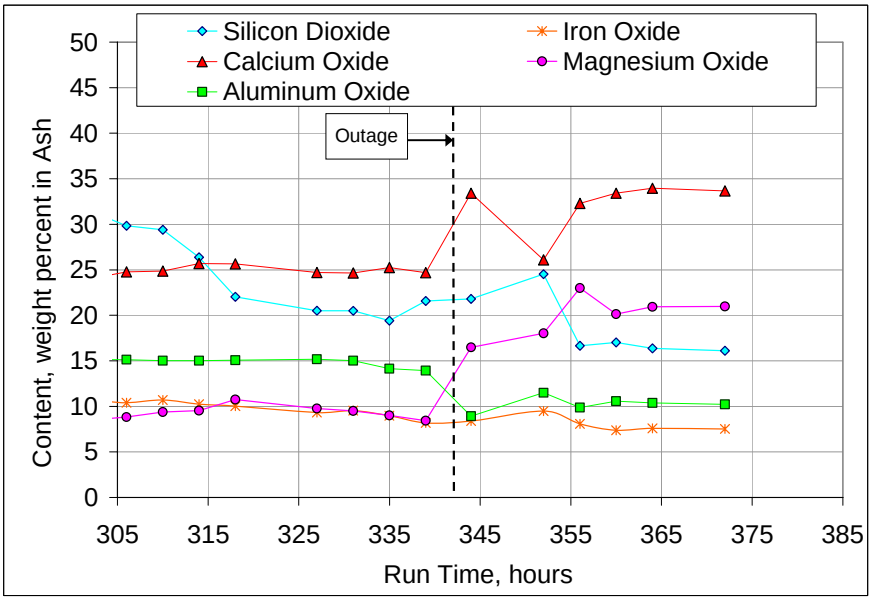


Figure 3-5. Concentrations of Major Constituents of PCD Solids.

The sodium content of the gasifier circulating solids, PCD solids, and the lignite feed are plotted in Figure 3-6. As expected, the sodium content in the gasifier circulating solids and PCD solids increased after the transition to the high sodium lignite. The sodium content in the gasifier circulating solids were lower during TC21 Part B due to the addition of dolomite.

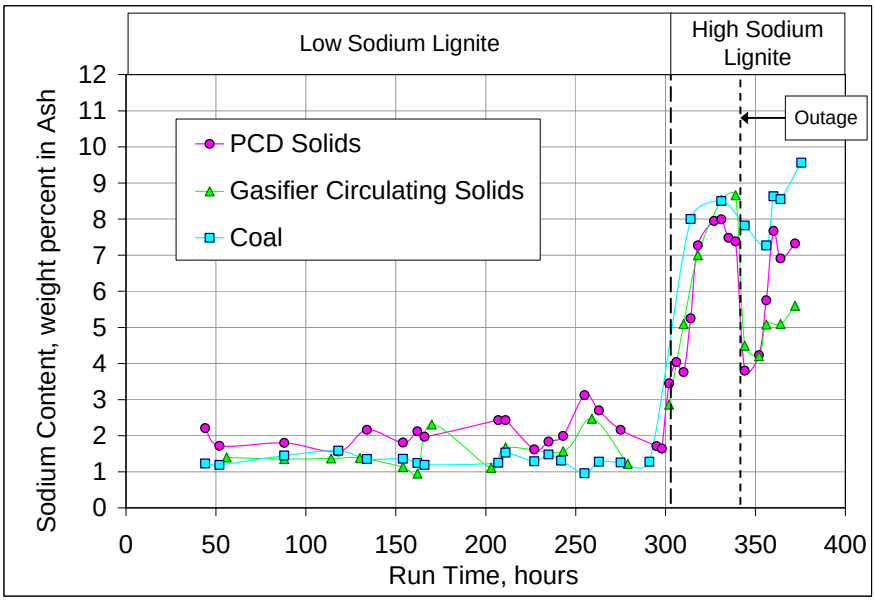


Figure 3-6. Sodium Content in Gasifier and PCD Solids and in Coal Feed.

*Solids Physical Analyses.* The particle sizes of the gasifier circulating solids and PCD solids are shown in Figure 3-7. The gasifier solids decreased in size from about 130 to 60 microns during the first 80 hours of TC21 as the start-up sand was replaced with gasification ash and then varied between 50 and 90 microns. Immediately after the transition to high sodium lignite, the particle size was similar to that from previous operation, but as the agglomeration formed, the particle size increased significantly, with a peak value of 180 microns at Hour 339 just before the outage. During TC21 Part B, the gasifier particle sizes were small due to the addition of fine dolomite.

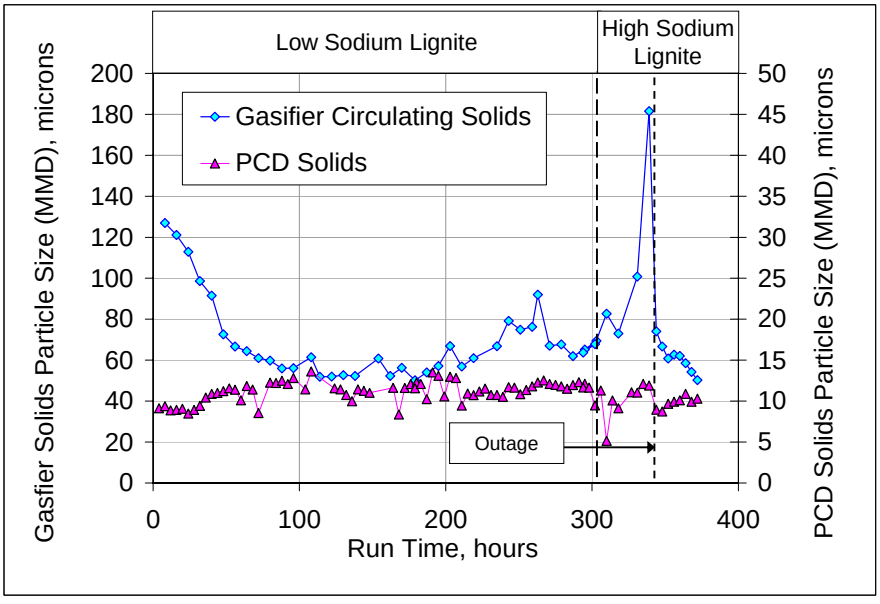


Figure 3-7. Particle Sizes of Gasifier Circulating Solids and PCD Solids.

Figure 3-8 depicts the gasifier circulating solids as sampled before and after the transition to high sodium lignite operation. At Hour 302, 2 hours before transitioning to the high sodium lignite, the gasifier solids were fairly uniform in size and color and did not show any signs of agglomeration. However, the sample taken at Hour 331, 27 hours after transitioning to lignite, showed a significant change in color and appearance with a large portion of the particles in the sample larger than 1,000 microns. Figure 3-9 compares the particle size distribution curves for these two samples, and shows a shift in the particle size coinciding with the agglomeration.

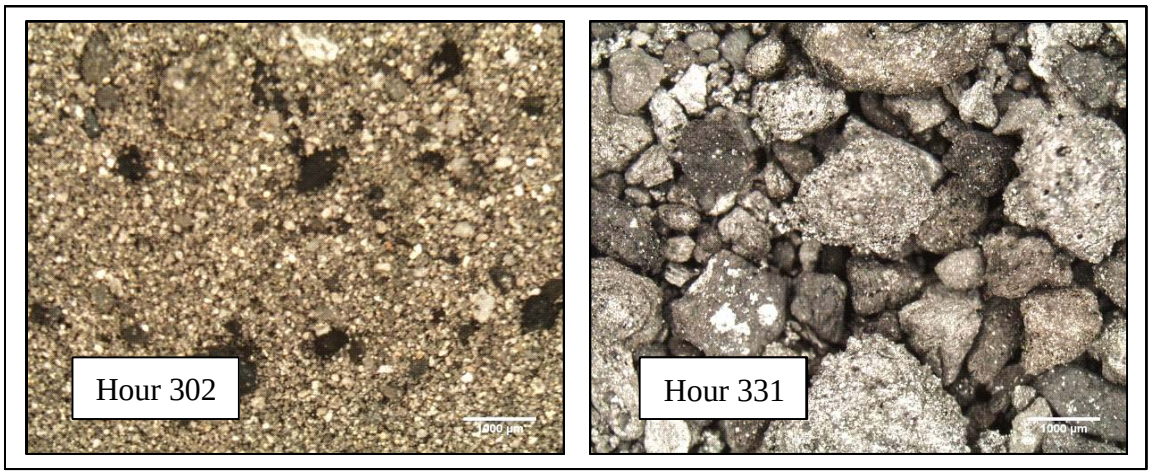


Figure 3-8. Photomicrographs of Gasifier Circulating Solids Before and After the Transition to High Sodium Lignite.

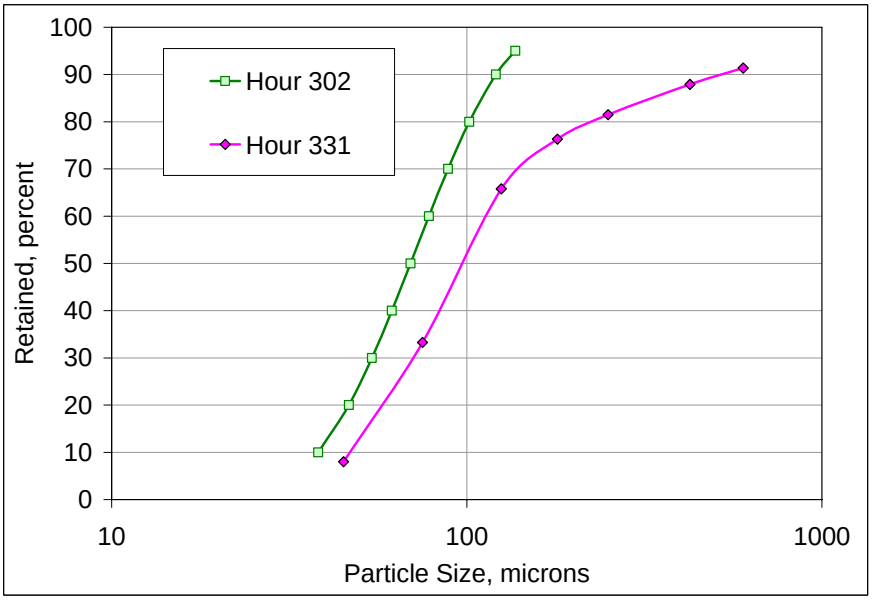


Figure 3-9. Particle Size Distributions for Gasifier Solids Samples Taken at Hours 302 and 331.

Bulk densities of the gasifier and PCD solids are plotted in Figure 3-10. The bulk density of the circulating solids decreased from about 90 to 50 lb/ft$^3$ during the first 80 hours of the test campaign as the start-up sand was replaced by gasification ash. Bulk density data was not

available after Hour 175. The density of both the gasifier circulating solids and the PCD solids showed a dramatic increase after the outage due to the addition of dolomite, which has a true density of about 175 lb/ft$^3$.

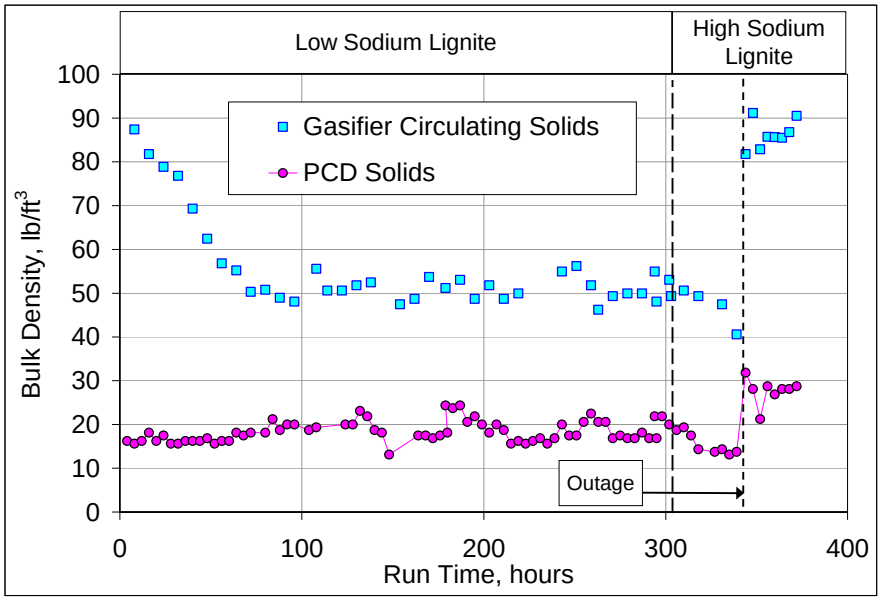


Figure 3-10. Bulk Densities of Gasifier Circulating Solids and PCD Solids.

***Gasification Ash Removal***. Figure 3-11 gives the solids rates for the gasification ash removed from the PCD by the CFAD system and the coarse gasification ash removed from the gasifier standpipe by the CCAD system. The CFAD rates, determined from PCD inlet in-situ sampling, were as high as 400 lb/hr. The CCAD rates were determined by a system ash balance, and were as high as 250 lb/hr.

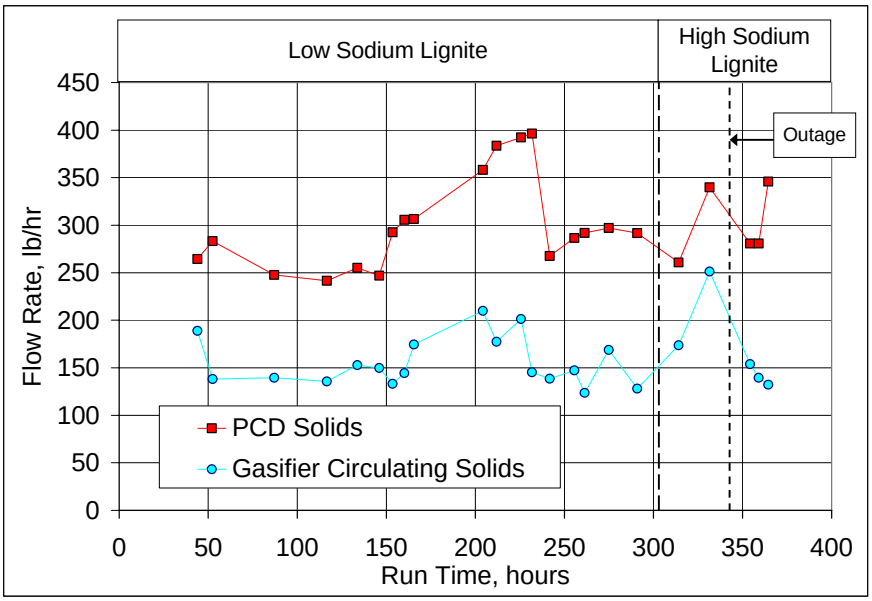


Figure 3-11. Gasification Ash Removal.

### 3.3 Gasifier Performance, Gas Analysis

Extractive syngas sampling was performed between the primary gas cooler and the PCD inlet, and the syngas constituents were analyzed using continuous analyzers and gas chromatography. In-situ samples of syngas moisture were made at the PCD outlet during the particulate sampling.

***Syngas Composition***. Concentrations of the major syngas components, $H_2$, CO, $CO_2$, $CH_4$, and $H_2O$, for the steady state operating periods are given in Figure 3-12. The $H_2$, CO, $CO_2$, and $CH_4$ concentrations were measured by a GC on a moisture-free basis and converted to wet gas concentrations using the water concentration. The water concentration for steady state periods was estimated based on the PCD outlet sampling and on a mathematical correlation based on the water-gas shift reaction equilibrium. The water content varied from about 10 to 15 mole percent during TC21 Part A, but increased to about 23 percent during TC21 Part B due to increased steam flow rates.

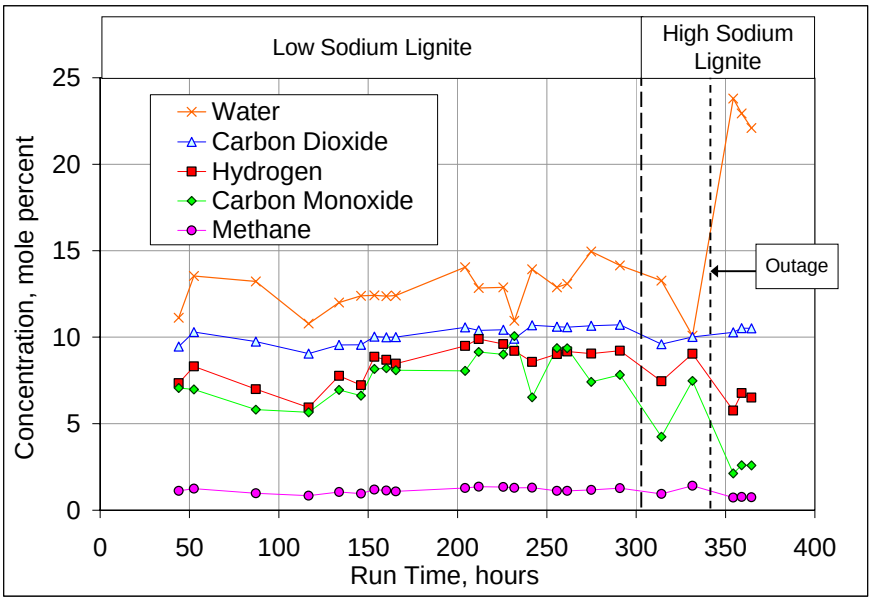


Figure 3-12. Syngas Composition.

Minor constituents in the syngas include reduced sulfur compounds such as hydrogen sulfide ($H_2S$) and carbonyl sulfide (COS) and reduced nitrogen compounds such as $NH_3$ and hydrogen cyanide (HCN). Some of the sulfur is captured in the solid phase by forming compounds with calcium in the coal ash, and the remaining gas phase sulfur is mostly in the form of $H_2S$. Figure 3-13 plots the $H_2S$ concentration, which ranged from about 800 to 1,200 ppm during low sodium operation and ranged from about 600 to 800 ppm during high sodium operation.

A large portion of the coal-bound nitrogen is converted to ammonia. Only two syngas ammonia measurements were taken due to the limited availability of the ammonia analyzer. The ammonia measured about 1,100 ppm at Hour 348 and 1,400 ppm at Hour 369. The concentrations were lower than typical since the samples were taken during times of high steam flow rates and low coal feed rates.

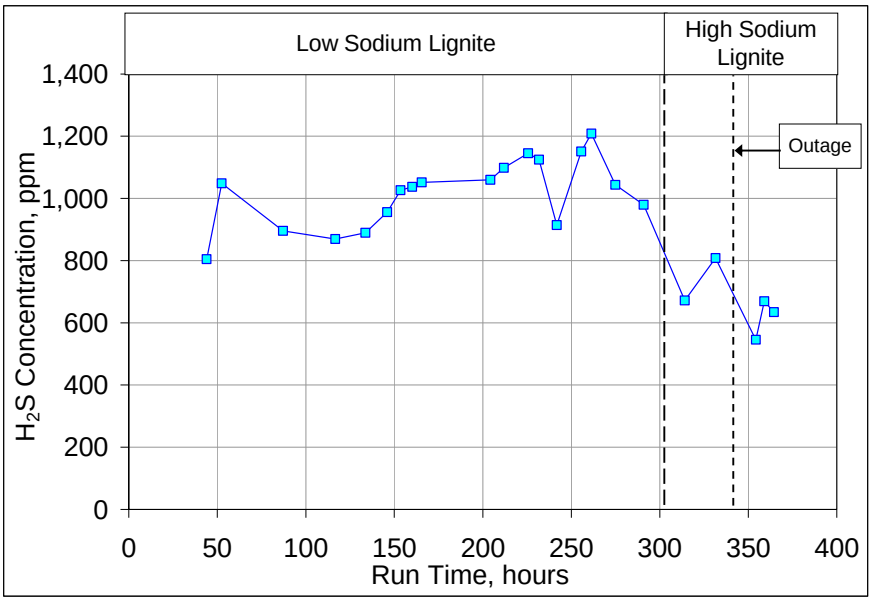


Figure 3-13. Hydrogen Sulfide Concentration.

***Syngas Heating Value***. The syngas lower raw wet heating value (LHV), plotted in Figure 3-14, varied from 40 to 70 Btu/SCF during TC21 Part A. The syngas lower heating value was only 30 to 34 Btu/SCF during Part B because of the higher steam flow rates and lower coal feed rates.

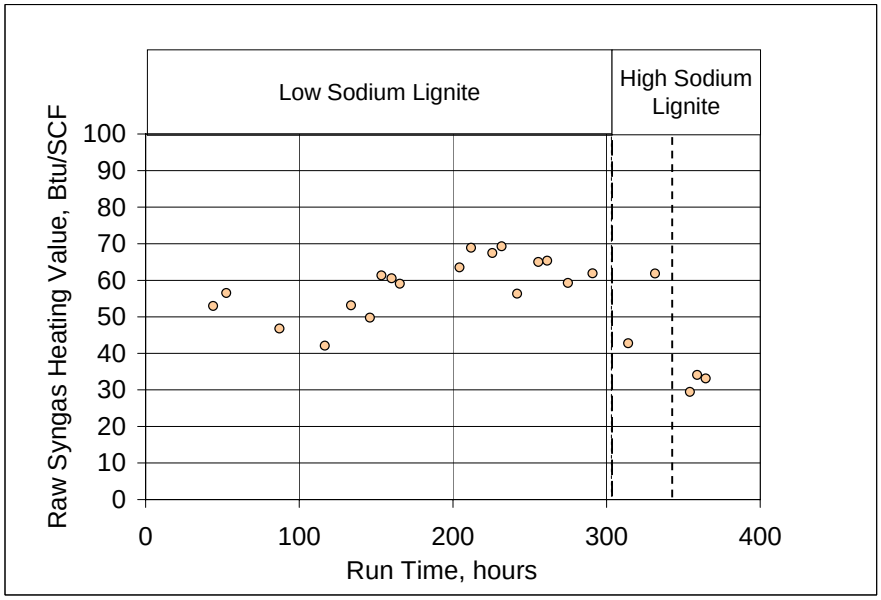


Figure 3-14. Raw Syngas Lower Heating Value

***Carbon Conversion.*** The carbon conversion plotted in Figure 3-15. The carbon conversion was acceptable during low sodium operation, varying from 96.5 to 98.2 percent. With high sodium lignite, the gasifier temperature was kept lower to prevent agglomerations, and the lower temperature had the effect of lowering carbon conversion. In TC21 Part B, the coal feed rate

was lowered, which increased the carbon conversion above that of TC21 Part A high sodium lignite operation. Higher carbon conversions are achieved at lower coal feed rates. Additional reasons for variations in carbon conversion are given in Section 3.6 and are supported by results of parametric tests.

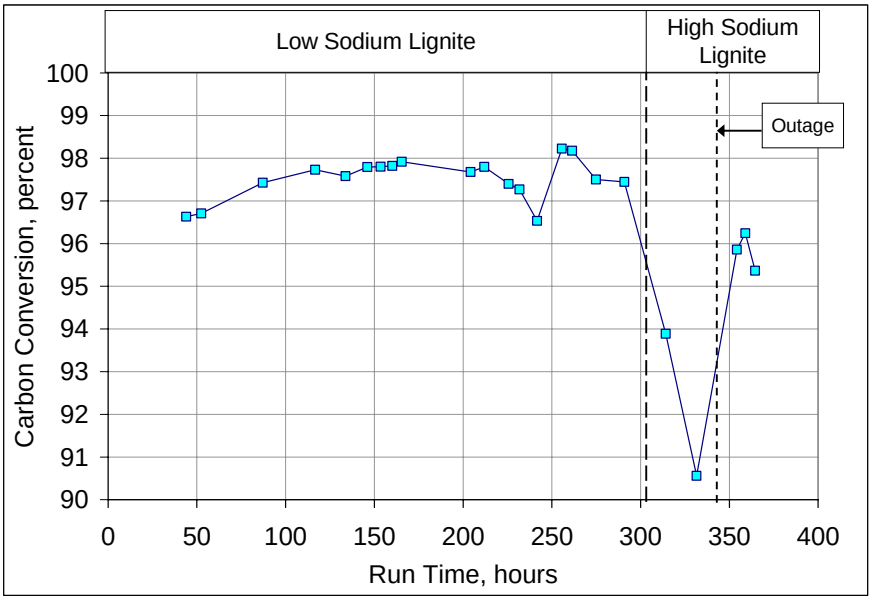


Figure 3-15. Carbon Conversion

***Gasification Efficiency.*** The cold gasification efficiency was between 40 to 60 percent, and the hot gas efficiency varied from 80 to 90 percent during TC21 operation. Variations in the efficiencies were due to changes in operating conditions impacting the carbon conversion and heating value.

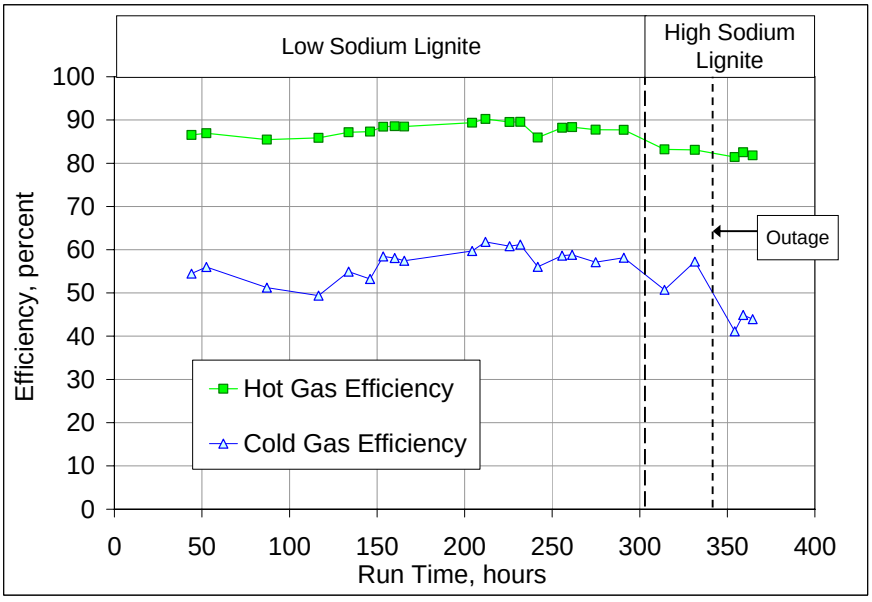


Figure 3-16. Cold and Hot Gasification Efficiency.

### 3.4 Gasifier Performance, Parametric Testing

A number of tests were performed to evaluate operations with lignite. The parametric testing completed included temperature, pressure, air-to-coal ratio, recycle gas, transport air, and coal feed rate effects on gasifier operations and performance. Increasing coal particle size for testing was not performed due to issues with the coal mills. Analysis for the parametric tests is presented below. To obtain meaningful analyses, data were analyzed using selected steady state periods which held other variables nearly constant to focus on the variable of interest.

Figure 3-17 gives the effect of temperature on carbon conversion at a gasifier pressure between 210 and 214 psig, air-to-coal mass ratios between 3.0 and 3.2, and coal feed rates ranging from 3600 to 4200 lb/hr. The results show a positive correlation between carbon conversion and temperature as expected with a significant decrease in carbon conversion at a much lower temperature of about 1470°F.

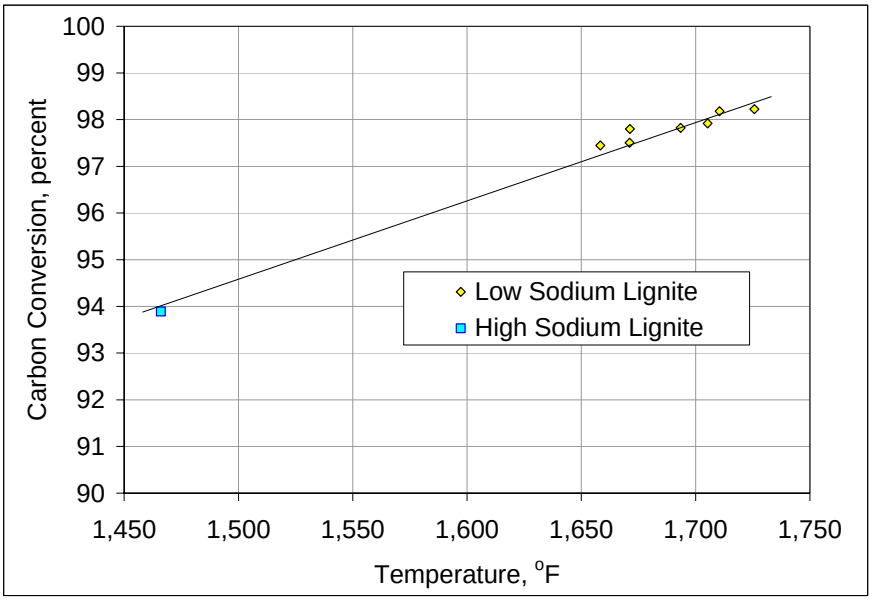


Figure 3-17. Carbon Conversion as a Function of Gasifier Temperature.

Gasifier pressure was varied to evaluate its effects on the methane Figure 3-18 below shows the effect of pressure on the syngas methane content, represented by a relative value, the methane factor. During steady state periods from which the data was extracted, the air-to-coal mass ratios were maintained between 3.1 and 3.6, the gasifier temperature ranged from 1,650 to 1,690°F, and coal feed rates were between 3,300 to 3,900 lb/hr. The methane factor showed a positive correlation with gasifier pressure as expected.

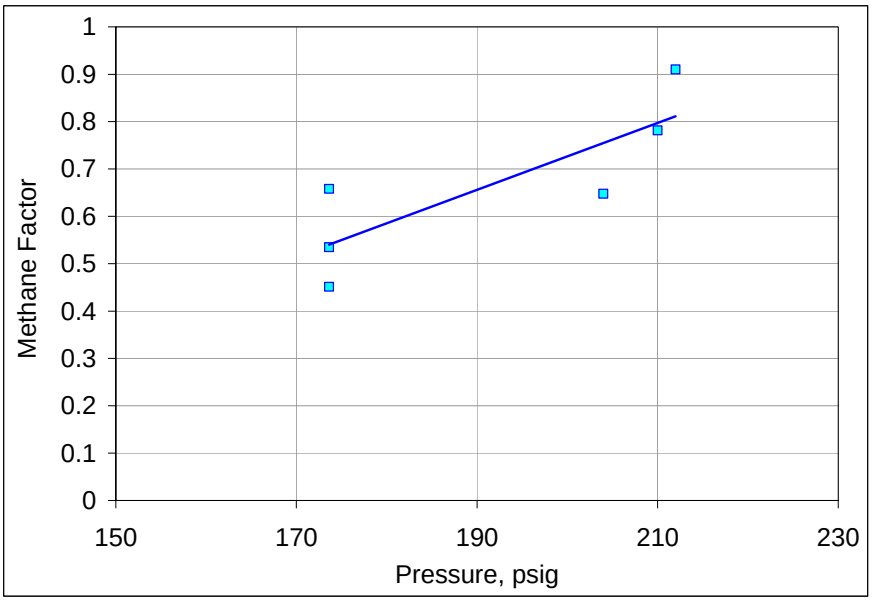


Figure 3-18. Methane Content as a Function of Gasifier Pressure.

Figure 3-19 shows the raw dry syngas heating value as a function of coal feed rate. This plot included the steady state data taken when the air-to-coal mass ratio was between 3.0 and 3.6. As shown in the figure, a positive correlation exists between the syngas heating value and coal feed rate.

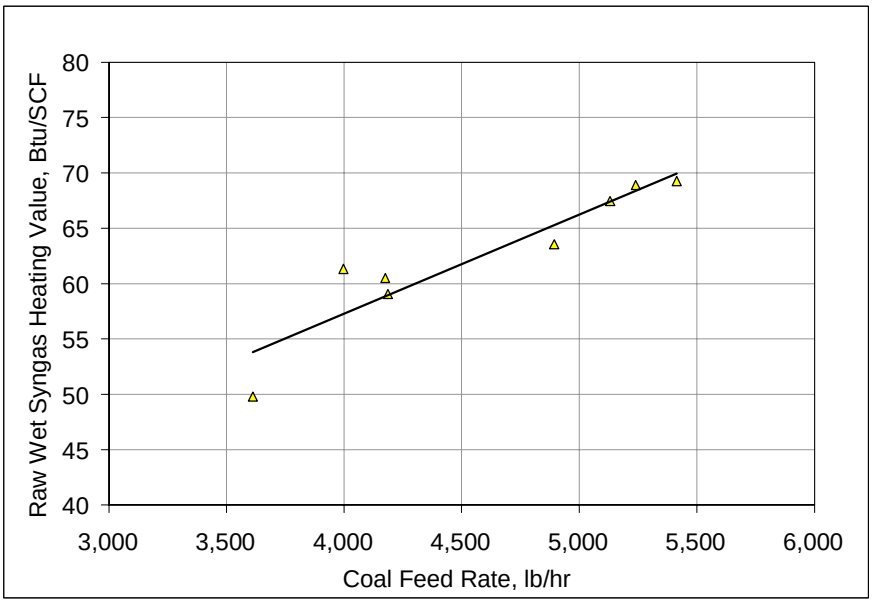


Figure 3-19. Syngas Heating Value as a Function of Coal Feed Rate.

Figure 3-20 shows the instantaneous effect of using transport air to convey the coal instead of nitrogen on the syngas heating value. After the transfer to transport air, the syngas heating value immediately increased and stabilized with an increase of 15 Btu/SCF, a 23 percent increase in

the syngas heating value. The data shown below is for all low sodium lignite steady state periods and for coal feed rates ranging from 3,300 to 5,400 lb/hr.

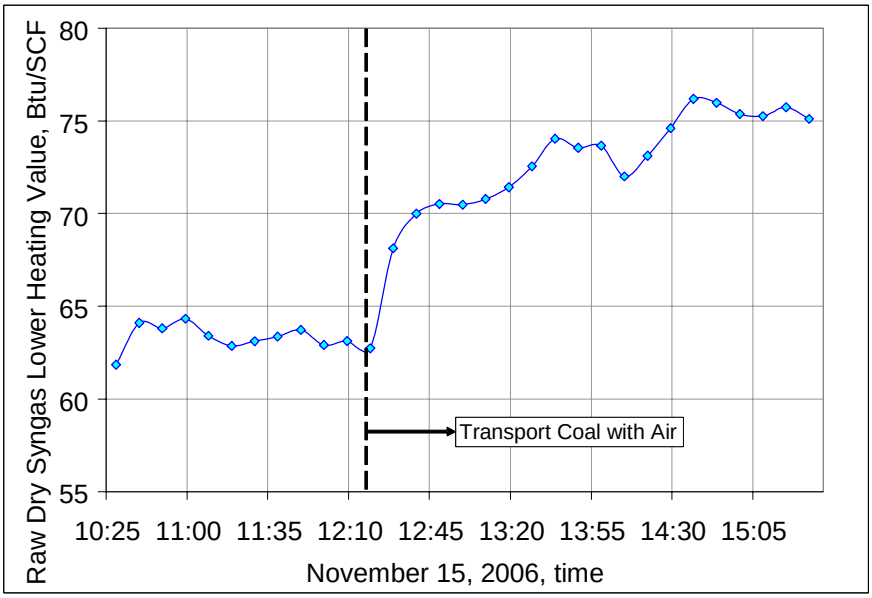


Figure 3-20. Effect of Transport Air on Syngas Lower Heating Value.

Figure 3-21 shows the effect of coal conveying with air or nitrogen by plotting the lower heating value and air-to-coal ratio. There is an improvement in lower heating value with using air to convey coal compared to using nitrogen at the same air to coal ratio.

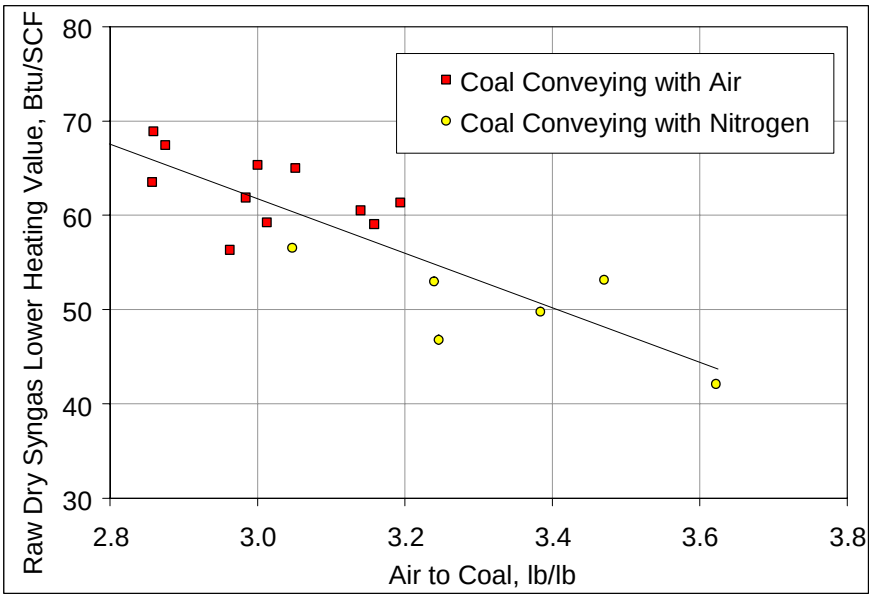


Figure 3-21. Effect of Air-to-Coal Ratio on Syngas Lower Heating Value.

Figure 3-22 shows the instantaneous effect on syngas heating value when utilizing recycle gas for aeration. The plot shows the syngas heating value versus a relative time for two different time periods when the aeration gas was transition from nitrogen to recycle gas. The syngas heating value increased about 5 Btu/SCF, an 8 percent increase. Gasifier operation was stable, and the coal feed rate was constant during both time periods.

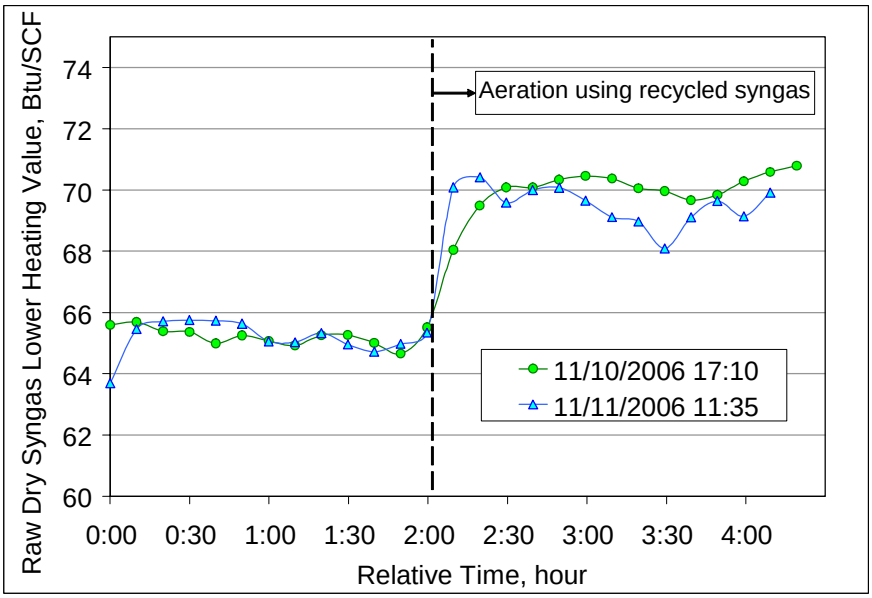


Figure 3-22.. Effect of Recycle Gas Use for Gasifier Aeration on Syngas Heating Value.

## 3.5 Gasifier Inspections

### 3.5.1 Post-TC21 Part A Inspections

Inspection following TC21 Part A revealed severe agglomeration in the lower and upper mixing zones as seen in the Figure 3-23 photographs. The riser, solids separation unit, standpipe, J-leg, and burner leg did not contain agglomeration, and the refractory was in good condition.


Figure 3-23. Post-TC21 Part A Inspection of the Gasifier Mixing Zone.

The primary gas cooler was inspected and showed no signs of plugging at the inlet or fouling in the tubes. Figure 3-24 shows the inlet of the primary gas cooler. The secondary gas cooler was not inspected, but process data indicated no significant fouling. Also, the pressure control valve downstream of the secondary gas cooler was inspected and found to be clean.

Figure 3-24. Post-TC21 Part A Inspection of the Primary Gas Cooler.

### 3.5.2 Post-TC21 Part B Inspections

The gasifier mixing and zone and riser were visually inspected after TC21. There was some hard and soft deposition present in the lower and upper mixing zone as well as the riser; however, the extent of agglomeration was much less than observed after TC21 Part A due to the short duration of operation and the changes in the operating conditions. Figure 3-25 shows some of the material that was removed from the LMZ during the inspection.


Figure 3-25. Material Removed from Lower Mixing Zone after TC21 Part B.

Examination of the material by scanning electron microscope (SEM) revealed that the particles forming the deposits were bonded together. Energy dispersive X-ray spectrometry analysis identified magnesium (Mg), calcium (Ca), aluminum (Al), silicon (Si), iron (Fe), and sodium (Na) as the predominant elements present. The SEM image and the EDS analysis are given in Figure 3-26. The magnesium and calcium concentrations were attributed to the dolomite which was fed to the gasifier, and the other elements originated from the lignite ash. Lab testing, which entailed pulverizing the deposits and heating them to determine the minimum temperature at which reconsolidation occurred, indicated that the material reconsolidated at temperatures as low

as 1000°F. Further lab testing was completed to identify additives that would be more effective than dolomite in preventing agglomeration so that future operation with this lignite could be completed and the results will be presented in a subsequent report.

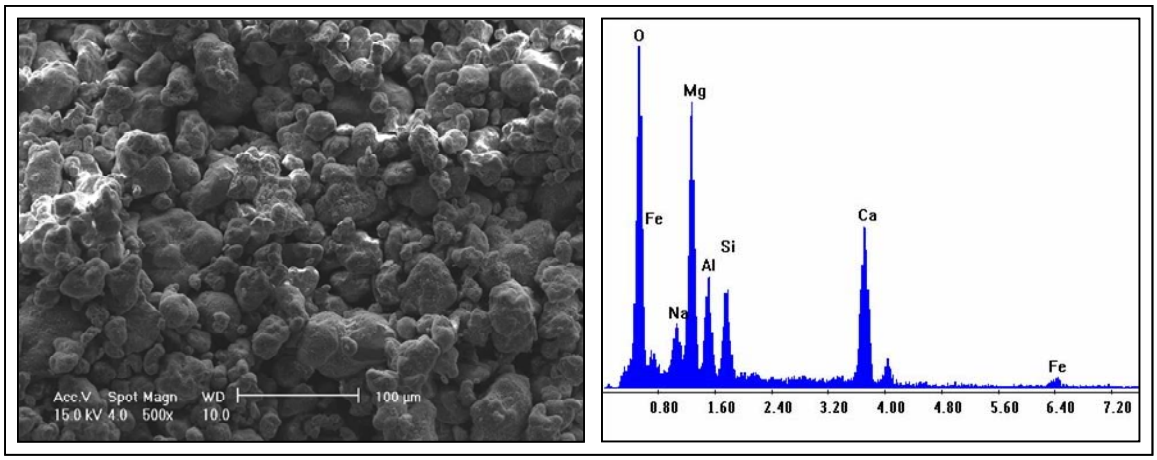


Figure 3-26. SEM Image and EDS Analysis of Gasifier Deposit.

The atmospheric syngas combustor refractory continued to show wear after over 25,000 hours of operation and was repaired on site at the conclusion of TC21. Figure 3-27 contains photographs of the syngas combustor before and after the refractory repair.


Figure 3-27. Atmospheric Syngas Combustor Before and After Refractory Repairs.

# 4.0 SENSOR DEVELOPMENT

## 4.1 Real-Time Particle Monitors

Development of real-time particulate monitors continued in TC21with the testing of the PCME DustAlert-90 and the Process Particle Counter (PPC) by Process Metrix. The PCME DustAlert-90 particulate monitor, referred to as the PCME, was operational throughout TC21. Because the instrument is not sensitive to particles smaller than 30 to 50 microns, it did not detect any of the slightly elevated particulate levels at the PCD outlet that were detected through in-situ sampling.

The Process Metrix Process Particle Counter (PPC) was retrofitted with coolant and purge gas heaters prior to TC21. The purge gas which flows around the optical windows to keep them clean was heated to 250°F, while the high pressure head coolant was heated to 150°F. A critical parameter in heating the PPC cell is the temperature limit (190°F) of the cement used to create the complex optical lenses located just behind the pressure boundary windows. With the above conditions, new thermocouples installed for this purpose indicated that the lenses operated between 160 and 170°F in TC21. After some initial shakedown problems, the PPC extraction and optical system operated reliably throughout TC21. The increased temperatures appeared to resolve the window contamination problems experienced in previous test campaigns.

For the first few days of TC21, the PPC indicated very high particle loading, even when syngas was not flowing. This was traced to a grounding problem that was allowing electrical noise to infiltrate into the counting circuit. Once the noise problem was resolved, the PPC gave very little output for the remainder of TC21. It did not detect the increased outlet particle concentrations during the in-situ sample Run 8, probably for the same reason that the PCME instrument did not. The vast majority of the mass consisted of particles smaller than the 3-micron lower limit of the PPC. Although light scattering particle counters are capable of measuring particles down to about 0.5 microns, this instrument was calibrated by Process Metrix to ignore small particles with this instrument for the purpose of increased sensitivity for larger particles that are more likely to damage turbines or other downstream equipment.

## 4.2 Pressure Differential Indicator Ceramic Inserts

To reduce instrument purge flow requirements and reduce plugging problems, ceramic inserts were installed on three gasifier pressure differential indicators (PDIs). These porous, ceramic inserts, manufactured by Foreman Instrumentation and Controls, prevent solids flow into the instrument, thereby reducing the amount of required purge flow by over 50 percent.

Testing of the inserts began in 2005 with installation in the riser and in the solids separation unit. Ceramic inserts were installed on two PDIs on the riser and one PDI on the seal leg. The ceramic inserts on the riser are the SGC05 design, a high differential pressure, low purge flow design. The seal leg differential pressure was fitted with MAC10 inserts, a low differential pressure, higher purge flow design. The SGC05 design has lower purge flow requirements but may be more prone to plugging. The main objective for insert testing during TC21 was to evaluate operability.

PDIs are calibrated prior to each test campaign. Calibration occurs while there is no significant flow or pressure drop to in the gasifier. Purge flows are set at an initial flow on the high and low legs of the analyzer, and the flow is tuned to zero the transmitter measurement. The SGC05 inserts proved difficult to calibrate, but the MAC10 insert calibrated well. Purge flow was established and adjusted to zero the transmitters prior to gasifier operation. Early in the test campaign, the PDI measurements with high pressure differential SGC05 inserts became plugged, and the associated pressure differential measurements were not usable. The MAC10-fitted PDI measurements corresponded closely with measurements from a standard PDI in approximately the same location.

### 4.3 Thermowell Materials

Because of the harsh gasifier conditions, demonstrating gasifier instrument longevity has been an ongoing objective. To this end, evaluation of gasifier thermowell materials continued during TC21. Wear of the thermowell tip is a primary concern in temperature element performance, and two materials have been tested and found suitable for gasifier operation: ceramic and HR-160 metal. The ceramic tips have generally shown higher erosion resistance than the HR-160 tips, but the ceramics are more prone to breakage, particularly during installation and removal.

Gasifier thermowell and thermocouple longevity has increased significantly since the gasifier modification of 2006, which had the effect of lowering riser velocities. just riser?. All of the eleven ceramic thermowells installed in the gasifier maintained acceptable condition, with no significant wear and no thermocouple failures. Most of the 45 HR-160 thermowells used in TC21 performed without problems, although one HR-160 thermowell failure occurred due to improperly installed insulating refractory which promoted corrosion. Three HR-160 thermowells which were located near an area in which agglomerations occurred showed significant wear from corrosion, although the associated thermocouples functioned throughout the test campaign. The corrosion on these thermowells may have been accelerated by high localized velocity from channeling around the deposit. Figure 4-1 shows the typical erosion observed on these three thermowells.

Figure 4-1. Eroded Gasifier Thermowell.

### 4.4 Promecon Velocity Probes

Gas velocity through the gasifier has not been measured continuously, but is estimated from the gas flow rate, pressure, and temperature measurements. To develop useful velocity measurements, six velocity probes manufactured by Promecon were modified to operate in a pressurized environment, and were installed in several locations of the riser at varying insertion lengths. Syntemp was licensed to modify the Promecon velocity probes for use in the gasifier, and these modifications included retrofitting the probes with ceramic tips and pressure resistant seals.

Velocity data from the probes contained much scatter and did not correspond well with the calculated velocity values. The instruments failed shortly after the test campaign began. Inspections revealed significant degradation of the probe tip sheath. Ceramic insulation on the probes was broken or missing on the probes, and the probes were sent to the manufacturer for further inspection.

### 4.5 Babcock & Wilcox High Frequency Pressure Sensors

The PSDF also provided the testing site for high frequency pressure sensors developed under sponsorship of the Electric Power Research Institute (EPRI) by Oak Ridge National Laboratory (ORNL) and Babcock &Wilcox. These sensors utilize advanced nonlinear signal analysis techniques for the purpose of monitoring gasifier performance.

For this testing, the Kistler piezotron pressure sensors were mounted on existing sensing lines at three locations on the gasifier—the lower standpipe and the middle and upper sections of the mixing zone. Data was collected during various phases of gasifier operation with high sodium lignite. Also, the PCD backpulse valve-open times, frequency, and pressure were varied to study perturbations in gasifier operation. Data analysis will be completed by Babcock & Wilcox.

### 4.6 Sensor Research and Development Semi-Conducting Metal Oxide Gas Sensors

During TC21, the PSDF provided the testing site for a prototype system developed by the Sensor Research and Development (SRD) Corporation as part of the Department of Energy (DOE) sensor program. The system tested was a prototype sensor system for in-situ real time detection, identification, and measurement of coal combustion gases. The sensor system incorporates SRD's semi-conducting metal oxide sensors and novel gas pre-filtration techniques. SRD had previously shown optimization of the gas delivery, sensor chamber, and data acquisition and control system for the testing of simulated flue gas.

SRD installed the miniaturized sensors to measure the composition of the flue gas from the atmospheric syngas combustor. The measurements trended well with the PSDF flue gas analyzer measurements. However, problems developed with the gas delivery system due to condensation in the inlet lines, and further testing was delayed.

# 5.0 PARTICULATE CONTROL DEVICE

The effects of lignite operation with the modified gasifier on PCD particulate characteristics and collection performance were quantified by in-situ particulate sampling at the inlet and outlet of the PCD and by physical and chemical analyses. Filter element testing continued with the exposure of 76 sintered-fiber Dynalloy HR-160 and 14 sintered-powder iron aluminide (FEAL) filter elements; however, on-line failsafe testing, which is typically completed during test campaigns, was not conducted due to outage time constraints. Further analyses of pressure drop performance and filter element condition were completed.

## 5.1 PCD Particle Collection Performance

In-situ particulate sampling was performed at the PCD inlet and outlet using the in-situ batch sampling systems described in previous reports. The inlet particle measurements were used to characterize PCD pressure drop performance and to calculate transient drag. The outlet measurements indicate the collection performance of the PCD.

***PCD Inlet Mass Loadings.*** Particle mass concentrations and mass rates measured at the PCD inlet are given in Table 5-1. The first eight inlet measurements were made with low sodium lignite and averaged 11,700 ppmw or 272 lb/hr. Run 9 with high sodium lignite gave slightly lower values of 10,200 ppmw and 179 lb/hr. Dolomite was fed when the last two samples, Runs 10 and 11, were taken. Run 10 produced a very high rate of 512 lb/hr, but a coal feeder trip during the sampling may have contaminated the sample with bed material. During Run 11, the coal feed rate was very low, so this data was not representative of normal operation.

Table 5-1. Results of In-Situ Sampling at the PCD Inlet and Outlet.

| | PCD Inlet | | | | | PCD Outlet | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Test Date | Run No. | Start Time | End Time | Particle Loading, ppmw | Particle Loading, lb/hr | Run No. | Start Time | End Time | $H_2O$ Vapor, vol % | Particle Loading, ppmw[2] |
| Low Sodium Lignite | | | | | | | | | | |
| 11/9/06 | -- | -- | -- | -- | -- | 1 | 8:50 | 14:00 | 9.5 | <1.04[1] |
| 11/10/06 | 1 | 10:15 | 10:30 | 12500 | 279 | 2 | 10:00 | 14:00 | 10.9 | 0.21 |
| 11/11/06 | 2 | 12:15 | 12:30 | 11700 | 262 | 3 | 9:30 | 13:30 | 14.2 | 0.16 |
| 11/14/06 | 3 | 9:00 | 9:15 | 10000 | 230 | 4 | 8:30 | 12:30 | 12.2 | 0.10 |
| 11/15/06 | 4 | 10:45 | 11:00 | 10600 | 247 | 5 | 8:45 | 12:45 | 13.4 | 0.17 |
| 11/16/06 | 5 | 9:00 | 9:15 | 11300 | 271 | 6 | 8:30 | 12:30 | 13.2 | <0.10 |
| 11/21/06 | 6 | 15:00 | 15:15 | 15100 | 399 | 7 | 12:00 | 16:00 | 14.0 | <0.10 |
| 11/22/06 | 7 | 8:30 | 8:45 | 14200 | 301 | 8 | 8:00 | 9:00 | 13.6 | 1.330 |
| 11/22/06 | 8 | 13:15 | 13:30 | 8300 | 185 | 9 | 13:20 | 14:20 | 13.8 | <0.10 |
| High-Sodium Lignite | | | | | | | | | | |
| 12/2/06 | 9 | 14:15 | 14:30 | 10200 | 179 | 10 | 14:05 | 15:05 | 11.6 | 0.49 |
| 1/25/07 | 10 | 12:25 | 12:36 | 24800 | 512[3] | 11 | 12:15 | 14:45 | 24.9 | 0.46[4] |
| 1/26/07 | 11 | 10:30 | 10:45 | 3200 | 66[5] | 12 | 10:00 | 13:30 | 25.5 | 0.41 |

Notes:
1. Coal feeder trip may have contaminated sample. Stopped from 8:52 till 12:30.
2. All outlet samples contaminated with iron sulfide particulate.
3. Coal feeder trip may have caused carryover. Dolomite feed ~300 lb/hr.
4. Run stopped from 12:36 till 13:06 for coal trip.
5. Very low coal feed rate. Reactor circulation problems.

The PCD inlet mass rates are plotted as a function of coal feed rate in Figure 5-1. The solid circles are the data collected with the low sodium lignite without dolomite addition, while the open circles show the results for high sodium lignite with dolomite added. The solid line is a linear regression to the low sodium data. The open triangles show the data collected during the TC20 test campaign with PRB coal. Comparison of the TC20 and TC21data sets indicates that the modified gasifier configuration is working for the low sodium lignite about the same as for the PRB coal. The difference between the two data sets is proportional to the ash content of the coal. Analysis of the modified gasifier configuration with high sodium lignite and dolomite is more problematic. The solid square symbols are data collected during TC16 with high sodium lignite and dolomite addition rates of 150 to 400 lb/hr. For the same coal feed rate, the PCD mass rate was three times higher during TC16. One of the TC21 data points approaches this level, but this sample may have been contaminated with bed material. However, even if the measured concentration is used, it still indicates a reduction in mass attributable to improved efficiency of the gasifier solids separation devices.

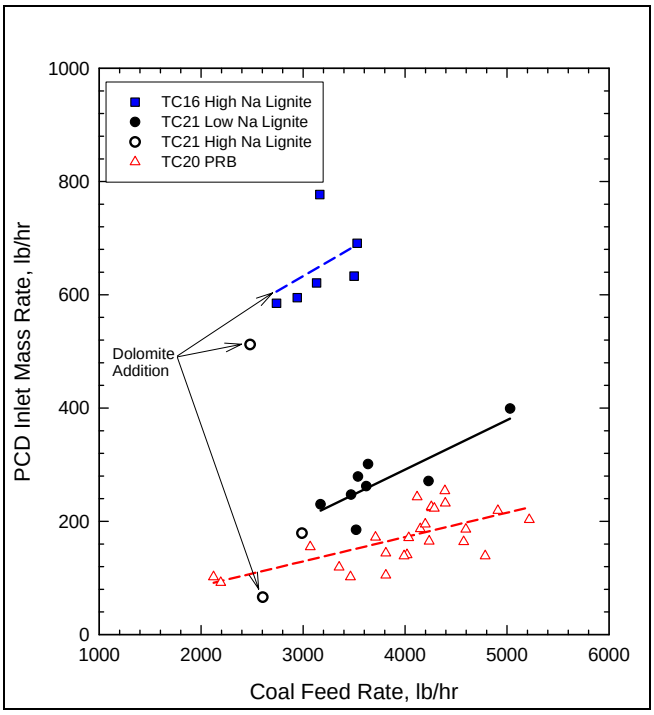


Figure 5-1. PCD Inlet Mass Rate as a Function of Coal Feed Rate.

*PCD Outlet Mass Loadings.* Particle concentrations measured at the PCD outlet are included in Table 5-1 and are plotted as a function of time in Figure 5-2. The graph also contains values measured during TC18, TC19, and TC20. Bars in the graph that are below the "Minimum Measurement Resolution" line are not actually measured values but merely placeholders to indicate the numbers of tests that had immeasurably low concentrations. As discussed in previous reports, it is common to see an elevated particle concentration at the outlet of the PCD during the first few days of a test campaign. This may be due to seasoning of filter elements and plugging of gasket pores or to particulate from corrosion products and mechanical assembly of the PCD. At the start of TC21, the particulate loadings remained above 0.1 ppmw (the minimum

measurement resolution) for the first 6 days of the test campaign. This was consistent with the initial operation during TC20 with the same filter element types in the PCD.

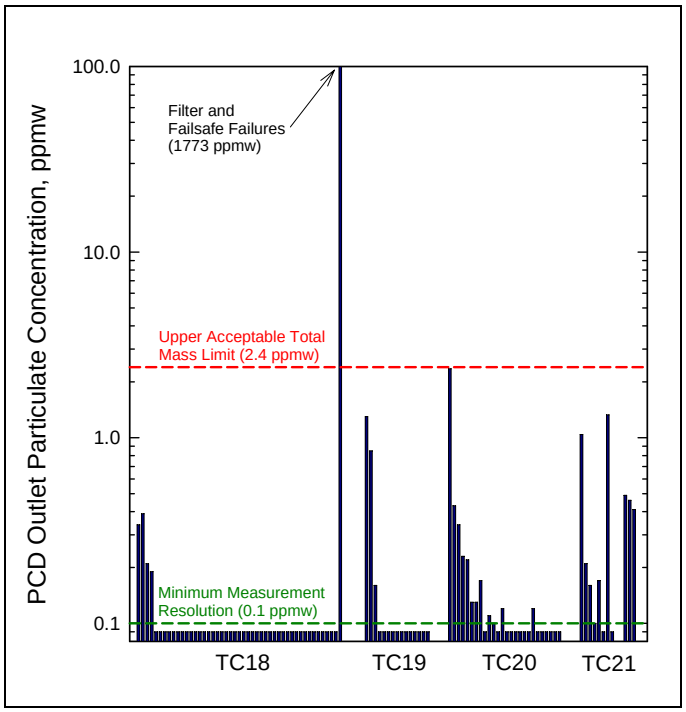


Figure 5-2. PCD Outlet Concentrations from TC18 through TC21.

Outlet Test 8 indicated a relatively high level of mass concentration (1.3 ppmw) at the PCD outlet. Since this test was conducted at a low gasifier temperature as part of parametric testing, the mass was assumed to be tar. This appeared to be confirmed when the next test conducted on the same day with a higher gasifier temperature did not show this mass. However, subsequent microscopic examination did not show the spherical tar globules and wet contamination generally associated with tar contamination. Instead the fine (less than 5 microns), black particles shown in Figure 5-3 were observed. The long fibers in the picture are part of the underlying sample filter. When ashed in air, the majority of the particulate changed color from black to rust red. When gasification ash is ashed it turns from black to dirty white. Energy dispersive X-ray spectroscopy (EDS) results from the original and the ashed particulate are shown in Figures 5-4 and 5-5, respectively. These data indicated that before ashing the particles were almost entirely composed of iron sulfide and that heating in air converted them to iron oxide. The small amounts of silicon (Si) and calcium (Ca) in the spectra are from the sample filter.


Figure 5-3. Scanning Electron Microscope Image of Sample Filter from Outlet Run 8.

After obtaining this result in TC21, many past sample filters were re-examined and iron sulfide contamination was found in sample filters starting in TC16, although it generally occurred in the first days of the test campaigns, and the degree of contamination was relatively minor. The possibility of corrosion product contamination of the outlet of the PCD was first introduced in the TC20 report. For the TC21 samples, all of the tests that show elevated concentrations had some degree of iron sulfide contamination, although the fraction of the total mass cannot be estimated. Of the three samples collected with high sodium lignite, a majority of the mass appears to be associated with iron sulfide.

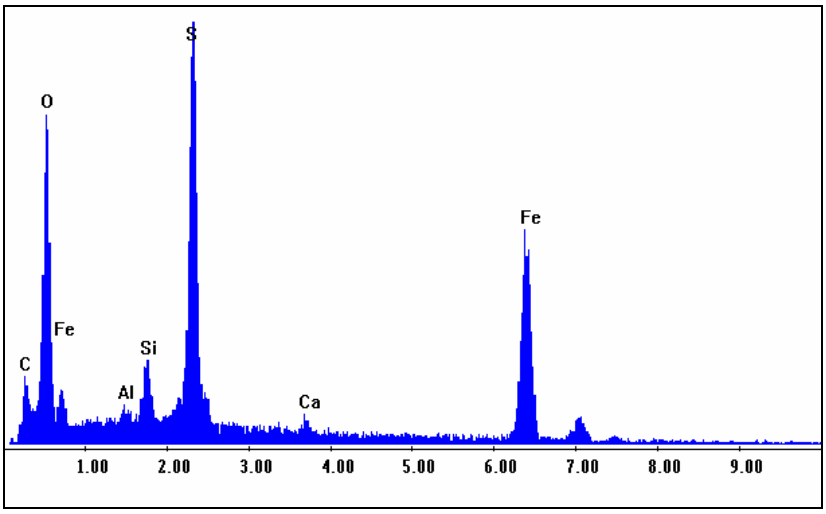


Figure 5-4. EDS Spectrum for Particles on Sample Filter from Outlet Run 8.

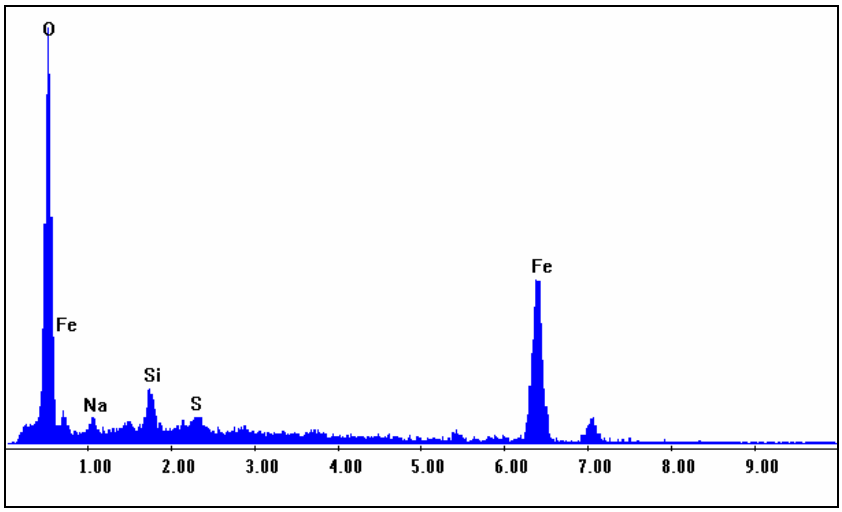


Figure 5-5. EDS Spectrum for Ashed Particles on Sample Filter from Outlet Run 8.

There are several possible routes for the iron sulfide particulate to appear at the PCD outlet. A fine fume of iron sulfide particles generated in the gasifier could penetrate through the PCD filter elements, or the particles could be generated at the outlet of the PCD. Since some of the particles are as large as 5 microns, penetration through the PCD as a particulate seems unlikely, even with a majority of the metal fiber filter elements installed in the PCD. Penetration of a vapor through the PCD with downstream condensation during contact with cool back-pulse gas is possible, but a mechanism for producing iron sulfide particles in this manner has not been determined. Sources at the outlet of the PCD could include contaminated backpulse gas, contaminated instrument purge gas, or entrainment of corrosion products from the metal surfaces in the outlet of the PCD. This issue will be further evaluated during future test campaigns.

## 5.2 PCD Solids Analysis

PCD pressure drop, cleaning requirements, and bridging tendency can be influenced by changes in the characteristics of the solids being collected in the PCD. Important characteristics of the solids include particle size distribution, bulk density, true density, porosity, surface area, composition, and flow resistance. The effect of all these parameters must be considered in analyzing the performance of the PCD.

### 5.2.1 Particle Size Distributions

A Microtrac X-100 particle size analyzer was used to measure the particle size distributions of the in-situ particulate samples collected at the PCD inlet and the PCD hopper sample used for the laboratory drag measurements. The most significant change in particle parameters expected to result from the change in the gasifier modifications was a shift in particle size distribution, since the cyclonic action of the solids separation devices tends to retain the largest particle fractions leaving a higher percentage of small particles. A very fine size distribution can cause high pressure drop across the PCD tubesheet. TC21 data will determine if the same effect is obtained with lignite coal as for the PRB.

***In-Situ Samples.*** Figure 5-6 shows the average differential mass particle size distribution measured on the PCD inlet in-situ samples and compares these data to a similar distribution from the second half of TC20. Only the low sodium lignite data are included here because of unstable operation with the high sodium fuel. These data indicate that the increased mass at the PCD inlet with the lignite coal is composed of particles larger than 3 microns and not in the small particle range. This change could be expected to lower the normalized drag of the particulate collected in the PCD (which will be examined in a later section). The data also indicate a shift in the right side of the distribution for particles larger than 20 microns.

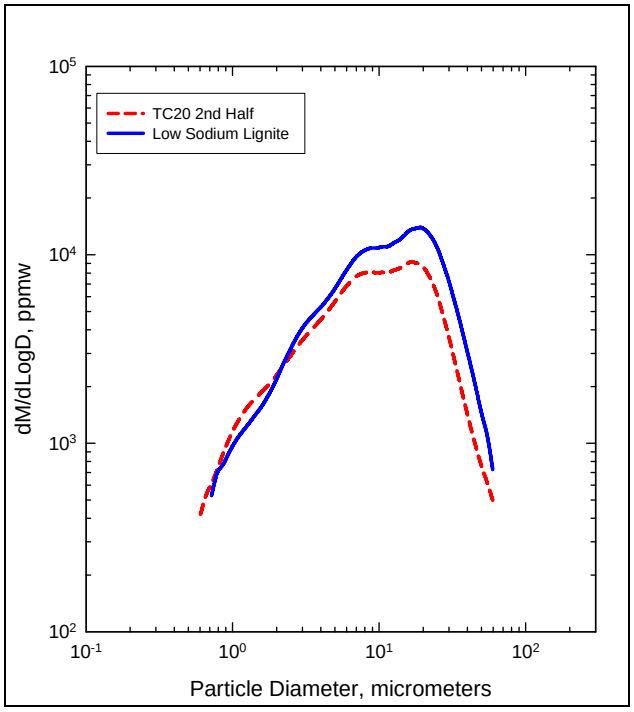


Figure 5-6. Comparison of Particle Size Distributions from In-Situ Samples.

***Hopper Samples.*** Figure 5-7 compares the differential mass percentage distributions for the in-situ samples with the original composite hopper sample used for the TC21 lab drag measurements. (Although the in-situ samples are a more accurate representation of the particulate entering the PCD at a given time, they are far too small of be useful for drag measurements.) The data almost perfectly overlay, indicating that the hopper sample selected is representative of the low sodium lignite particulate generated in TC21.

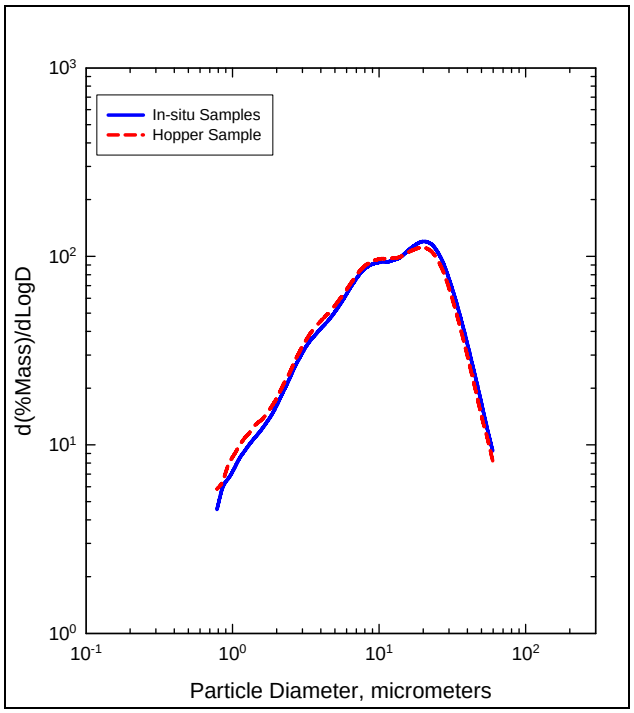


Figure 5-7. Comparison of TC21 Particle Size Distributions.

### 5.2.2 Dustcake Observations

One of the objectives of TC21 was to commission a dedicated combustion air control system installed at the PCD inlet to affect a controlled burnoff of the dustcake after the system shutdown. As explained in previous reports, a controlled burnoff of the carbon in the dustcake may be desirable for commercial PCD operations so that the system can be safely restarted after a shutdown. If any combustible dustcake is left on the filter elements after a shutdown, the cake could burn in an uncontrolled fashion during the restart in combustion mode, and this could damage the filter elements. To avoid this scenario, the commercial shutdown procedure may include a controlled burnoff of the dustcake.

Dustcake burnoff tests with the new air control were conducted on December 3 and December 4, 2006. The burnoff test on December 3 was started with the initial filter element temperatures in the range of 510 to 530°F without coal feed. Air was introduced to gradually increase the oxygen level to 2 to 3 percent where a maximum temperature rise of about 14°F was measured by thermocouples installed on the filter elements. During subsequent testing at higher air flows, the air flow control valve did not function properly under automatic control, but it did close automatically as programmed when the oxygen level reached 6 percent.

After the first burnoff test on December 3, the problem with the air flow control valve was resolved, and the gasifier was operated on coal for about 20 hours before the second burnoff test was done on December 4, 2006. Since the temperature rise during the first test was only 14°F, this time PCD backpulsing was stopped 5 minutes prior to stopping coal feed to provide plenty of combustible char for the burnoff. The air line to the PCD inlet had been warmed up for about 10 minutes prior to the second burnoff test, and the PCD inlet temperature was about 680°F.

To start the second burnoff test, the air flow into the PCD inlet was gradually increased to produce 1 percent oxygen in the gas, but no temperature increases were observed on the filter element thermocouples. The air flow was then increased to produce 2 percent oxygen in the gas, and large temperature spikes (up to 920°F) were noted on one of the top plenum thermocouples and one of the bottom plenum thermocouples. This sudden spike in temperature caused an automatic shutdown of the air flow and activated the automatic nitrogen back-pulse system. After the trip, the air line was reopened, and the oxygen level was gradually increased to 5 percent without any temperature increases. It was not obvious whether the burnoff had been effective, but the entire cake was preserved for subsequent sampling to assess the degree of burnout.

The dustcake was sampled through the PCD manway on December 6, 2006. The dustcake sample did not appear to show any signs of adverse effects from the burnoff procedure, such as sintering, but the appearance of the cake suggested that it still contained a lot of carbon (60 percent NCC, as discussed in a later section). Despite the lack of burnout, the new air line was successfully commissioned, and the automatic shutdown of the air flow in response to temperature spikes and high oxygen levels was successfully demonstrated.

During the subsequent portion of TC21, gasifier operation was unsteady due to agglomeration problems with the high sodium lignite. Moreover, the dustcake formed in this portion of the test campaign was probably not representative due to the addition of large amounts of dolomite. Because of these concerns, no burnoff test was conducted at the conclusion of TC21, and no dustcake samples were analyzed. The dustcake from December 6, 2006, was analyzed and will be discussed in the next section.

### 5.2.3 Particulate Physical Properties and Chemical Compositions

Measurements of the physical properties and chemical composition were made on all of the TC21 in-situ samples collected at the PCD inlet, on one composite hopper sample that was used for laboratory drag measurements, and on the December 6 dustcake sample. The composite hopper sample that was tested was representative of steady operation on the low sodium lignite. A composite hopper sample was not prepared for the high sodium lignite portion of the test campaign, since test conditions were too unstable to draw meaningful conclusions.

*In-Situ Samples.* Tables 5-2 and 5-3 give the physical properties and chemical compositions of the in-situ samples collected at the PCD inlet and the composite hopper sample used for lab drag measurements. All of the in-situ samples had fairly consistent densities and porosities, but there were substantial variations in surface area and non-carbonate carbon (NCC) content. As observed in the past, the surface area increased with increasing NCC (see Figure 5-8). Due to the limited number of samples obtained with the high sodium lignite, it is difficult to make any definitive comparisons of the particulate properties with the low and high sodium lignite coals. However, the surface area of the high sodium lignite ash appeared to be relatively low compared to that of the low sodium lignite ash. In the past, the high sodium lignite ash generally has had very low surface area and low drag.

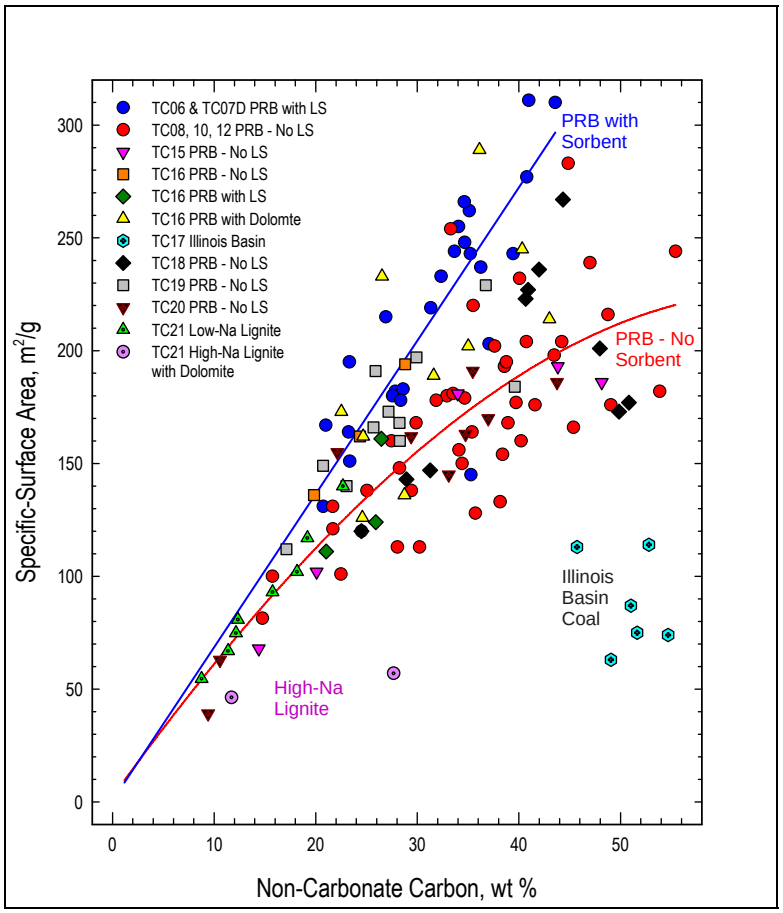


Figure 5-8. Specific Surface Area as a Function of Non-Carbonate Carbon Content.

Table 5-2. Physical Properties of In-Situ Samples and Sample Used for Lab Measurements.

| Sample ID | Run No. | Sample Date | Bulk Density, g/cc | True Density, g/cc | Bulk Porosity, % | Surface Area, $m^2/g$ | Mass Median Particle Size, µm | Loss on Ignition, % |
|---|---|---|---|---|---|---|---|---|
| *In-Situ Samples, Low-Sodium Lignite* | | | | | | | | |
| AB22493 | 1 | 11/10/06 | 0.28 | 2.53 | 88.9 | 102 | 13.4 | 18.73 |
| AB22494 | 2 | 11/11/06 | 0.31 | 2.57 | 87.9 | 93 | 13.6 | 17.59 |
| AB22495 | 3 | 11/14/06 | 0.33 | 2.74 | 88.0 | 67 | 12.6 | 12.27 |
| AB22496 | 4 | 11/15/06 | 0.34 | 2.77 | 87.7 | 55 | 11.4 | 9.41 |
| AB22497 | 5 | 11/16/06 | 0.31 | 2.74 | 88.7 | 75 | 12.2 | 12.56 |
| AB22498 | 6 | 11/21/06 | 0.27 | 2.57 | 89.5 | 117 | 9.6 | 19.00 |
| AB22499 | 7 | 11/22/06 | 0.31 | 2.47 | 87.4 | 140 | 10.8 | 23.51 |
| AB22500 | 8 | 11/22/06 | 0.30 | 2.69 | 88.8 | 81 | 11.1 | 12.91 |
| *In-Situ Samples, High-Sodium Lignite* | | | | | | | | |
| AB22501 | 9 | 12/02/06 | 0.37 | 2.39 | 84.5 | 57 | 9.2 | 32.50 |
| AB22682 | 10 | 01/25/07 | 0.60 | 2.91 | 79.4 | 46 | 7.0 | 14.92 |
| AB22683 | 11 | 01/26/07 | 0.40 | N.M. | N.M. | N.M. | 12.0 | N.M. |
| *Sample Used for Lab Drag Measurements* | | | | | | | | |
| AB22603 | Composite | 11/14/06 | 0.30 | 2.62 | 88.5 | 85 | 10.9 | 15.65 |

Table 5-3. Chemical Composition of In-Situ Samples and Sample Used for Lab Measurements.

| Sample ID | Run No. | Sample Date | $CaCO_3$ Wt % | CaS Wt % | CaO Wt % | Non-Carbonate Carbon Wt % | Inerts (Ash/Sand) Wt % | Loss on Ignition Wt % |
|---|---|---|---|---|---|---|---|---|
| *In-Situ Samples - Low-Sodium Lignite* | | | | | | | | |
| AB22493 | 1 | 11/10/06 | 2.98 | 3.40 | 13.47 | 18.15 | 60.69 | 18.73 |
| AB22494 | 2 | 11/11/06 | 2.55 | 2.19 | 13.97 | 15.74 | 64.43 | 17.59 |
| AB22495 | 3 | 11/14/06 | 1.73 | 1.83 | 16.72 | 11.37 | 67.58 | 12.27 |
| AB22496 | 4 | 11/15/06 | 1.68 | 1.28 | 19.06 | 8.77 | 68.47 | 9.41 |
| AB22497 | 5 | 11/16/06 | 2.34 | 1.66 | 17.35 | 12.15 | 65.47 | 12.56 |
| AB22498 | 6 | 11/21/06 | 3.45 | 4.07 | 13.62 | 19.18 | 58.16 | 19.00 |
| AB22499 | 7 | 11/22/06 | 3.09 | 3.32 | 11.43 | 22.68 | 58.11 | 23.51 |
| AB22500 | 8 | 11/22/06 | 2.34 | 2.08 | 14.62 | 12.34 | 67.58 | 12.91 |
| *In-Situ Samples - High-Sodium Lignite* | | | | | | | | |
| AB22501 | 9 | 12/02/06 | 4.39 | 0.76 | 15.19 | 27.67 | 50.07 | 32.50 |
| AB22682 | 10 | 01/25/07 | 2.52 | 0.00 | 21.43 | 11.72 | 63.22 | 14.92 |
| AB22683 | 11 | 01/26/07 | Insufficient Sample for Analysis | | | | | |
| *Sample Used for Lab Drag Measurements* | | | | | | | | |
| AB22603 | CFAD Composite | 11/14/06 | 2.80 | 2.26 | 14.50 | 15.56 | 63.66 | 15.65 |

*Hopper Samples.* For lab drag measurements, a composite sample was prepared from hopper samples collected on November 11, 2006, during a period of stable, representative operation with the low sodium lignite. Due to the operational problems with the high sodium lignite, it was not possible to identify hopper samples that were representative of stable operation with high sodium. Therefore, only the physical properties and chemical composition of the low sodium sample are included here. The composite hopper sample for this condition appeared to be similar to the in-situ samples in terms of both physical properties and chemistry and thus was a representative sample for the laboratory drag measurements with the low sodium lignite ash.

*Dustcake Samples.* Tables 5-4 and 5-5 give the physical properties and chemical composition of the dustcake sample taken on December 6 after the dirty shutdown. Prior to TC20, the dustcake had a finer mean particle size than the in-situ samples. This effect, which has been attributed to

fine-particle enrichment associated with reentrainment of backpulsed particulate, was not seen in TC20, and was also not seen in TC21. The reason is unknown but may be related to the collection of finer particles in the gasifier solids separation devices.

Table 5-4. Physical Properties of Dustcake Sample.

| Sample ID | Sample Date | Bulk Density g/cc | True Density g/cc | Uncompacted Bulk Porosity % | Specific Surface Area $m^2/g$ | Mass-Median Diameter μm | Loss on Ignition Wt % |
|---|---|---|---|---|---|---|---|
| *Bulk Dustcake after Burnoff, Sampled 12/6/06* | | | | | | | |
| AB22545 | 12/06/06 | 0.25 | 2.03 | 87.7 | 258 | 12.1 | 68.32 |

Table 5-5. Chemical Composition of Dustcake Sample.

| Sample ID | Sample Date | $CaCO_3$ Wt % | CaS Wt % | CaO Wt % | Non-Carbonate Carbon Wt % | Inerts (Ash/Sand) Wt % | Loss on Ignition Wt % |
|---|---|---|---|---|---|---|---|
| *Bulk Dustcake after Burnoff, Sampled 12/6/06* | | | | | | | |
| AB22545 | 12/6/06 | 4.23 | 2.66 | 3.80 | 60.47 | 28.84 | 68.32 |

## 5.3 PCD Pressure Drop Performance

*Transient PCD Drag.* The pressure drop rise within a cleaning cycle of the PCD is a direct measure of the characteristics of the particulate being collected at that time. Under stable operation the vast majority of this particulate is removed from the filter elements during cleaning so this is referred to as the transient pressure drop. Since pressure drop is a function of the gas velocity, temperature (gas viscosity), particulate loading, and the flow resistance of the particulate, describing PCD operation in terms of pressure drop makes comparison of different conditions and dusts difficult. Instead, a value of normalized drag is calculated which is pressure drop normalized to 1 ft/min face velocity, 1 $lb/ft^2$ areal particulate loading, and viscosity of air at 70°F. The result is a fundamental parameter that describes the flow resistance of the collected dustcake, and it allows direct comparisons to the drag measurements made in the lab.

During each in-situ sampling run at the PCD inlet, the PCD transient drag was calculated using the measured particle concentration along with the pressure drop increase and face velocity during the period of the in-situ test. All of the particulate measured at the PCD inlet is assumed to be collected on the filter elements and to contribute to pressure drop. The inputs and results of the drag calculations are shown in Table 5-6. The calculated transient drag at PCD conditions is listed under the column heading "PCD." The corresponding value of transient drag normalized for viscosity (air at room temperature) is listed under the heading "PCD@RT". These values are

comparable to the lab drag measurements discussed in a later section and may also be compared directly to other test campaigns that operated at different temperatures.

Table 5-6. Transient Drag Determined from PCD Pressure Drop and from Lab Measurements.

| Run No. | ΔP/Δt, inwc/min | Δ(AL)/Δt, lb/ft$^2$/min | FV, ft/min | MMD, μm | NCC, % | Drag, inwc/(lb/ft$^2$)/(ft/min) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | PCD | PCD@RT | Lab |
| Low Sodium Lignite | | | | | | | | |
| 1 | 0.64 | 0.017 | 3.04 | 13.4 | 18.2 | 37 | 23 | 25 |
| 2 | 0.50 | 0.016 | 3.16 | 13.6 | 15.7 | 31 | 19 | 23 |
| 3 | 0.43 | 0.014 | 3.84 | 12.6 | 11.4 | 30 | 18 | 22 |
| 4 | 0.41 | 0.015 | 3.93 | 11.4 | 8.8 | 27 | 16 | 23 |
| 5 | 0.49 | 0.017 | 3.38 | 12.2 | 12.2 | 29 | 17 | 24 |
| 6 | 1.09 | 0.025 | 3.71 | 9.6 | 19.2 | 44 | 26 | 38 |
| 7 | 0.65 | 0.019 | 2.82 | 10.8 | 22.7 | 35 | 21 | 37 |
| 8 | 0.31 | 0.011 | 3.03 | 11.1 | 12.3 | 27 | 16 | 27 |
| High Sodium Lignite | | | | | | | | |
| 9 | 0.37 | 0.011 | 3.34 | 9.2 | 27.7 | 33 | 21 | 52 |
| 10 | 0.31 | 0.032 | 4.34 | 7.0 | 11.7 | 10 | 6 | 45 |
| 11 | 0.15 | 0.004 | 4.26 | 12.0 | NA | 37 | 23 | |
| Avg | 0.49 | 0.016 | 3.53 | 11.2 | 16.0 | 31 | 19 | 32 |
| Lab drag data calculated from linear regression to MMD and NCC of lab drag samples. | | | | | | | | |

Nomenclature:
ΔP/Δt = rate of pressure drop rise during particulate sampling run, inwc/min.
Δ(AL)/Δt = rate of increase in areal loading during sampling run, lb/min/ft$^2$.
FV = average PCD face velocity during particulate sampling run, ft/min.
MMD = mass-median diameter of in-situ particulate sample, microns.
NCC = non-carbonate carbon.
LOI = loss on ignition.
RT = room temperature, 77°F (25°C).

The TC21 data shown in Table 5-6 indicate an average normalized drag value of 19 in$H_2O$/(ft/min)/(lb/ft$^2$). This is much lower than the TC20 value of 78 in$H_2O$/(ft/min)/(lb/ft$^2$) with PRB coal. The much lower drag with the lignite coal is attributable to the larger particle size distribution, lower surface area, lower carbon content of the particulate, and perhaps differences in particle morphology. Because of the reduced drag, the increased mass loading to the PCD with the higher ash content of the lignite fuel should not result in increased PCD pressure drop.

Normalized PCD transient drag is plotted as a function of carbon content in Figure 5-9. As seen in previous test campaigns, transient drag increases with increasing carbon content in the

gasification ash. This correlation shows a lot of scatter in the data, because it does not take into account the effect of particle size. However, both the low sodium lignite without dolomite addition and the high sodium lignite with dolomite addition fall around the same line previously established for lignite coals. It would appear that the dolomite addition has little effect on drag.

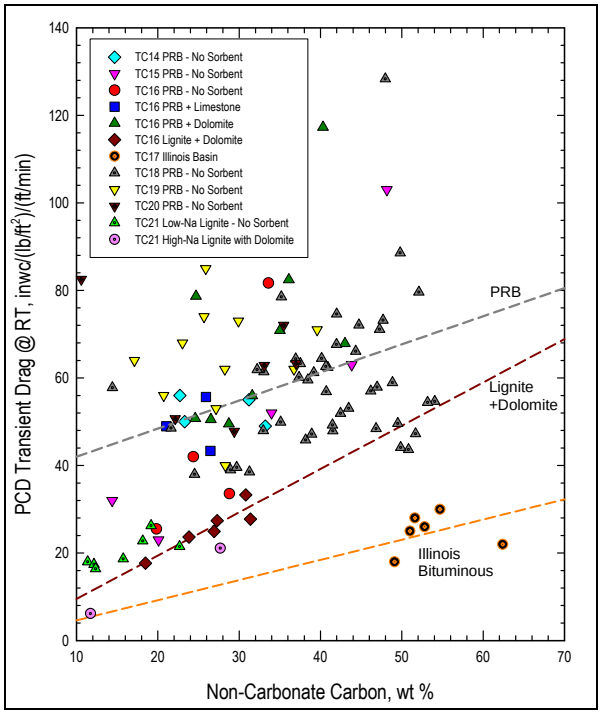


Figure 5-9. PCD Transient Drag as a Function of Non-Carbonate Carbon Content.

Figure 5-10 shows the PCD transient pressure drop rise rate for TC20 and for the low sodium lignite operation during TC21. The rise rate is calculated from the PCD pressure drop just before pulse cleaning minus the pressure drop just after cleaning divided by the cleaning cycle time. Both test data sets indicated that the pressure drop rise declined with time, but on average the TC21 transient pressure drop was about half that observed in TC20. This is consistent with TC21 measurements indicating twice as high inlet loading with drag values four times lower at about the same temperature and gas flow conditions. The high sodium test at the end of TC21 was too short and unstable for analysis.

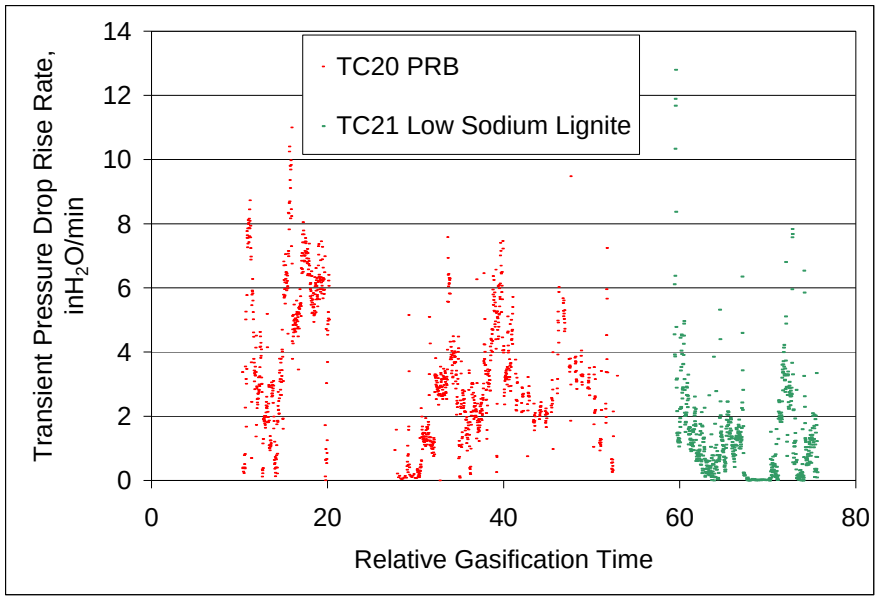


Figure 5-10. Pressure Drop Rise Rate for TC20 and TC21 Low Sodium Lignite Operation.

## 5.4 Prediction of PCD Drag and Pressure Drop

***Lab Drag Measurements.*** Drag measurements were made in the lab flow resistance test device on the single low sodium lignite hopper sample. The lab apparatus uses a series of cyclones between the dust generator and the dustcake collection surface to vary the particle size distribution of the dustcake. The results are illustrated in Figure 5-11 with normalized drag plotted against the mass median diameter (MMD) of the collected dustcake. The actual lab data points are indicated by the squares, while the solid line is a linear regression to the data.

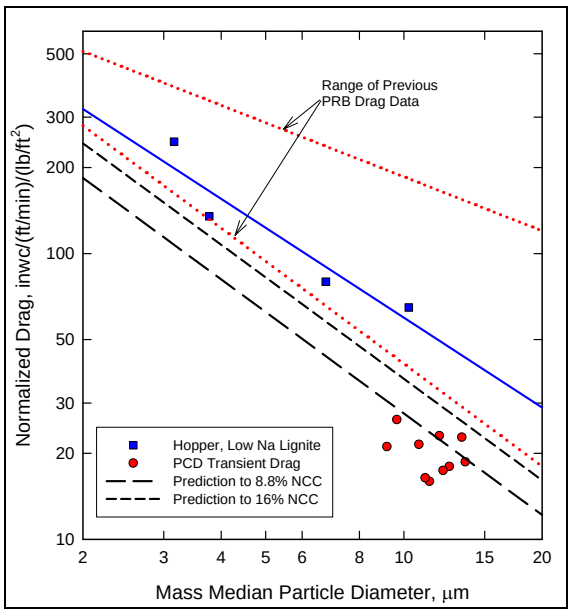


Figure 5-11. Lab Measured Drag as a Function of Particle Size.

The dotted lines on the graph represent the range of PRB drag data measured previously. The TC21 lab data fall toward the bottom of this range as is typical of lignite. The solid circle symbols on the graph are the values of PCD transient drag calculated for each of the in-situ samples from Table 5-6. As seen in recent test campaigns, all of the PCD data points fell below the lab measurements partially because of differences in carbon contents. When the actual value of carbon in the lab samples was used (26 to 36 percent) instead of the bulk value of 16 percent, the following multiple regression equation was obtained:

$$\text{Drag} = 10^{(2.498 - 1.179 \cdot \text{Log}(\text{MMD}) + 0.0129 \cdot \text{NCC})}, \text{ with an } r^2 = 0.94.$$

The regression equation suggests that the slope of drag as a function of particle size was about the same as for PRB, while the effect of carbon content was about double for the lignite. The y-intercept was also lower for the lignite, dropping the whole curve to lower drag values.

The regression was used to calculate drag versus particle size with two different carbon contents that are equal to the lowest and the average carbon contents of the in-situ samples, 8.8 percent and 16 percent NCC, respectively. These predictions are shown on Figure 5-12 as the dashed lines. Although not in perfect agreement, the predictions made from the regression technique match the PCD data reasonably well.

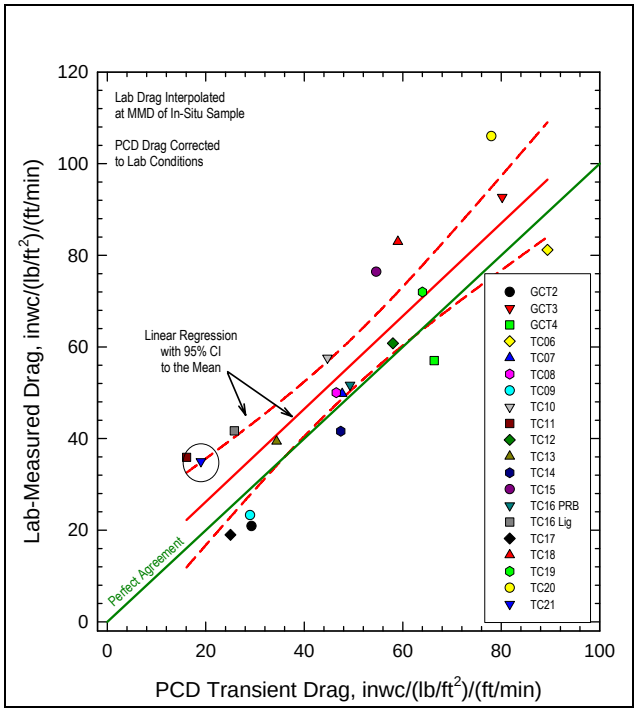


Figure 5-12. Comparison of PCD Transient Drag with Lab Measurements.

The results of regression predictions for each individual value of PCD transient drag are shown in the rightmost column of Table 5-6. These calculations use the MMD and NCC of each in-situ sample to predict the transient drag of the PCD during that test. The lab predictions are higher than the actual PCD data for both each individual value and the average for TC20, but this still appears to be reasonable agreement.

*Comparison of Lab Measurements with Transient Drag.* Average lab and PCD drag values for all gasification test campaigns are summarized in Table 5-7. The comparison shows excellent overall historical agreement (average difference of about 12 percent), even though the difference is much higher for certain test campaigns. For TC21, the difference was 51 percent, which is the second largest disagreement observed. The lignite coals have extremely low drag, and more disagreement can probably be tolerated. The results for all gasification test campaigns are plotted in Figure 5-12 and continue to show that the data points are scattered around the perfect agreement line. The TC21 data point is circled to make it easier to locate on the graph. Despite the large percentage disagreement for this test campaign the point actually lies right on the 95 percent confidence interval to the mean of the data.

Table 5-7. Comparison of Average Drag Values Determined from PCD Performance and Lab Measurements.

| Run | Coal | Average Transient Drag Determined from PCD Performance, inwc/(lb/ft$^2$)/(ft/min) | Average Drag Determined from RAPTOR Lab Measurements, inwc/(lb/ft$^2$)/(ft/min) | Difference from Mean Value*, % |
|---|---|---|---|---|
| GCT2 | PRB | 29.3 | 20.9 | -33.5 |
| GCT3 | PRB | 80.2 | 92.7 | 14.5 |
| GCT4 | PRB | 66.4 | 57 | -15.2 |
| TC06 | PRB | 89.4 | 81.2 | -9.6 |
| TC07 | PRB | 47.7 | 49.8 | 4.3 |
| TC08 | PRB | 46.5 | 50 | 7.3 |
| TC09 | Hiawatha | 29.0 | 23.3 | -21.8 |
| TC10 | PRB | 44.7 | 57.6 | 25.2 |
| TC11 | Falkirk Lignite | 16.1 | 35.9 | 76.2 |
| TC12 | PRB | 58.0 | 60.8 | 4.7 |
| TC13 | Freedom Lignite | 34.4 | 39.4 | 13.6 |
| TC14 | PRB | 47.4 | 41.6 | -13.0 |
| TC15 | PRB | 54.6 | 76.4 | 33.3 |
| TC16 | PRB + Limestone | 49.3 | 51.7 | 4.8 |
| TC16 | Lignite + Dolomite | 25.8 | 41.7 | 47.1 |
| TC17 | IL Basin | 24.8 | 18.7 | -27.8 |
| TC18 | PRB | 59.0 | 82.0 | 32.6 |
| TC19** | PRB | 64.0 | 72.0 | 11.8 |
| TC20** | PRB | 78.0 | 108.0 | 32.3 |
| TC21** | Lignite | 19.0 | 32.0 | 51.0 |
| *Average* | | 48.2 | 54.6 | 11.9 |

* D = (R1-R2)/(R1+R2)/2*100
** Technique modified to use carbon content of lab drag sample

## 5.5 Analysis of PCD Filter Element Condition

At the end of TC21, all the filter elements and failsafes were removed from the PCD to analyze the state of the filter elements and to allow reconfiguration of the filter element layout. A main purpose of the layout used during TC20 and TC21 was to evaluate the collection performance of the PCD with a majority of Dynalloy fiber filter elements installed. Since these elements demonstrated acceptable performance, future plans are to install an equal number of FEAL sintered-powder and Dynalloy fiber elements to allow direct comparison of these two filter element types in subsequent test campaigns.

Since the dustcake was burned off at the end of TC21, the filter elements removed from the PCD were flow tested in two conditions, with the dustcake mechanically removed (but particulate still in the pores) and with the dustcake completely removed by pressure washing. There were only a few FEAL sintered-powder filter elements installed for TC21, and the pressure drops in air at a face velocity of 3 ft/min are plotted in Figure 5-13. As seen previously, both the dirty pressure drop and the clean pressure drop increase with total gasification exposure time for a given filter element, although the dirty pressure drop increases more quickly. In the next test campaign, 36 FEAL sintered-powder filter elements will be installed to provide a better sampling of the elements for assessment of corrosion and filter element life.

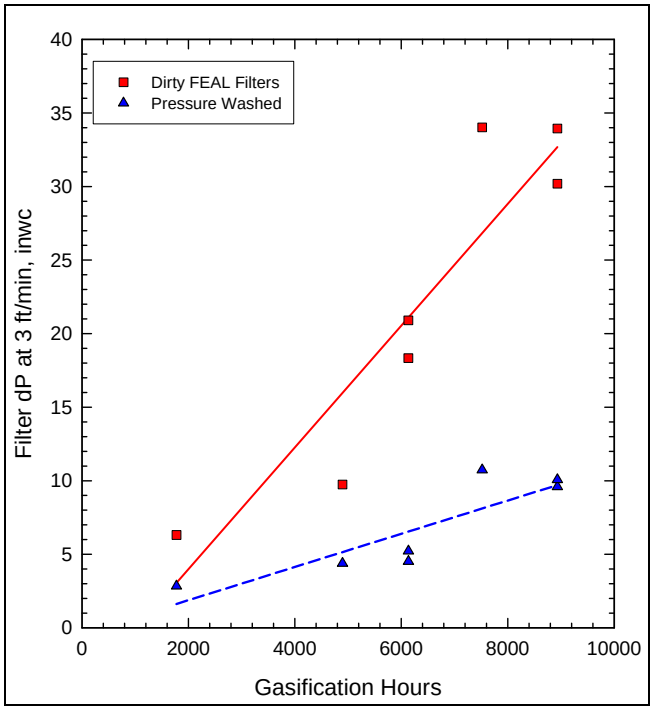


Figure 5-13. Effect of Gasification Hours on FEAL Filter Element Pressure Drop.

Figure 5-14 shows the flow test results for a number of the Dynalloy HR-160 fiber filter elements. These filter elements are still relatively young and have either 1,982, 1,674, or 1,258 gasification exposure hours after TC21. Although there is a slight positive slope to the regression line to the dirty data, it is very shallow and unlike the FEAL results to date. When the

Dynalloy filter elements are pressure washed, the filter element pressure drop is nearly immeasurable on the flow test device.

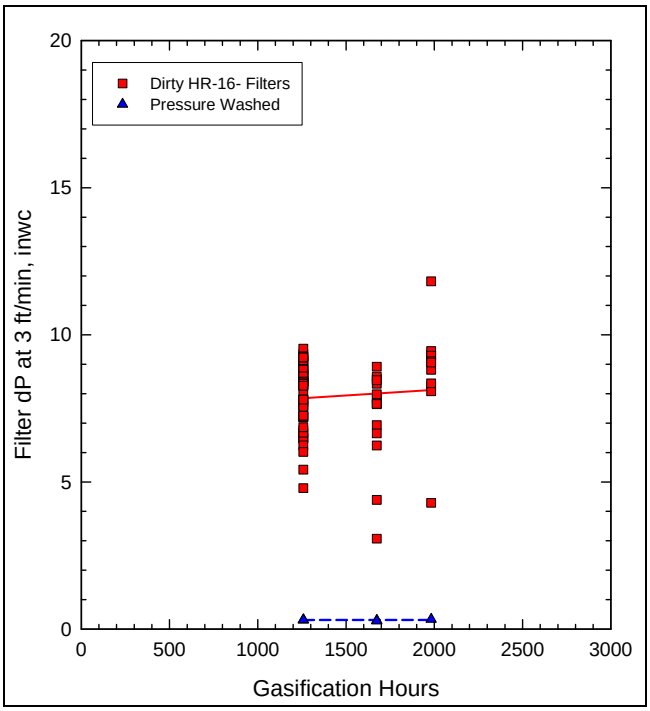


Figure 5-14. Effect of Gasification Hours on Dynalloy Filter Element Pressure Drop.

## 6.0 ADVANCED SYNGAS CLEANUP

The advanced syngas cleanup unit was used in TC21 for testing of COS hydrolysis with the Alcoa 200 catalyst. Syngas desulfurization was also performed using the Puraspec 2010 and Puraspec 2020 sorbents from Synetix. After the sulfur treatment, the syngas was delivered to the TDA Research trace metals removal test unit. Syngas cooler fouling was evaluated while temperatures were lowered below the dew point of the syngas stream.

### 6.1 COS Hydrolysis Testing

During TC21, the Alcoa 200 COS hydrolysis catalyst was tested for a period of 183 hours, 158 hours during low sodium lignite operation and 25 hours during high sodium lignite operation. The same catalyst material was utilized in TC20, and the total syngas exposure hours for this material at the conclusion of TC21 was 313 hours.

During gasifier operation with low sodium lignite, the syngas flow through the catalyst bed was maintained at 30 lb/hr, the inlet temperature was 400°F, and the operating pressure was 200 psig. The average inlet COS concentration was 62 ppmv, and the average COS conversion was 89 percent. During high sodium lignite operation, testing was conducted with a syngas flow rate of 20 lb/hr at 375ºF and 120 psig. The average inlet COS concentration was 14 ppmv, and the average COS conversion efficiency was 87 percent. The measured inlet COS concentration and the conversion efficiency are shown in Figure 6-1, and the nominal catalyst properties and operating parameters for the COS hydrolysis testing are shown in Table 6.1.

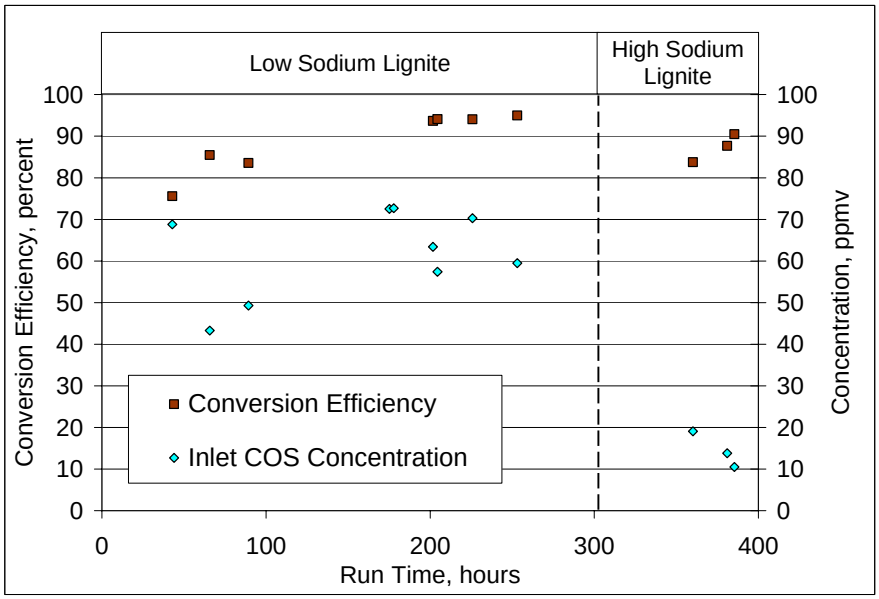


Figure 6-1. COS Hydrolysis Testing.

Table 6-1. COS Hydrolysis Catalyst Properties and Nominal Operating Parameters.

| | |
|---|---|
| Catalyst Supplier | Alcoa |
| Catalyst Type | F200 |
| Physical Properties | |
| Aluminum Oxide Content, wt % | 94—100 |
| Shape | Spheres |
| Size, mm | 3.2 |
| Density, lb/ft$^3$ | 43.1 |
| Catalyst Bed Mass, lb | 10.8 |
| Catalyst Bed Height, in | 19 |
| Operating Parameters | |
| Pressure, psig | 120—200 |
| Temperature, $^o$F | 375—400 |
| Inlet COS Concentration, ppm | 16.5—-57.2 |
| Outlet COS Concentration, ppm | 2.4—4.8 |
| COS Conversion | 90 |
| Operating Time, hr | 183 |

## 6.2 Syngas Desulfurization

To supply syngas with ultra low concentrations of sulfur for trace metals removal testing by TDA Research, the syngas from the COS hydrolysis unit was sent through a two-step desulfurization process. Desulfurization of the syngas was accomplished in fixed bed reactors arranged in series, with the first reactor filled with Puraspec 2010 for bulk sulfur removal and the second reactor filled with Puraspec 2020 for sulfur polishing. The sulfur concentration at the outlet of the second reactor was below the detection limit, which is typically 1.5 ppm. The sorbent properties and desulfurization operating parameters are given in Table 6-2.

Table 6-2. Sulfur Sorbent Properties and Nominal Operating Parameters.

| | | |
|---|---|---|
| Sorbent Supplier | Synetix | Synetix |
| Sorbent Type | Puraspec 2010 | Puraspec 2020 |
| Physical Properties | | |
| Zinc Oxide Content, wt % | 84—91 | 84—91 |
| Shape | Spheres | Spheres |
| Size, mm | 2.8—4.75 | 2.8—4.75 |
| Density, lb/ft$^3$ | 62—84 | 47—62 |
| Catalyst Bed Mass, lb | 45 | 35 |
| Catalyst Bed Height, in | 51 | 44 |
| Operating Parameters | | |
| Pressure, psig | 200 | 200 |
| Temperature, $^o$F | 620 | 385 |
| Operating Time, hr | 98 | 98 |

## 6.3 Syngas Cooler Fouling Testing

The syngas cooler on the advanced syngas cleanup slipstream was operated for a period of 300 hours to cool syngas using a recirculating loop chiller so that the condensate from the syngas could be collected for examination. The syngas flow through the cooler was maintained at 30 lb/hr. The syngas cooler inlet temperature was approximately 500ºF, and the outlet temperature was approximately 120ºF. Gas velocity through the cooler tube was 49 ft/sec. Exchanger tube fouling with organics was observed when the chiller water inlet temperature was lowered to 50ºF. The condensate collected was transparent.

## 6.4 Trace Metals Removal Testing by TDA Research

As part of development of a DOE sponsored project for sorbent-based high temperature removal of trace metals from coal-derived syngas, TDA Research performed testing at the PSDF using the advanced syngas cleanup slipstream. The sorbent-based process is designed to remove trace metals, including mercury, arsenic, selenium, and cadmium. High temperature removal is potentially beneficial for future gasification power systems because of improved overall efficiency compared to cold gas cleanup systems. This process also has the benefit of reduced amounts of sorbent compared to currently available metals removal technologies.

This initial testing by TDA Research was performed during the low sodium portion of TC21 using syngas with the sulfur concentration reduced below the limit of measurement (about 1.5 ppmv). Further testing utilizing the PSDF slipstream will be conducted in future test campaigns.

# 7.0 CONCLUSIONS

During TC21, operation of the newly modified gasifier with low sodium Freedom lignite was stable, although with the high sodium Freedom lignite, the strong tendency of the coal solids to agglomerate resulted in severely restricted gasifier circulation and short operation duration. Despite the operating challenges encountered, several periods of steady state operation were achieved, and testing in various areas of advanced power generation technologies was performed.

***Lessons Learned.*** The main points gained from TC21 operation are listed below.

- Transport air for coal conveying was used successfully for 130 hours, or 39 percent of the total operating duration, and resulted in significant increase in syngas heating value.
- Adequate carbon conversions were achieved with low sodium lignite, with the highest conversion of 98.2 percent demonstrated during the period of highest gasifier temperature (~1,730$^{o}$F). During low sodium lignite operation, the lower gasifier temperature resulted in unusually low carbon conversions.
- Operation of the gasifier at relatively low temperature and the addition of dolomite sorbent were insufficient for mitigating the agglomerating tendency of the high sodium lignite, which contained as much as 9 percent sodium in the coal ash.
- Recycle syngas use for gasifier aeration was effective in enhancing the syngas heating value, with increases in heating value of up to 28 percent realized with recycle syngas in place of nitrogen aeration.
- The two PDI ceramic tips employing the SGC05 high differential pressure design became plugged during the test campaign, and thereby indicated an unacceptable differential pressure value. The lower differential pressure MAC10 design performed well.
- Although three of the HR-160 gasifier thermowells showed significant wear, the unusual operating conditions apparently exacerbated the erosion, and thermocouple durability was considered acceptable.
- The collection efficiency of the Dynalloy HR-160 PCD filter elements was acceptably high, and the filter elements did not show corrosion in 2,000 hours of accumulated exposure.
- COS hydrolysis and deep sulfur removal resulted in syngas sulfur concentrations below the detection limit, and made the syngas suitable for trace metals removal testing by TDA Research.

# APPENDIX A OPERATING HISTORY

System commissioning of the KBR Transport Reactor train and the first five test campaigns (TCs) were performed in combustion mode. Approximately 5,000 hours of combustion operation were completed from 1996 to 1999. The system was transitioned to gasification operation in late 1999. Four gasification commissioning tests (GCTs), each lasting nominally 250 hours, were completed by early 2001. At the conclusion of TC21, 16 gasification test campaigns were completed, each nominally 250 to 1,500 hours in duration, for a total of about 9,150 hours of coal gasification operation. Powder River Basin subbituminous coal is the most extensively tested fuel, although several bituminous and lignite coals have also been tested. The Transport Gasifier has operated successfully in both air-blown and oxygen-blown modes.

Table A-1 summarizes the gasification testing completed at the conclusion of TC21. The table lists the number of hours on coal, fuel type, and major objectives of each test. More information about the individual test campaigns may be found in the test campaign reports, located on the PSDF website, http://psdf.southernco.com.

Table A-1. Gasification Operating History.

| Test | Start Time | Duration (hrs) | Fuel Type* | Comments |
|---|---|---|---|---|
| GCT1 | September 1999 | 233 | PRB, Illinois #6, Alabama | First gasification testing |
| GCT2 | April 2000 | 218 | PRB | Stable operations |
| GCT3 | February 2001 | 184 | PRB | Loop seal commissioning |
| GCT4 | March 2001 | 242 | PRB | Final gasification commissioning test |
| TC06 | July 2001 | 1,025 | PRB | First long duration test campaign |
| TC07 | April 2002 | 442 | PRB, Alabama | Lower mixing zone commissioning |
| TC08 | June 2002 | 365 | PRB | First oxygen-blown testing<br>First on-line failsafe testing |
| TC09 | September 2002 | 309 | Hiawatha | New mixing zone steam system |
| TC10 | October 2002 | 416 | PRB | Developmental coal feeder |
| TC11 | April 2003 | 192 | Falkirk Lignite | First lignite testing |
| TC12 | May 2003 | 733 | PRB | Fuel cell testing |
| TC13 | September 2003 | 501 | PRB, Freedom Lignite | Syngas to combustion turbine |
| TC14 | February 2004 | 214 | PRB | Syngas to combustion turbine<br>CFAD commissioning |
| TC15 | April 2004 | 200 | PRB | Improved oxygen feed distribution |
| TC16 | July 2004 | 835 | PRB, Freedom Lignite | Fuel cell testing<br>High pressure $O_2$-blown operation |
| TC17 | October 2004 | 313 | PRB, Illinois Basin | Bituminous coal testing |
| TC18 | June 2005 | 1,342 | PRB | Recycle gas compressor commissioning |
| TC19 | November 2005 | 518 | PRB | CCAD commissioning |
| TC20 | August 2006 | 870 | PRB | Gasifier configuration modifications |
| TC21 | November 2006 | 387 | Freedom Lignite | Lignite testing with modified gasifier |

*Note: PRB is subbituminous coal; Illinois #6, Alabama, Hiawatha, and Illinois Basin coals are bituminous coals.

# APPENDIX B STEADY STATE OPERATING PERIODS AND MAJOR OPERATING PARAMETERS

TC21 Part A consisted of 20 steady state operating periods, 18 periods during low sodium lignite gasification and 2 periods with high sodium lignite. TC21 Part B had three steady state operating periods with high sodium lignite. All of the steady state periods were in air-blown gasification mode. Recycle syngas was used for gasifier aeration during 15 of the low sodium lignite operating periods and during one of the high sodium lignite periods. During these periods, the coal, steam, and air feed rates, operating pressure and temperature, carbon conversion, and syngas lower heating values were generally constant.

Table B-1 lists the operating periods and the operating parameters for each period. The coal feed rates were derived from the coal feeder weigh cell data, and the air, oxygen, and syngas flow rates were taken from flow indicators. The steam flow rates were taken from the flow indicators except for the last three operating periods, for which the steam rates were derived from a hydrogen balance. The PCD solids rates were interpolated between measured PCD solids rates during in-situ PCD inlet sampling, and the gasifier ash removal rates were calculated by an ash balance.

Table B-1. Steady State Operating Periods and Major Operating Parameters.

| .Steady State Operating Period | Start Time | End Time | Run Time Hours | Gasifier Mixing Zone Temperature, °F | Gasifier Outlet Pressure, psig | Coal Feed Rate, lb/hr | Air Feed Rate, lb/hr | Steam Feed Rate, lb/hr | Nitrogen Flow Rate, lb/hr | Syngas Rate, lb/hr | PCD Inlet Temperature, °F | Gasifier Solids Removal Rate, lb/hr | PCD Solids Removal Rate, lb/hr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TC21-1 | 11/10/2006 11:30 | 11/10/2006 16:30 | 44 | 1710 | 210 | 3,610 | 11,700 | 1,330 | 6,850 | 23,660 | 730 | 190 | 260 |
| TC21-2 | 11/10/2006 20:30 | 11/11/2006 0:30 | 53 | 1710 | 210 | 3,870 | 11,800 | 1,750 | 4,780 | 23,270 | 730 | 140 | 280 |
| TC21-3 | 11/12/2006 5:15 | 11/12/2006 13:00 | 87 | 1710 | 200 | 3,380 | 10,980 | 1,570 | 6,190 | 21,770 | 730 | 140 | 250 |
| TC21-4 | 11/14/2006 2:15 | 11/14/2006 7:00 | 117 | 1720 | 170 | 3,300 | 11,950 | 1,370 | 7,330 | 24,010 | 750 | 140 | 240 |
| TC21-5 | 11/14/2006 19:00 | 11/15/2006 0:30 | 134 | 1730 | 170 | 3,480 | 12,090 | 1,700 | 6,020 | 22,950 | 750 | 150 | 260 |
| TC21-6 | 11/15/2006 8:00 | 11/15/2006 12:00 | 146 | 1750 | 170 | 3,610 | 12,220 | 1,570 | 6,070 | 23,870 | 770 | 150 | 250 |
| TC21-7 | 11/15/2006 15:15 | 11/15/2006 19:45 | 153 | 1770 | 210 | 4,000 | 12,770 | 1,650 | 4,640 | 23,600 | 750 | 130 | 290 |
| TC21-8 | 11/15/2006 21:45 | 11/16/2006 2:30 | 160 | 1760 | 210 | 4,170 | 13,110 | 1,620 | 4,680 | 24,240 | 760 | 140 | 310 |
| TC21-9 | 11/16/2006 2:30 | 11/16/2006 8:30 | 165 | 1760 | 210 | 4,190 | 13,220 | 1,620 | 4,730 | 24,410 | 770 | 170 | 310 |
| TC21-10 | 11/20/2006 15:15 | 11/20/2006 23:15 | 204 | 1720 | 210 | 4,890 | 13,980 | 2,210 | 4,570 | 26,340 | 770 | 210 | 360 |
| TC21-11 | 11/21/2006 0:30 | 11/21/2006 5:15 | 212 | 1770 | 210 | 5,240 | 14,980 | 2,060 | 4,590 | 27,600 | 780 | 180 | 380 |
| TC21-12 | 11/21/2006 14:30 | 11/21/2006 18:45 | 226 | 1770 | 210 | 5,130 | 14,750 | 1,920 | 4,440 | 27,020 | 780 | 200 | 390 |
| TC21-13 | 11/21/2006 19:15 | 11/22/2006 2:15 | 232 | 1800 | 210 | 5,410 | 15,050 | 1,370 | 4,560 | 26,970 | 790 | 150 | 400 |
| TC21-14 | 11/22/2006 7:45 | 11/22/2006 9:45 | 242 | 1720 | 210 | 3,660 | 10,830 | 1,680 | 4,150 | 21,410 | 720 | 140 | 270 |
| TC21-15 | 11/22/2006 20:15 | 11/23/2006 1:00 | 256 | 1780 | 210 | 3,920 | 11,950 | 1,320 | 3,060 | 20,750 | 750 | 150 | 290 |
| TC21-16 | 11/23/2006 2:15 | 11/23/2006 6:30 | 261 | 1780 | 210 | 3,990 | 11,960 | 1,400 | 3,280 | 20,970 | 760 | 120 | 290 |
| TC21-17 | 11/23/2006 19:00 | 11/24/2006 0:45 | 275 | 1730 | 210 | 4,060 | 12,230 | 1,700 | 4,070 | 22,660 | 750 | 170 | 300 |
| TC21-18 | 11/24/2006 12:00 | 11/24/2006 15:45 | 291 | 1710 | 210 | 3,990 | 11,890 | 1,830 | 4,020 | 22,260 | 740 | 130 | 290 |
| TC21-19 | 12/3/2006 4:00 | 12/3/2006 8:15 | 314 | 1530 | 200 | 3,560 | 10,700 | 1,980 | 7,670 | 24,360 | 700 | 170 | 260 |
| TC21-20 | 12/4/2006 0:00 | 12/4/2006 5:00 | 332 | 1610 | 200 | 4,640 | 11,610 | 1,210 | 5,040 | 23,750 | 710 | 250 | 340 |
| TC21-21 | 1/25/2007 18:45 | 1/25/2007 21:45 | 354 | 1520 | 130 | 4,640 | 8,850 | 3,440 | 5,380 | 21,390 | 710 | 150 | 280 |
| TC21-22 | 1/25/2007 23:15 | 1/26/2007 2:45 | 359 | 1510 | 130 | 4,640 | 8,910 | 3,480 | 6,220 | 21,440 | 710 | 140 | 280 |
| TC21-23 | 1/26/2007 4:30 | 1/26/2007 8:30 | 364 | 1520 | 130 | 4,640 | 9,050 | 3,380 | 5,990 | 21,900 | 710 | 130 | 350 |

# APPENDIX C MATERIAL AND ENERGY BALANCES

The material and energy balances showed reasonable accuracy given the diversity of the measurements used for their calculation. The gasifier mass balance for the TC21 steady state operating periods is plotted in Figure C-1. The mass balance documents the accuracy of the solids and gas rates at the inlet and outlet of the gasifier. The data agreed within 10 percent.

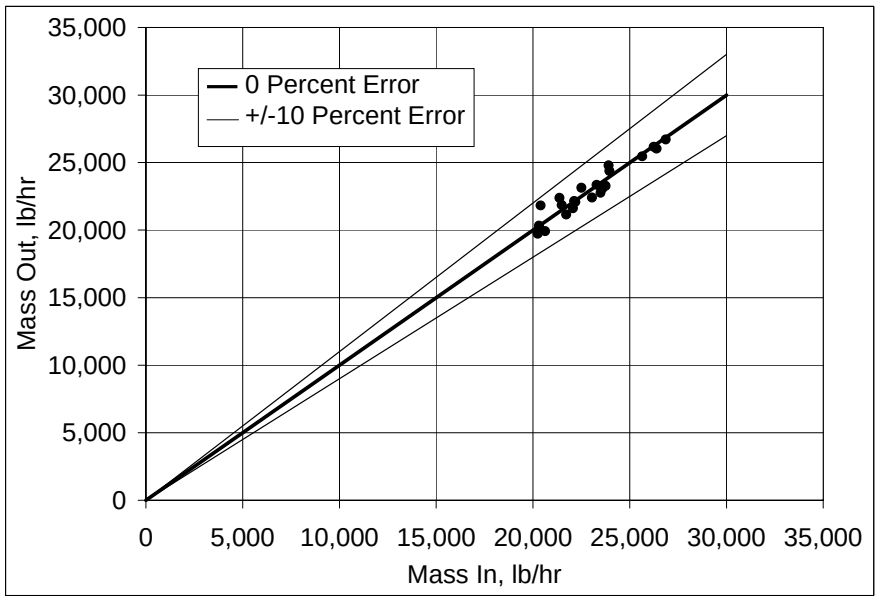


Figure C-1. Mass Balance.

The overall energy balance for the gasifier, presented in Figure C-2, was derived assuming 3.5 MMBtu/hr heat loss from the gasifier. This balance verifies the accuracy of the gasification efficiencies, and generally gives agreement within a 15 percent error range.

The carbon balance documents the accuracy of the carbon conversions, and is shown in Figure C-3. The data fell within a 10 percent error range.

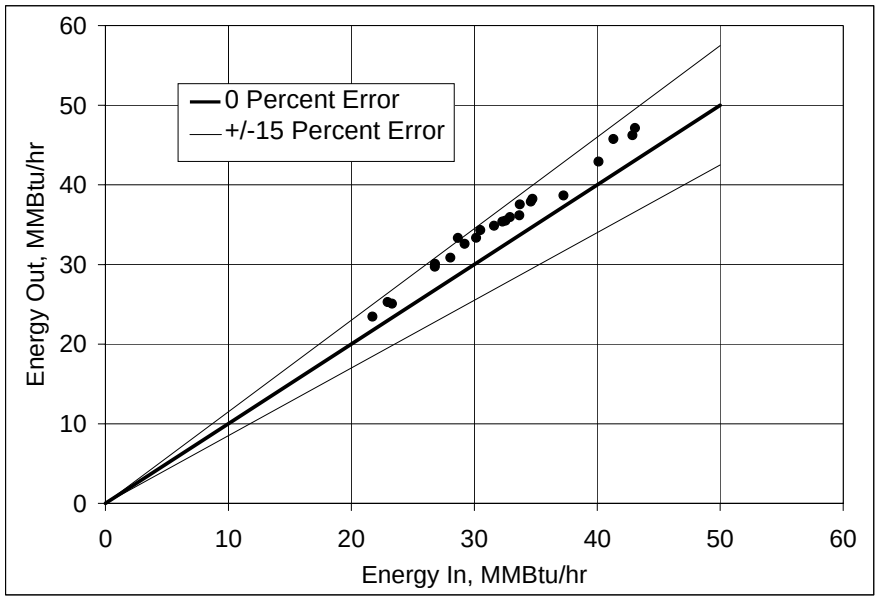


Figure C-2. Energy Balance.

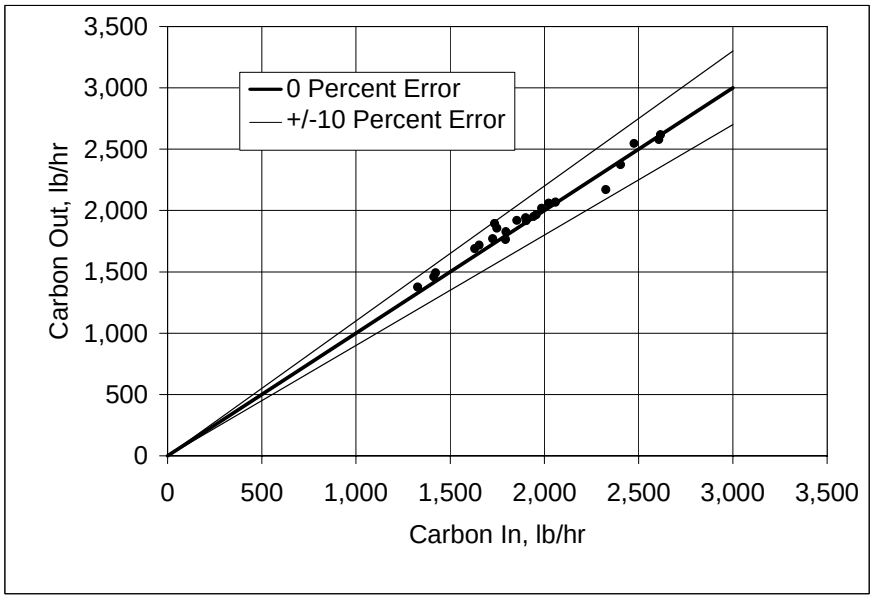


Figure C-3. Carbon Balance.

# APPENDIX D LIST OF ABBREVIATIONS AND UNITS

## Abbreviations

CCAD—Continuous Coarse Ash Depressurization
CFAD—Continuous Fine Ash Depressurization
DOE—Department of Energy
EDS—Energy Dispersive X-Ray Spectrometry
FEAL—Iron Aluminide
FTIR—Fourier Transform Infrared
GCT—Gasification Commissioning Test
GTI—Gas Technology InstituteHHV—Higher Heating Value
IGCC—Integrated Gasification Combined Cycle
LMZ—Lower Mixing Zone
LOI—Loss on Ignition
MMD—Mass Median Diameter
PCD—Particulate Control Device
PDI—Pressure Differential Indicator
PPC—Process Particle Counter
PRB—Powder River Basin
PSDF—Power Systems Development Facility
SEM—Scanning Electron Microscope
SMD—Sauter Mean Diameter
SRI—Southern Research Institute
TC—Test Campaign

## Units

Btu—British thermal units
$^{o}$F—degrees Fahrenheit
ft—feet
$ft^3$—cubic feet
$g/cm^3$ or g/cc—grams per cubic centimeter
hr— hours
in$H_2O$—inches of water
in—inches
inwc—inches of water column
lb—pounds
min—minutes
mm—millimeters
MMBtu—million British thermal units
mol—mole
μm—microns or micrometers
MW—megawatts
ppm—parts per million
ppmv—parts per million by volume
ppmw—parts per million by weight
psi—pounds per square inch
psig—pounds per square inch gauge
s or sec—second
SCF—standard cubic feet
wt—weight