

POWER SYSTEMS DEVELOPMENT FACILITY  
TOPICAL REPORT

GASIFICATION TEST CAMPAIGN TC23  
AUGUST 7, 2007 – AUGUST 27, 2007

DOE Cooperative Agreement  
DE-FC21-90MC25140

Prepared by:  
Southern Company Services, Inc.  
Power Systems Development Facility  
P.O. Box 1069  
Wilsonville, AL 35186  
Tel: 205-670-5840  
Fax: 205-670-5843  
<http://psdf.southernco.com>

September 2008

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor Southern Company Services, Inc., nor any of its employees, nor any of its subcontractors, nor any of its sponsors or cofunders, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report is available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161. Phone orders are accepted at (703) 487-4650.

## 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 coals. The PSDF is an engineering scale demonstration of key features of advanced coal-fired power systems, including a KBR Transport Gasifier, a hot gas particulate control device, advanced syngas cleanup systems, and high-pressure solids handling systems.

This report summarizes the results of test campaign TC23 of the PSDF gasification process, which occurred from August 7 to August 27, 2007. The test featured operation with high sodium lignite from the Freedom Mine (the largest lignite mine in the United States), located in Beulah, North Dakota. Start-up and initial operation utilized Powder River Basin (PRB) subbituminous coal. During TC23, the gasification process operated for a total of 481 hours, with over 300 hours of operation using high sodium lignite. Test objectives included characterizing operation and performance of the modified gasifier and related equipment with high sodium lignite, as well as testing of coal feeders, hot gas filter components, instrumentation enhancements, and syngas cleanup technologies.

## ACKNOWLEDGEMENT

The authors wish to acknowledge the contributions and support provided by various project managers, including Morgan Mosser of the Department of Energy, Tim Challand of KBR, and John Wheeldon of the Electric Power Research Institute. The project is sponsored by the U.S. Department of Energy National Energy Technology Laboratory under contract DE-FC21-90MC25140.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
Inside Cover	
Disclaimer	
Abstract	
Acknowledgement	
List of Figures	iii
List of Tables	v
1.0 EXECUTIVE SUMMARY	1-1
1.1 PSDF Overview	1-1
1.2 Process Description	1-1
1.3 Major Test Objectives	1-4
1.4 Secondary Test Objectives	1-5
1.5 Report Structure	1-6
2.0 FEED SYSTEMS	2-1
2.1 Coal Feed	2-1
2.1.1 Coal Characteristics	2-1
2.1.2 Original Coal Feeder Operation	2-5
2.1.3 Secondary Feeder Operations	2-6
2.2 Dry Sorbent Feed	2-6
2.3 Slurry Feed System	2-8
3.0 TRANSPORT GASIFIER	3-1
3.1 Gasifier Operating Parameters	3-1
3.2 Gasifier Performance, Solids Analyses	3-4
3.3 Gasifier Performance, Gas Analyses	3-10
3.4 Gasifier Parametric Testing	3-12
3.5 Post-Test Inspections	3-16
3.6 Tracer Gas Tests	3-19
4.0 SENSOR DEVELOPMENT	4-1
4.1 Pressure Differential Indicator Ceramic Inserts	4-1
4.2 Thermowell Materials	4-1
5.0 PARTICULATE CONTROL DEVICE	5-1
5.1 PCD Inlet and Outlet Particulate Measurements	5-1
5.2 PCD Solids Analysis	5-2
5.2.1 Particle Size Distributions	5-2
5.2.2 Dustcake Observations	5-3
5.2.3 Particulate Physical Properties and Chemical Composition	5-3
5.3 PCD Pressure Drop Performance	5-7
5.4 Filter Element Evaluation	5-12
5.5 On-Line Failsafe Testing	5-14

6.0	ADVANCED SYNGAS CLEANUP .....	6-1
6.1	Water-Gas Shift Reaction Testing .....	6-1
6.2	Direct Oxidation of H <sub>2</sub> S .....	6-1
6.3	CO <sub>2</sub> Capture .....	6-2
6.4	Inspections .....	6-3
7.0	SUPPORT EQUIPMENT .....	7-1
8.0	CONCLUSIONS .....	8-1
APPENDICES		
	Appendix A Operating History .....	A-1
	Appendix B Steady State Operating Periods and Major Operating Parameters .....	B-1
	Appendix C Material and Energy Balances .....	C-1
	Appendix D List of Abbreviations and Units .....	D-1

LIST OF FIGURES

<u>Figure</u> .....	<u>Page</u>
1-1 PSDF Gasification Process Flow Diagram.....	1-2
2-1 As-Fed Coal Moisture Content.....	2-2
2-2 Sodium Content in Coal Ash on an Oxide Basis.....	2-3
2-3 Coal Particle Sizes.....	2-4
2-4 Coal Fines and Oversize Particles.....	2-4
2-5 Coal Feeder Operating Envelope.....	2-5
2-6 Raw Kaolin.....	2-7
2-7 Kaolin Particle Size Distribution.....	2-7
2-8 Slurry Feed System.....	2-8
3-1 Gasifier Operating Temperatures and Pressure.....	3-2
3-2 Gasifier Feed Flow Rates.....	3-2
3-3 Gasifier Standpipe and Riser Differential Pressures.....	3-3
3-4 Primary Gas Cooler Plugging Ratio.....	3-4
3-5 Gasifier Circulating Solids and PCD Solids Particle Sizes.....	3-6
3-6 Bulk Densities of Gasifier Circulating Solids and PCD Solids.....	3-6
3-7 Gasification Ash Removal from the PCD and Gasifier.....	3-7
3-8 Photomicrographs of Gasifier Solids.....	3-8
3-9 Gasifier Solids before and after Baking in Muffle Furnace.....	3-9
3-10 Progressive Change in Coloration of Baked Standpipe Samples.....	3-9
3-11 Energy-Dispersive X-Ray Spectrometry of Raw Kaolin and Kaolin Particle in Gasifier Sample.....	3-10
3-12 Concentrations of Major Syngas Components.....	3-11
3-13 Carbon Conversion and Syngas Heating Value.....	3-12
3-14 Carbon Conversion as a Function of Gasifier Temperature for Lignite Operation.....	3-13
3-15 Syngas Methane Content as a Function of Gasifier Pressure for Lignite Operation.....	3-14
3-16 Syngas Hydrogen-to-Carbon Monoxide Ratio versus Steam-to-Coal Ratio.....	3-14
3-17 Syngas Heating Value as a Function of Lignite Feed Rate.....	3-15
3-18 Effect of Standpipe Level on Circulation Rate for Lignite Operation.....	3-15
3-19 Inspection of Riser and Lower Mixing Zone.....	3-16
3-20 Inspection of Lower Standpipe.....	3-16
3-21 Inspection of Actchem 85 VC Refractory.....	3-17
3-22 Inspection of Primary Gas Cooler Inlet and Outlet.....	3-18
3-23 Inspection of Primary Gas Cooler Tube Bundle.....	3-18
4-1 Post-TC21 and Post-TC23 Inspections of Worn HR-160 Thermowells.....	4-1
4-2 Inspections of HR-160 Thermowell with Minimal Wear.....	4-2
4-3 Ceramic Thermowell Damaged during Removal.....	4-2
5-1 Particle Size Distributions of PCD Inlet In-Situ and Hopper Samples.....	5-2
5-2 Effect of Carbon Content on Specific Surface Area of Gasification Ash.....	5-6
5-3 PCD Transient Drag versus Carbon Content of In-Situ Samples.....	5-9
5-4 Normalized PCD Baseline Pressure Drop from TC20 through TC23.....	5-9
5-5 Lab-Measured Drag as a Function of Particle Size.....	5-10
5-6 Comparison of PCD Transient Drag with Laboratory Measurements.....	5-12
5-7 Pressure Drop versus Exposure Hours for Iron Aluminide Filter Elements.....	5-13

<u>Figure</u> .....	<u>Page</u>
5-8 Pressure Drop versus Exposure Hours for Coarse Fiber Dynalloy HR-160 Filter Elements .....	5-13
7-1 Recycle Gas Compressor Operating Conditions .....	7-1
C-1 Mass Balance.....	C-1
C-2 Energy Balance.....	C-1
C-3 Carbon Balance .....	C-2
C-4 Sulfur Balance.....	C-2

LIST OF TABLES

<u>Table</u> .....	<u>Page</u>
2-1 PRB Subbituminous Coal and North Dakota Freedom Mine High Sodium Lignite As-Fed Properties.....	2-1
3-1 Gasifier Circulating Solids Analysis for High Sodium Lignite Operation Starting at Hour 206.....	3-4
3-2 PCD Solids Analysis for High Sodium Lignite Operation Starting at Hour 206 .....	3-5
5-1 PCD Inlet and Outlet In-Situ Particulate Measurements .....	5-1
5-2 Dustcake Thickness Measurements .....	5-3
5-3 Physical Properties of In-Situ Samples and Samples Used for Lab Measurements .....	5-4
5-4 Chemical Composition of In-Situ Samples and Sample Used for Lab Measurements.....	5-5
5-5 Physical Properties of Dustcake Samples.....	5-6
5-6 Chemical Composition of Dustcake Samples .....	5-7
5-7 Transient Drag Determined from PCD Pressure Drop and from Lab Measurements .....	5-8
5-8 Average Drag Values Determined from PCD and Lab Measurements .....	5-11
6-1 Composition of Sud-Chemie T-2822 Shift Catalyst.....	6-1
B-1 Steady State Operating Periods and Major Operating Parameters.....	B-2

## 1.0 EXECUTIVE SUMMARY

This report summarizes the results of the PSDF gasification process operation during test campaign TC23, which occurred from August 7 to August 27, 2007. Coal gasification operation began with Powder River Basin (PRB) subbituminous coal to establish steady state conditions and to complete initial test objectives, which included air compliance stack testing and tracer gas testing to support gasifier dynamics studies. Operation later transitioned to high sodium lignite from the North Dakota Freedom Mine, the largest lignite mine in the United States, in an ongoing effort to optimize gasifier operation with this lignite coal.

In addition to characterizing operation and performance of the modified gasifier and related equipment with the high sodium lignite, test objectives included testing of coal feeders, hot gas filter elements and failsafes, instrumentation enhancements, and advanced syngas cleanup technologies.

### 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) power 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



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 solid particles of gasification ash. 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 coarse 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 four MW 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.

Appendix A gives a brief description of the PSDF gasification testing history.

### 1.3 Major Test Objectives

**Evaluation of High Sodium Lignite Operation.** One of the major objectives for this test was to evaluate the process operational stability and performance using North Dakota high sodium lignite. This coal had been tested previously with the PSDF gasification process (TC13 in October of 2003, TC16 in August of 2004, and TC21 in December of 2006 and January 2007), and presented operational challenges in maintaining adequate solids circulation in the gasifier due to reactions of the sodium in the lignite with other lignite ash components and/or start up bed material to form low melting point compounds. To prevent the agglomerations experienced previously, initial operation of TC23 was performed using PRB coal so that the start-up sand was replaced with gasification ash prior to lignite feed, and a kaolin additive was fed with the lignite. The use of kaolin proved successful in eliminating agglomeration within the gasifier; however, ash deposition in the primary gas cooler located downstream of the gasifier and subsequent loss of heat transfer became an operational issue as the test campaign progressed. The gasification process was operated for a total of 481 hours in TC23, with over 300 hours of operation with high sodium lignite.

Several parametric tests were performed to evaluate gasifier operations at various operating conditions to optimize performance. The positive correlations were demonstrated with carbon conversion with gasifier temperature; syngas heating value and coal feed rate; syngas methane content with operating pressure; and solids circulation rate and standpipe level. In addition, an increase in the hydrogen-to-carbon monoxide ratio was observed as the steam-to-coal feed ratio was increased.

**Coal Feeder Testing.** Both the original and developmental coal feeders were tested during TC23 at various feed rates. The original coal feed system operated for 480 hours at rates varying from 2,080 to 4,065 lb/hr and particle sizes varying from 243 to 864 microns. The original coal feeder experience operational difficulties due to the coal feed discharge line, the pressure balance line, and the dispense vessel vent line plugging frequently. Feeder operation improved after several operating parameters were adjusted.

The secondary coal feeder was operated briefly, but operation was stopped due to recurring discharge line plugging resulting from the high-resistance coal flow path. These plugging problems had been experienced in previous test campaigns, and modifications to the discharge line will be incorporated in the future to improve the flow path.

**Advanced Syngas Cleanup Testing.** TC23 marked the initial testing of several new syngas cleanup technologies. These included testing of the water-gas shift reaction with a catalytic filter element and a fixed bed reactor, direct oxidation of H<sub>2</sub>S in a fixed bed reactor, and CO<sub>2</sub> capture in a batch reactor. The initial phase of testing was conducted in offline mode with bottled gases.

**Air Permit Compliance Testing.** Annual air compliance testing was completed during the PRB portion of TC23 operation. The testing was conducted in accordance with U.S. Environmental Protection Agency rules and regulations and with the requirements contained in the operating permit issued by the Alabama Department of Environmental Management. The pollutants measured included particulate matter, sulfur dioxide, nitrogen oxides, carbon monoxide, and volatile organic compounds. Compliance was verified for all pollutants.

#### 1.4 Secondary Test Objectives

**Tracer Gas Testing.** A tracer gas test was performed during PRB operation in TC23 to enhance the understanding of the hydrodynamics in the mixing zone and riser, and solids flow from the first solids separation device to the standpipe, and the standpipe. A tracer gas, Argon-41, was injected into the gasifier at two locations, one in the mixing zone and one in the riser, at separate times under various operating conditions. The test provided data to evaluate solids mixing in the area around the coal feed nozzles and operation of the seal leg and standpipe.

**Filter Element and Failsafe Testing.** Testing of iron aluminide and HR-160 filter elements was continued, and the elements showed very high collection efficiency. Long-term performance evaluation showed the continued trend of increasing pressure drop with gasification operation time for the iron aluminide elements. On-line failsafe testing was conducted with an HR-160 reversed-media failsafe, which effectively plugged when exposed to a low concentration of particulate.

**Recycle Gas System Testing.** When recycled syngas was used to replace nitrogen aeration, the raw syngas lower heating value increased about 10 percent during both PRB and lignite operations, comparable to previous testing results. The control trip logic for the recycle syngas compressor was modified prior to TC23 to increase the availability of the recycle syngas system. As a result of these modifications, the compressor availability was more than doubled, increasing from about 40 percent in recent test campaigns to over 80 percent in TC23. The higher availability increased test data available for analysis by shortening the time required to re-establish steady state conditions following coal feeder and certain gasifier trips. In addition, nitrogen costs were reduced by over \$20,000.

**Continued Sensor Development.** One area of focus of the sensor development program has been low flow, ceramic-tipped pressure differential measurement ports. However, due to the limited potential commercial benefit, further testing was suspended.

Two types of thermowell materials, metal HR-160 and ceramic, were tested during TC23 for continued evaluation of thermowell durability and longevity. Some wear was found on three of the HR-160 elements, although most showed only minimal wear. Eight ceramic thermowells were tested in TC23, and these thermowells have operated over 2,200 hours and show only

minimal wear on the thermowell tips. However, failures incurred during removal of the ceramic thermowells continued to be a concern.

*Slurry Feeder Testing.* The slurry feed system was commissioned in TC23. Initially the feeder was tested with water and a sand flour slurry in an off-line mode, which allowed for feeding to a receiver vessel that was operated from atmospheric pressure up to 200 psig. After completion of off-line testing, the feeder was lined up to the gasifier through the new dispersing nozzles. The feeder was started on water, and the safety interlocks and control logic were successfully tested. However, feed to the gasifier was not implemented due to the inability to maintain adequate feed pressure.

## 1.5 Report Structure

The following report presents the operational data and results of gasification technology development at the PSDF during TC23, compiled in the sections listed below. Inspection results are also included.

- Section 2 Feed Systems — Discusses operation of the original coal feed and secondary coal feed systems. Presents coal moisture values and particle sizes and their effect on coal feed system performance. Discusses operation of the sorbent feed system and presents sorbent composition and particle size information. Also covers commissioning of the slurry feed system.
- Section 3 Transport Gasifier — Includes the major gasifier operating parameters and the gasifier performance as indicated by solids and gas analyses. Also includes the results of parametric testing such as the effects of varying temperature and pressure on gasifier performance.
- Section 4 Sensor Development — Covers progress of instrumentation improvements including ceramic-tipped pressure differential measurements and thermowell materials.
- Section 5 Particulate Control Device — Describes the hot gas filter particulate characteristics, PCD performance, and filter element testing.
- Section 6 Advanced Syngas Cleanup — Describes the initial testing of several new syngas cleanup technologies.
- Section 7 Support Equipment — Describes operations of the recycle gas compressor.
- Section 8 Conclusions — Lists the major conclusions and lessons learned.

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. Appendix C shows material and energy balances, and Appendix D lists the abbreviations and units used in this report.

## 2.0 FEED SYSTEMS

Four feed systems were tested during TC23: the original coal feed system, a secondary coal feed system, the dry sorbent feed system, and the slurry feed system. The original coal feed system operated for about 480 hours, while testing of the secondary coal feed system was limited due to discharge line plugging. After addressing some initial operating problems, the dry sorbent feed system was operated for 308 hours to feed kaolin to the gasifier. The slurry feed system was commissioned in off-line mode, but the inability to maintain pressure prevented feeding directly to the gasifier.

### 2.1 Coal Feed

The original coal feeder operated during the entire test campaign (180 hours with PRB and 301 hours with high sodium lignite) at rates from 2,085 to 4,065 lb/hr and particle sizes varying from 243 to 864 microns mass median diameter (MMD). Due to operational problems with the sorbent feed system, the coal feed system was utilized to feed kaolin simultaneously with the lignite during the initial operation of high sodium lignite (from Hours 180 to 220).

#### 2.1.1 Coal Characteristics

Table Table 2-1 gives the average, minimum, and maximum, and standard deviation of the as-fed properties of the PRB subbituminous and Freedom Mine lignite coals used during TC23. Prior to Hour 320, the lignite ash averaged 4.7 percent Na<sub>2</sub>O, and after Hour 320, the lignite ash averaged 9.7 percent Na<sub>2</sub>O.

Table 2-1. PRB Subbituminous Coal and North Dakota Freedom Mine High Sodium Lignite As-Fed Properties.

	PRB				High Sodium Lignite			
	Average Value	Minimum Value	Maximum Value	Standard Deviation	Average Value	Minimum Value	Maximum Value	Standard Deviation
Moisture, wt%	13.5	12.4	15.0	1.0	20.1	16.4	24.3	2.1
Carbon, wt%	58.9	57.8	59.9	0.8	51.7	49.0	54.5	1.5
Hydrogen, wt%	3.96	3.43	4.14	0.21	3.17	2.92	3.48	0.16
Nitrogen, wt%	1.05	1.02	1.07	0.02	0.94	0.88	1.01	0.03
Oxygen, wt%	16.1	15.4	16.8	0.6	15.3	14.1	16.5	0.5
Sulfur, wt%	0.28	0.22	0.34	0.03	0.73	0.66	0.95	0.06
Ash, wt%	6.1	5.5	6.9	0.4	8.0	7.2	8.9	0.4
Volatiles, wt%	35.6	34.9	36.3	0.5	32.8	31.3	34.2	0.9
Fixed Carbon, wt%	44.8	43.7	45.9	0.8	39.1	37.1	41.2	1.2
Dry Heating Value, Btu/lb	10,078	9,865	10,257	134	8,646	8,160	9,117	246
As-Received Heating Value, Btu/lb	9,574	9,395	9,748	129	8,147	7,635	8,628	254
CaO, wt % in Ash	22.8	21.3	24.3	0.9	25.3	22.7	29.2	2.0
SiO <sub>2</sub> , wt % in Ash	34.8	33.4	36.0	1.0	19.1	16.7	21.1	1.0
Al <sub>2</sub> O <sub>3</sub> , wt % in Ash	16.4	15.6	17.6	0.6	11.6	10.7	12.3	0.3
MgO, wt % in Ash	4.8	4.5	5.2	0.2	4.6	2.5	6.0	1.5
Na <sub>2</sub> O, wt % in Ash	1.6	1.4	1.8	0.1	8.2	4.5	11.2	2.5

Figure 2-1 plots the TC23 as-fed coal moisture content, with the demarcation line showing lignite feed beginning at Hour 180. The lignite-kaolin mixture fed from the original coal feeder from Hours 180 to 224 is also marked, and the fuel samples during this time period contained both materials. The moisture content in the as-fed PRB was typically below 15 percent, with one sample higher than 20 percent. The lignite was processed in two separate mills, which resulted in a larger variation in moisture content than seen with the PRB, with was processed in only one mill. During lignite operation, one mill was operating at a lower gas mass flow through the system, resulting in a lower drying capacity and thus a higher coal moisture content than with the second mill. The lignite moisture content ranged from 16 to 24 percent. Generally, the lignite as-fed moisture content was higher than the PRB since the lignite as-received moisture content was higher.

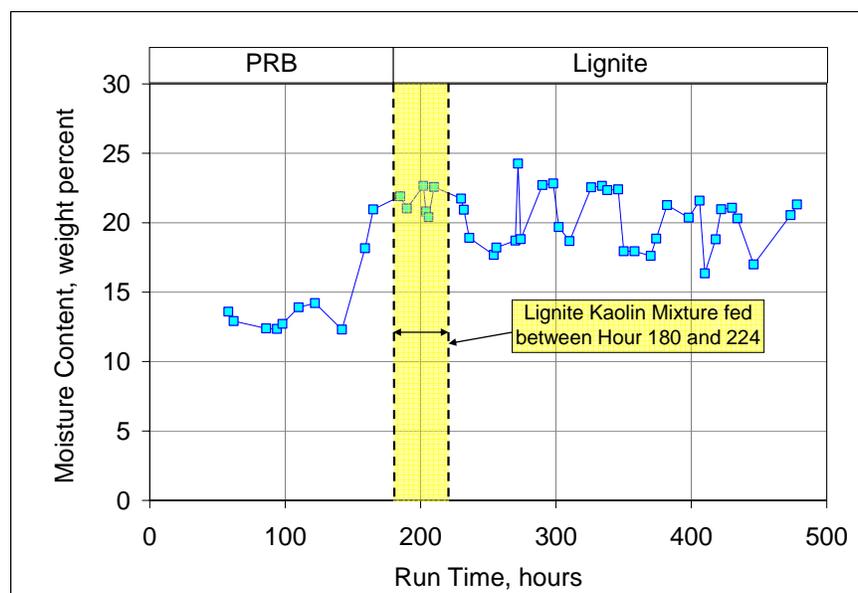


Figure 2-1. As-Fed Coal Moisture Content.

Figure 2-2 gives the coal ash sodium content on a sodium oxide ( $\text{Na}_2\text{O}$ ) weight percent basis. The sodium content for the PRB coal ash was about two percent. The sodium content remained low for about 50 hours after the transition from PRB to lignite (during the co-feeding of lignite and kaolin) but increased to about 4.7 percent at Hour 230. The kaolin diluted the amount of sodium in the kaolin-lignite mixture. At Hour 310 the sodium content increased to about 10 percent and did not change to Hour 478.

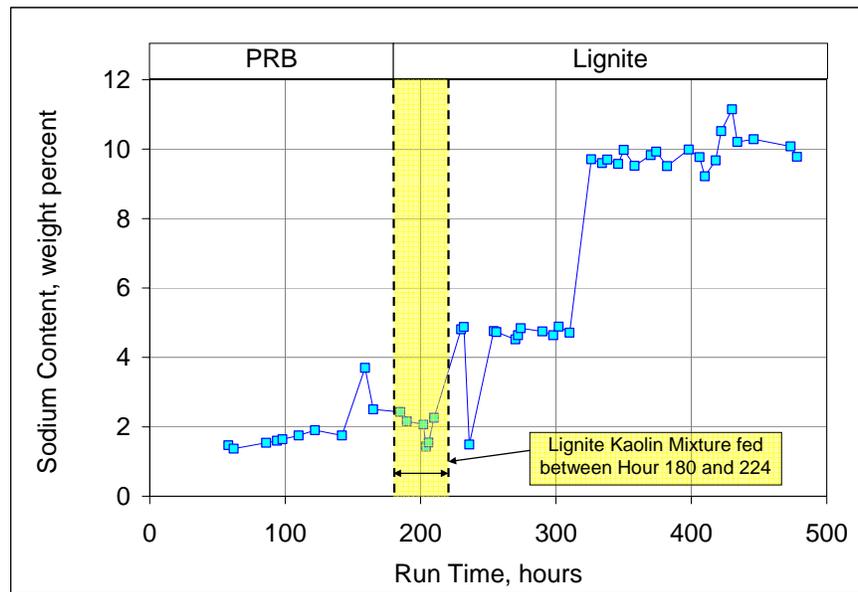


Figure 2-2. Sodium Content in Coal Ash on an Oxide Basis.

Figure 2-3 gives the TC23 coal particle sizes in MMD. Data from Hour 180 to Hour 224 reflect the lignite kaolin mixture. The PRB coal particle size MMD varied from 243 to 437 microns with an average of 348 microns and standard deviation of 45 microns, while the lignite coal particle size MMD varied from 271 to 864 microns with an average of 505 microns and standard deviation of 134 microns. The PRB particle sizes were slightly smaller and had less variability than the lignite particles sizes due to the differences in the two mill operations.

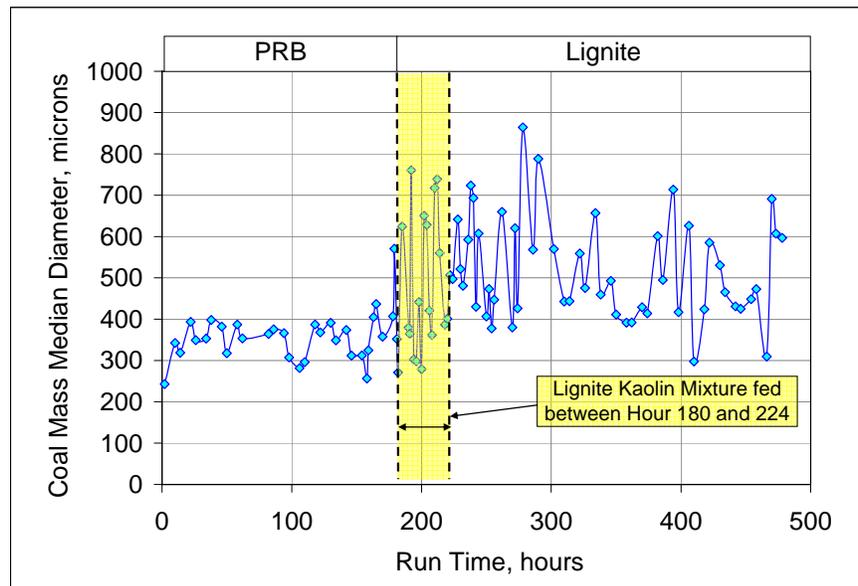


Figure 2-3. Coal Particle Sizes.

The percentage of coal particles above 1,180 microns and the percentage of coal particles below 45 microns are shown in Figure 2-4. The oversize particles above 1,180 microns were between 9 and 36 percent with an average of 16 percent. The coal fines less than 45 microns were between 1 and 20 percent with an average of 5 percent. PRB and lignite feeds contained the same percentage of fines, while the lignite feed contained about twice the percentage of course particles compared to PRB feed.

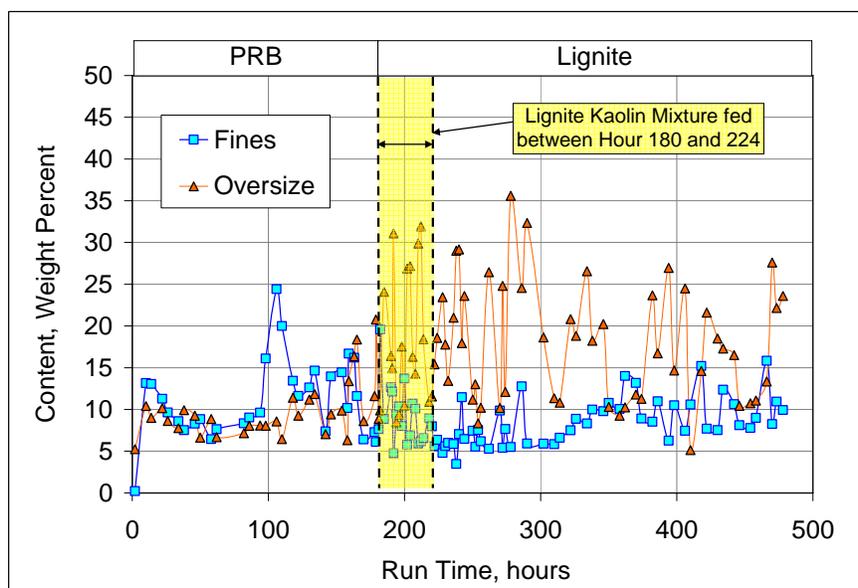


Figure 2-4. Percent Fine and Oversize Coal.

### 2.1.2 Original Coal Feeder Operation

Nitrogen was used as coal transport gas for the majority of the test campaign; however, transport air was tested for about 20 hours. Material plugging the balance line, dispense vessel vent line, and discharge line caused some coal feed interruptions. The transport gas velocity and dispense vessel fluidization were varied during the test campaign to optimize operations.

Initially, material plugging in the discharge line caused the coal feeder to trip every four hours. The coal feed transport velocity was increased from 35 to 40 ft/s, and the trips due to the discharge line plugging were reduced to about once per day. The velocity was further increased to 45 ft/s and the trip frequency was again reduced.

Due to operational problems with the sorbent feed system, the coal feed system was utilized to feed kaolin simultaneously with the lignite during the initial operation of high sodium lignite (from Hour 180 to Hour 220). Additional problems were encountered with the discharge line plugging when feeding the lignite and kaolin simultaneously due to the size of the kaolin. Some of the large kaolin particles caused the discharge line to become plugged. The transport gas velocity was increased to 70 ft/s to reduce the frequency of trips. Additional testing is needed to conclusively evaluate the effect of changes in the dispense vessel fluidization on feeder operations.

Based on TC23 operation, the coal feeder operating envelope for coal moisture content and particle size was further developed. Figure 2-5 shows the range of moisture and particle sizes for acceptable feeder operation for PRB and high sodium lignite as compared to previous testing.

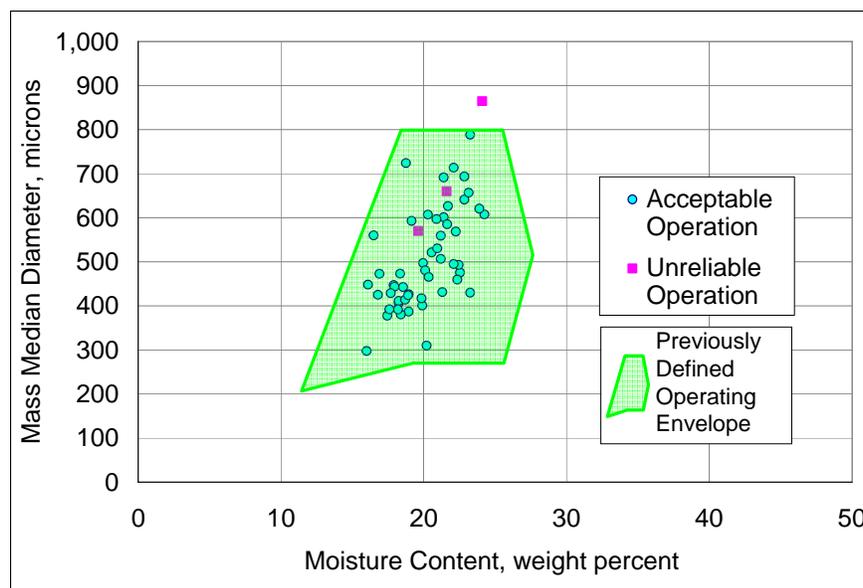


Figure 2-5. Coal Feeder Operating Envelope.

### 2.1.3 Secondary Coal Feeder Operation

The secondary coal feeder was operated briefly, but operation was stopped due to continued problems with the discharge line plugging. The discharge line will be modified in a future outage to improve the flow path.

## 2.2 Dry Sorbent Feed

Several sorbents including vermiculite, kaolin, kaolinite, dolomite, calcite, sand flour, and bauxite were evaluated as additives for testing with the high sodium lignite to address the agglomeration issues in the gasifier. Lab tests performed in a muffle furnace at the PSDF showed that the sorbent effectiveness extent of sodium capture, based on Energy Dispersive X-Ray Spectrometry (EDS) of the various reaction products, from greatest to least was: sand flour, kaolinite, kaolin, waste-derived kaolinite, Arkansas bauxite, vermiculite, and high-alumina bauxite. The finer kaolin and kaolinite showed a similar degree of consolidation as that with sand flour; however, the larger kaolin particles, of about 1,000 microns, did not show any signs of consolidation.

Initially, sand flour was selected as the additive for high sodium lignite testing since the amount of additive required is much lower than with kaolin or kaolinite due to the lower molecular weight. The existing sorbent feed system could not be used to feed the sand flour due to the small particle size. Thus, a slurry feed system was designed, procured, and installed to feed the sand flour.

In preparation for TC23, PSDF personnel consulted with researchers at the Energy and Environmental Research Center (EERC), a non-profit technology branch of the University of North Dakota (UND). Experiments at UND in a test unit at similar gasification conditions showed kaolin and kaolinite were successful in eliminating agglomeration in the gasifier. The suggested chemical process was the reaction of kaolin with sodium to form the sodium aluminum silicates with a higher melting point than the maximum gasifier operating temperature; however due to the chemical properties of kaolin and kaolinite, a high kaolin- or kaolinite-to-sodium ratio is required. Since commissioning the slurry feed system was progressing slowly and feeding kaolin or kaolinite could be accomplished through existing systems, it was decided to first test kaolin since it was available locally. Kaolin is a mineral consisting mostly of equal amounts of silica and alumina.

The sorbent feed system, a lock hopper based system with a volumetric feeder that delivers material into a feed pipe that is then pneumatically conveyed into the gasifier, was used to feed kaolin into the Transport Gasifier during high sodium lignite operation. The kaolin tested, shown in Figure 2-6, was a minus 14-mesh, CK-46 Meta-kaolin purchased from CE Minerals. Meta-kaolin is a calcined kaoline clay with approximately 1.5 percent loss on ignition (LOI) and generally less than 1 percent quartz. The particle size distribution of the material is given in Figure 2-7. The sorbent feeder operated for 240 hours at rates from about 100 to 400 lb/hr. Due to a material shortage, the kaolin feed rate was decreased below the required stoichiometric ratio for about 160 hours. Operating at the lower kaolin-to-sodium ratios was evident in the gasifier solids visual appearance as discussed in Section 3.



Figure 2-6. Raw Kaolin.

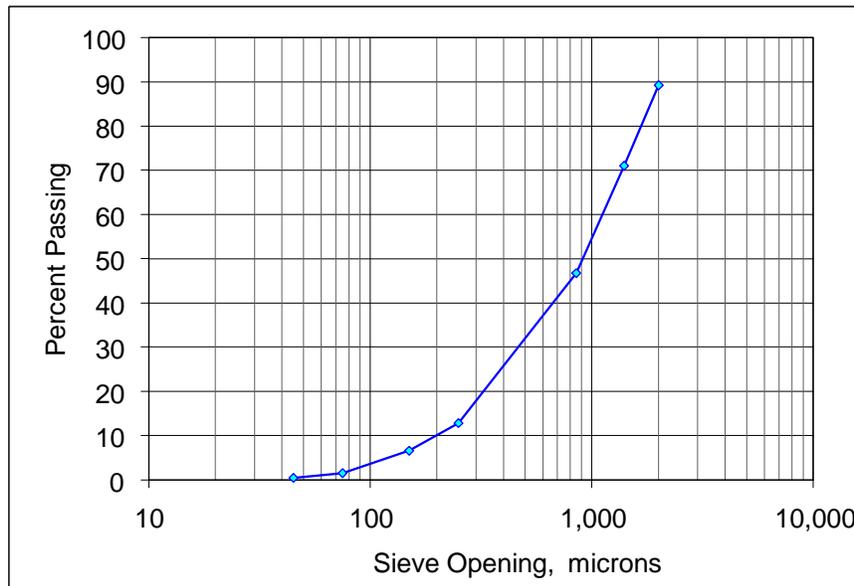


Figure 2-7. Kaolin Particle Size Distribution.

The raw kaolin was received in 2,000 pound super-sacks and was pneumatically conveyed to the surge hopper of the sorbent feed system utilizing a dense phase conveying system. Since this system was designed to handle a smaller particle size, the conveying line plugged periodically. Operational problems were encountered with the sorbent feed system when trying to establish operation initially. Since the sorbent feed system was not available, kaolin and lignite were fed simultaneously from the original coal feeder. Troubleshooting of the sorbent feeder showed that a failed level probe in the dispense vessel had caused the dispense vessel and lock vessel to become overfilled. This overfilling resulted in plugging of the lock vessel and dispense vessel vent lines, rendering the sorbent feeder inoperable. After the probe was replaced, kaolin feed was successfully established using the sorbent feeder and was maintained for the remainder of the test campaign.

### 2.3 Slurry Feed System

A slurry feed system was installed to add sand flour to the gasifier to address the agglomeration issues related to the high sodium content in the North Dakota lignite. The slurry feed system consists of a solids feed bin and feed screw, a mix screw, and a progressive cavity pump. The solids feed bin has a hood and vacuum system above the bin to contain the sand flour while being loaded, and the feed system was enclosed in an independent structure. Figure 2-8 shows the slurry feeder system.

The slurry feed system was commissioned in TC23. Initially the feeder was tested with water and a sand flour and water slurry in an off-line mode which allowed for feeding to a receiver vessel that was operated from atmospheric pressure up to 200 psig. The slurry concentrations ranged from 45 to 55 weight percent at flow rates of 100 to 150 lb/hr. Feed screw stalling problems were encountered after transitioning from water to the slurry mix. A larger air motor was added, and the dry box between the feed and mix screws were redesigned to improve feed system operation.

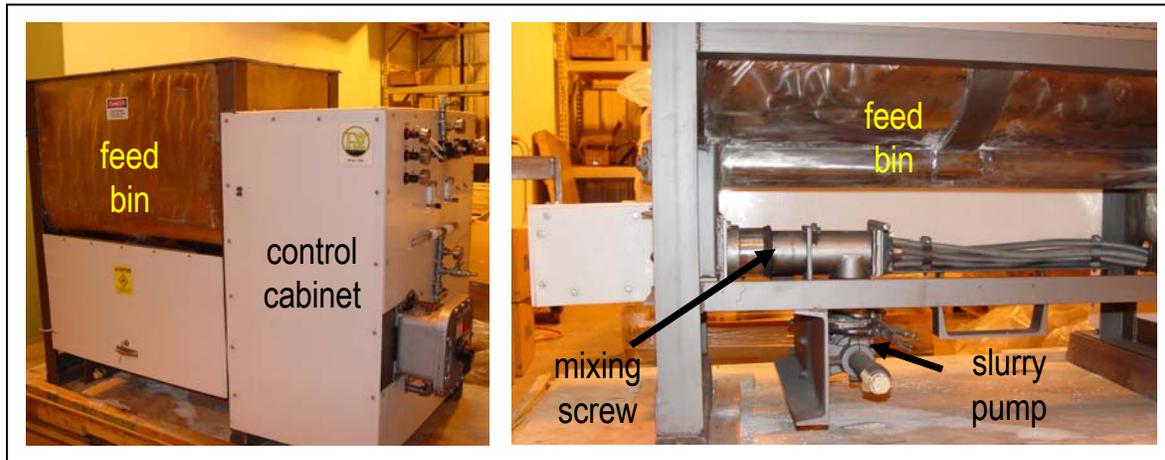


Figure 2-8. Slurry Feeder System.

After completion of off-line testing, the feeder was lined up to the gasifier through the new dispersing nozzles. The feeder was started on water and the safety interlocks and control logic were successfully tested. However, the feeder could not maintain a discharge pressure higher than gasifier pressure. Initial investigation revealed that the rubber stator and stainless steel rotor of the pump need to be replaced. Therefore, slurry feed to the gasifier was not completed.

### 3.0 TRANSPORT GASIFIER

A major objective of TC23 was the continued evaluation of gasifier performance with high sodium North Dakota lignite, which had been tested in several earlier test campaigns. After start-up and initial operation with PRB coal, during which steady state operation was achieved and the start-up sand bed material was replaced with gasification ash, the gasifier feedstock was transitioned to high sodium lignite. To prevent agglomeration that had occurred during some of the previous high sodium lignite testing, kaolin sorbent was fed to the gasifier for the first time during TC23. Several parametric tests were performed during lignite operation to evaluate and optimize gasifier performance at various operating conditions. Gasifier operation was stable with the high sodium lignite, achieving carbon conversions up to 97.6 percent and projected syngas lower heating values from 125 to 140 Btu/SCF at the turbine inlet.

There were twenty-eight steady state periods in TC23, including twelve periods with PRB and sixteen periods with lignite. Only two steady state periods did not include recycle gas use for gasifier aeration. The steady state operating periods and major operating parameters are shown in Appendix B.

#### 3.1 Operating Parameters

Figure 3-1 gives the gasifier temperatures and pressures for the TC23 steady state periods. The mixing zone temperature varied between 1,725 and 1,795°F for PRB and varied between 1,580 and 1,661°F for lignite. The gasifier was operated at relatively low temperatures and pressures during initial high sodium lignite operation as a conservative approach to minimize the chance for particle consolidation in the gasifier. The mixing zone temperature was gradually increased as the lignite testing progressed. The gasifier outlet pressure varied from 176 to 208 psig during PRB operation and varied from 130 to 220 psig during lignite operation. The lower gasifier pressures during initial lignite operation were used to generate higher riser velocities. The primary gas cooler outlet temperature was constant at about 800°F during the PRB operation and for the first 120 hours of lignite operation. At Hour 300, the primary gas cooler outlet temperature slowly increased to about 950°F by the end of TC23.

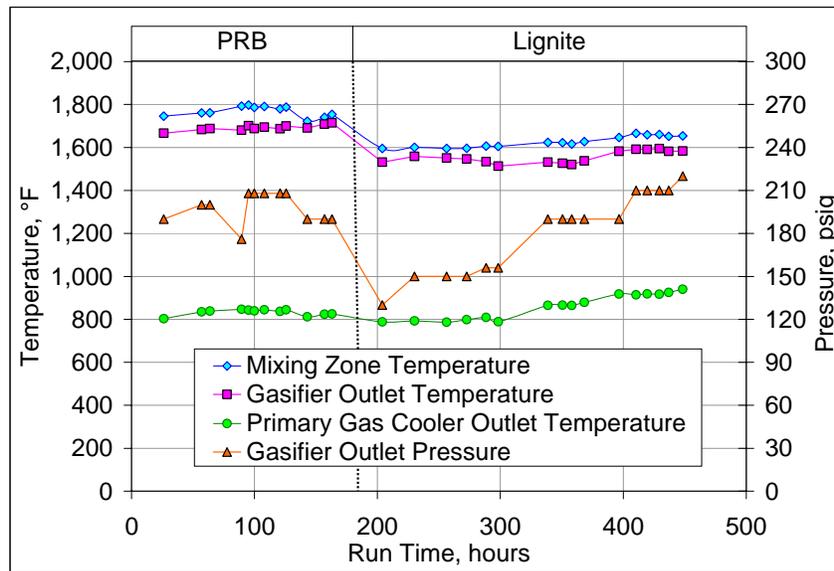


Figure 3-1. Gasifier Operating Temperatures and Pressure.

The major feed streams to the gasifier are shown in Figure 3-2. The coal feed rates were calculated from the feeder weigh cells, and the air, nitrogen, recycle gas, and steam flow rates were taken from flow indicators. The PRB coal was fed at a rate of about 4,000 lb/hr, and was reduced to about 2,000 lb/hr prior to the transition to lignite feed. The lignite feed rate started at about 3,300 lb/hr and then was decreased to around 2,000 lb/hr around Hour 230 due to the kaolin shortage. The lignite feed rate was increased to around 4,000 lb/hr at Hour 273 and was held constant until the end of TC23.

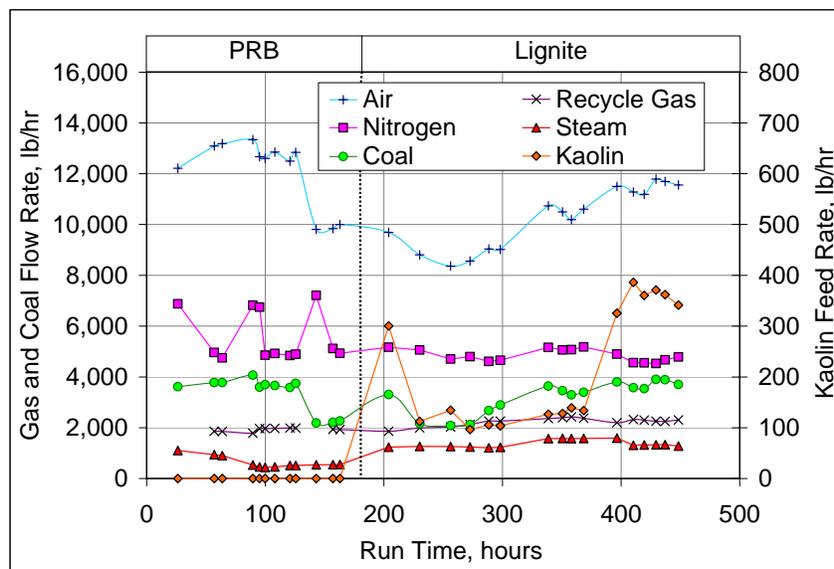


Figure 3-2. Gasifier Feed Flow Rates.

Figure 3-3 shows the standpipe levels (as differential pressures) and the riser differential pressures. The standpipe level was between 150 and 215 inH<sub>2</sub>O for PRB testing and was controlled by the operation of the CCAD system. For the first two steady state periods of lignite operation, the standpipe level was maintained at about 187 inH<sub>2</sub>O. When the kaolin and coal feed rates were decreased at Hour 230, the standpipe level decreased, so operation of the CCAD system was suspended. The standpipe height decreased to 84 inH<sub>2</sub>O by Hour 298 and then began increasing around Hour 300 as the coal feed rate was increased. When the kaolin rate was increased to about 370 lb/hr around Hour 396, the standpipe level quickly increased up to 150 inH<sub>2</sub>O. As expected, the riser differential pressure tracked the standpipe level.

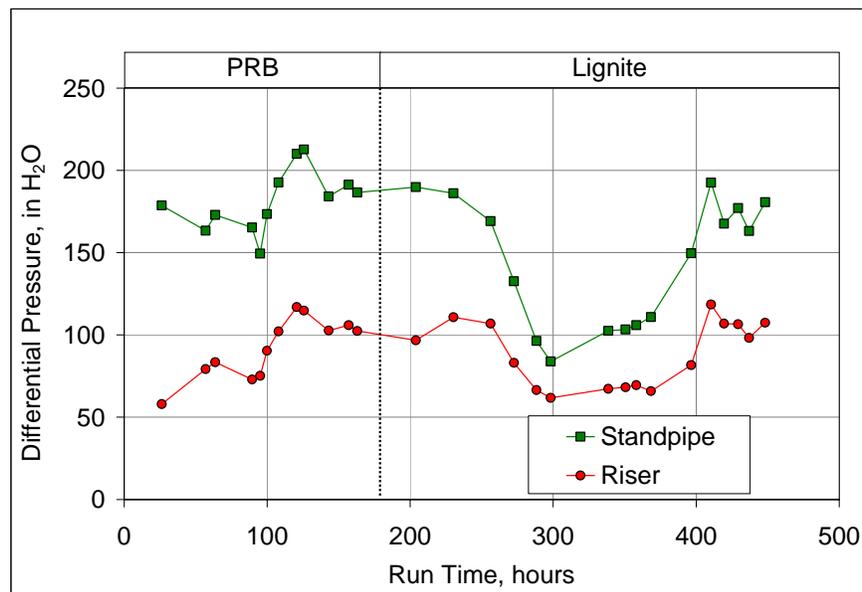


Figure 3-3. Gasifier Standpipe and Riser Differential Pressures.

Figure 3-4 shows the primary gas cooler plugging ratio over the course of the test campaign. The plugging ratio is the percentage of lost cross-sectional area in the cooler tubes due to plugging. It is calculated based on the tube side pressure drop normalized to a constant temperature, pressure, and gas flow, and compared to the cooler pressure drop at the same normalized process conditions with no restrictions. During PRB operation, the plugging ratio was consistently below ten, indicating no plugging. However, during lignite operation, the plugging ratio increased significantly. There was a steady increase from Hour 224 to 300 and from Hour 425 until the process was shut down. The increase in plugging ratio contributed to the decrease in performance and increase in outlet temperature of the primary gas cooler.

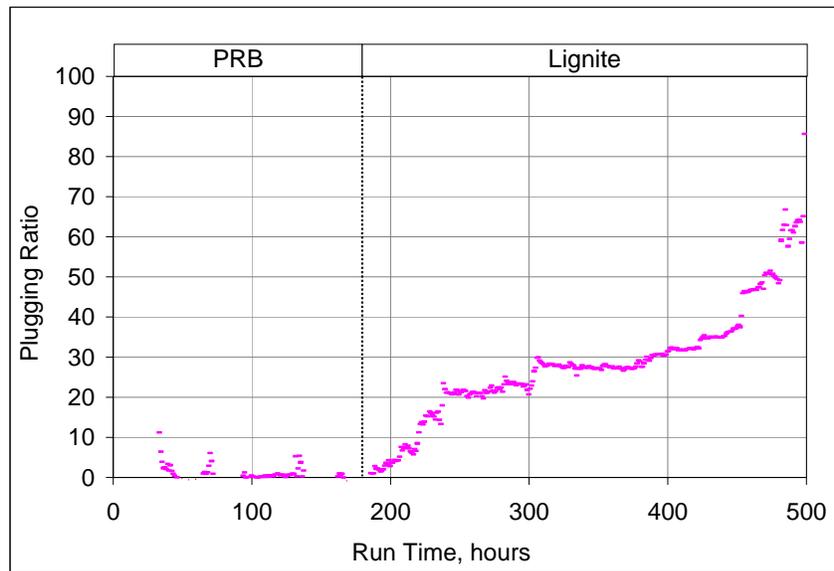


Figure 3-4. Primary Gas Cooler Plugging Ratio.

### 3.2 Gasifier Performance, Solids Analyses

The solids analyses presented for the gasifier circulating solids are sampled from the standpipe, and the PCD solids are sampled from the CFAD system.

**Solids Chemical Analyses.** The chemical analyses of the gasifier and PCD solids were used to monitor transition of the solids inventory from the sand start-up bed material to gasification ash and to characterize operation of the gasifier solids separation devices. These analyses for PRB operation were typical of those from previous PRB operation. During PRB operation, the SiO<sub>2</sub> content decreased from 95 to 46 percent while the other ash mineral components contents increased as the gasification ash replaced the sand. The chemical analyses for the gasifier and PCD solids during lignite operation are given in Table 3-1 and Table 3-2, respectively.

Table 3-1. Gasifier Circulating Solids Analysis for High Sodium Lignite Operation Starting at Hour 206.

	Average	Standard Deviation	Minimum Value	Maximum Value
SiO <sub>2</sub> , wt%	46.5	1.4	43.1	48.9
Al <sub>2</sub> O <sub>3</sub> , wt%	39.5	3.0	33.2	43.8
Fe <sub>2</sub> O <sub>3</sub> , wt%	1.9	0.6	1.1	3.2
Na <sub>2</sub> O, wt%	4.7	1.1	2.8	6.9
Other Inerts (P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O, BaO & TiO <sub>2</sub> ), wt%	2.3	0.2	2.1	2.9
CaCO <sub>3</sub> , wt%	0.3	0.2	0.1	0.8
CaS, wt%	0.0	0.1	0.0	0.2
CaO, wt%	3.8	2.1	0.6	8.3
MgO, wt%	0.7	0.4	0.1	1.5
Organic Carbon, wt%	0.3	0.2	0.07	1.1

Table 3-2. PCD Solids Analysis for High Sodium Lignite Operation Starting at Hour 206.

	Average	Standard Deviation	Minimum Value	Maximum Value
SiO <sub>2</sub> , wt%	25.0	4.0	19.4	31.9
Al <sub>2</sub> O <sub>3</sub> , wt%	19.6	3.3	14.7	24.9
Fe <sub>2</sub> O <sub>3</sub> , wt%	4.2	1.1	3.5	10.0
Na <sub>2</sub> O, wt%	4.8	0.9	2.4	6.1
Other Inerts (P <sub>2</sub> O <sub>5</sub> , K <sub>2</sub> O, BaO & TiO <sub>2</sub> ), wt%	6.0	1.5	4.9	13.6
CaCO <sub>3</sub> , wt%	3.2	0.8	1.5	4.8
CaS, wt%	1.3	0.6	0.3	2.8
CaO, wt%	10.7	1.9	8.4	14.9
MgO, wt%	3.1	0.3	1.8	3.6
Organic Carbon, wt%	25.9	6.9	13.4	37.1
Heating Value, As Received, Btu/lb	3660	1230	1500	5740

**Physical Analyses.** The MMD particle sizes of the gasifier circulating solids and the PCD solids are plotted in Figure 3-5. During PRB operation, the gasifier circulating solids were between 100 and 150 microns, and showed two periods of decreasing particle sizes. The first was from the start-up sand particle size of 150 microns, which then decreased down to 100 microns at Hour 82. The second one started at Hour 90 when the CCAD system operation was stopped to increase the standpipe level. This allowed larger particles to accumulate in the gasifier, thus increasing the standpipe solids particle size to 140 microns. The standpipe particle size again decreased down to 110 microns at Hour 164.

The gasifier particle sizes were constant around 100 to 150 microns during the first fifty hours of lignite feed. After Hour 230, when the lignite and kaolin feed rate were decreased resulting in a decrease in standpipe level and the suspension of CCAD operations, the particle sizes began increasing to about 800 microns at Hour 300. This increase in particle size in the samples also occurred during PRB operations when the CCAD system operation was suspended around Hour 90. From Hours 300 to 400, the coarse solids particles sizes varied between 350 and 900 microns. At Hour 396, the kaolin feed rate was increased to 370 lb/hr, and CCAD was started at Hour 402. After Hour 400, the coarse solids particle size decreased down to about 200 microns. The particle size during the last hours of lignite operation was similar to the sizes at the beginning of lignite feed.

During PRB operation, the PCD solids ranged between 7 and 13 microns and averaged 10 microns. For lignite operating, the PCD solids sizes measured between 8 and 14 microns and averaged 12 microns.

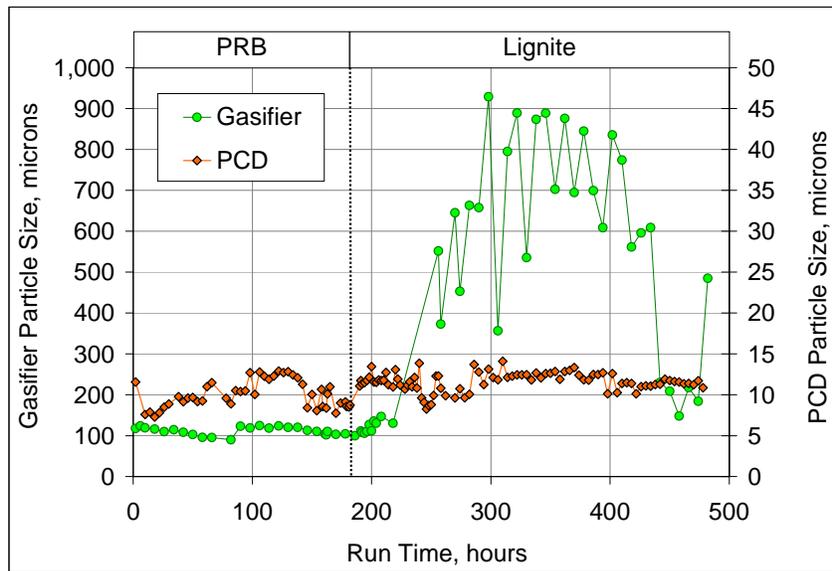


Figure 3-5. Gasifier Circulating Solids and PCD Solids Particle Sizes.

Bulk densities of the gasifier and PCD solids are plotted in Figure 3-6. The bulk density of the circulating solids decreased from about 90 to 70 lb/ft<sup>3</sup> during the first 80 hours of the test campaign as the start-up sand was replaced by gasification ash. The density of both the gasifier circulating solids and the PCD solids showed a slight increase after the transition from PRB to lignite operation with the addition of kaolin.

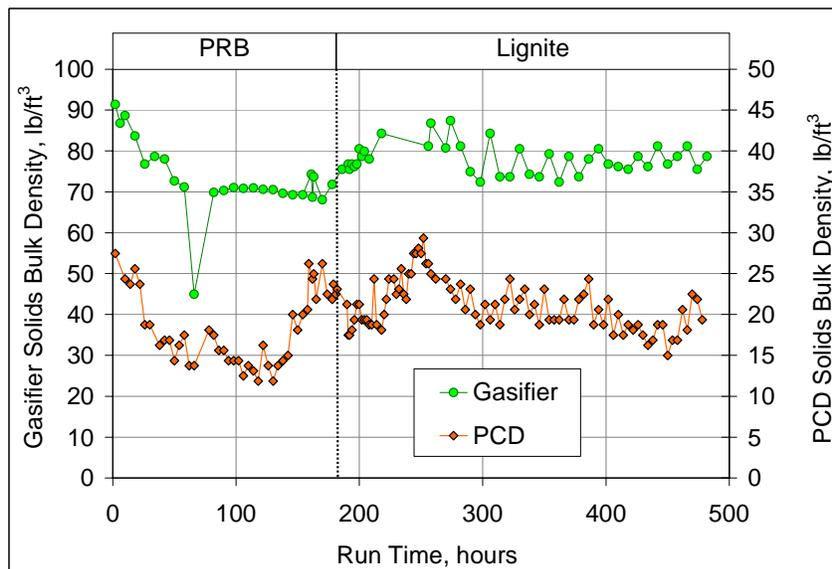


Figure 3-6. Bulk Densities of Gasifier Circulating Solids and PCD Solids.

**Gasification Ash Removal.** Figure 3-7 shows 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. CFAD and CCAD operated well, accumulating a combined 800

operating hours. The PCD solids rates were determined from the PCD inlet solids concentration, and the CCAD rates were determined by a system ash balance. The CFAD system discharged fines from the PCD at rates up to 540 lb/hr, and the maximum CCAD system withdrawal rate of hot ash from the gasifier was about 390 lb/hr. The solids removed by the CCAD system were between 17 and 39 percent of the total solids removed for PRB and were between 10 and 54 percent of the total solids for lignite operation.

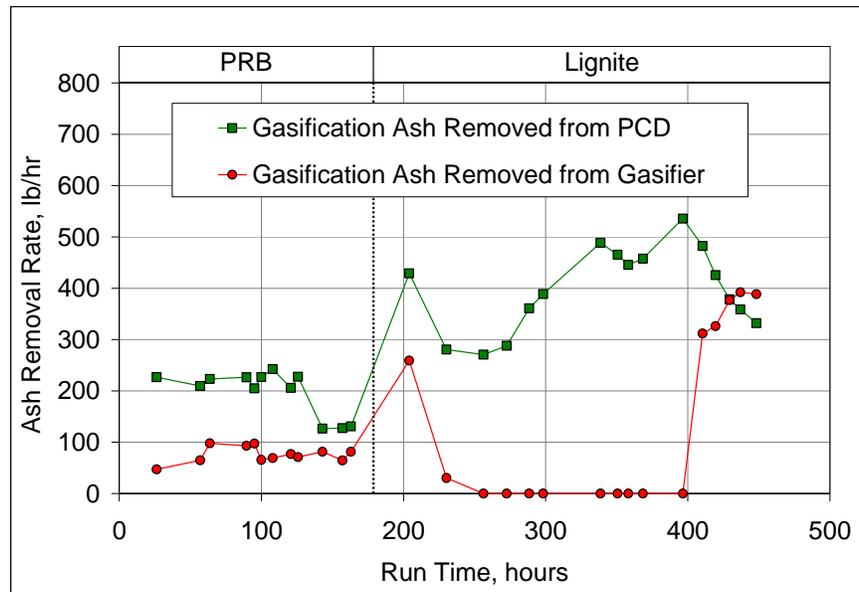


Figure 3-7. Gasification Ash Removal from the PCD and Gasifier.

After the transition from PRB coal to high sodium lignite with kaolin addition, the gasifier solids were closely monitored to detect any signs of agglomeration. In addition to monitoring the particle sizes, the gasifier solids were visually inspected using an optical microscope. Photomicrographs of the gasifier solids sampled from the standpipe at various times are presented in Figure 3-8. Observations by the visual inspection of the samples corresponded well with data provided by the measured particle sizes.

The Hour 100 sample shown in Figure 3-8 is typical gasification ash from PRB operation. The Hour 196 sample shows the solids about 16 hours after the transition to lignite feed with kaolin. Some fine ash remained and a few raw kaolin particles were seen. Samples taken at Hour 204 and 212 have a similar appearance as Hour 196, however the Hour 236 samples is noticeably different. There was less fine ash present, and larger ash and kaolin particles were more prevalent. This sample was taken about 6 hours after the lignite and kaolin feed rates were reduced and CCAD operation was suspended. The lignite feed rate was increased at Hour 273, and the sample taken at Hour 276 shows mostly large kaolin particles. Samples taken at Hours 300, 324, and 372 contained mostly larger particles as well. These samples had a high percentage larger than 1,000 microns. When the kaolin feed rate was increased at Hour 396, the increase in kaolin-to-sodium ratio combined with the removal of solids from the gasifier through CCAD altered the gasifier solids composition and size. The samples at Hour 460 and Hour 476 showed an accumulation of finer ash material and fewer larger particles.

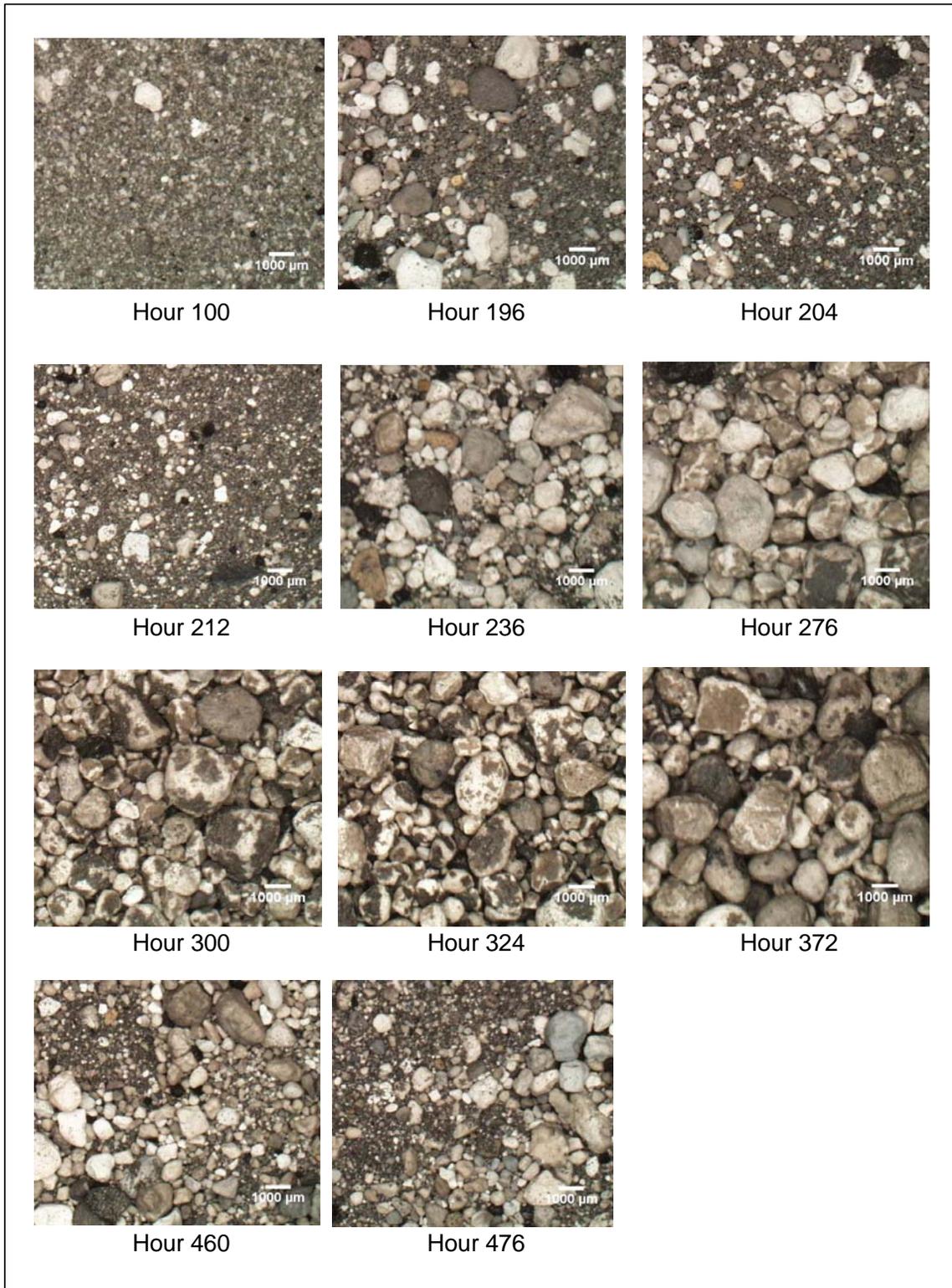


Figure 3-8. Photomicrographs of Gasifier Solids.

The gasifier solids from a sample taken on August 22, 2007, were baked in a laboratory muffle furnace to determine if exposure to higher temperatures would cause sintering and agglomeration before increasing the operating temperature after the initial stabilization of operating conditions with lignite. No evidence of sintering or agglomeration was found in any of the samples tested. However, the large kaolin particles retained in the standpipe gradually became coated with a thin layer of very fine ash. When the samples were heated at 1,800°F for five hours, the gray coating of ash was converted to a reddish-brown ash, as shown in the micrographs in Figure 3-9.

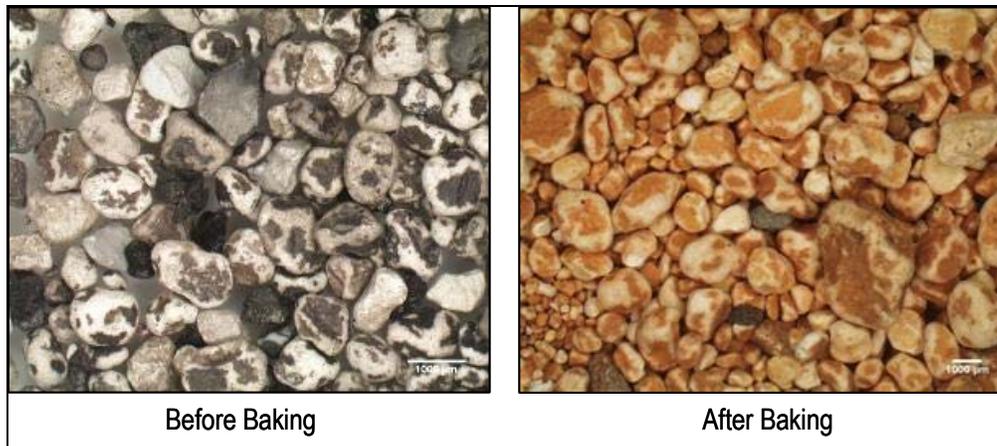


Figure 3-9. Gasifier Solids before and after Baking in Muffle Furnace.

Based on the coloration of the standpipe samples, the amount of ash coating on the surface of the kaolin seemed to increase over time as shown in Figure 3-10, but there was no evidence that this had an adverse effect on the performance of the kaolin.

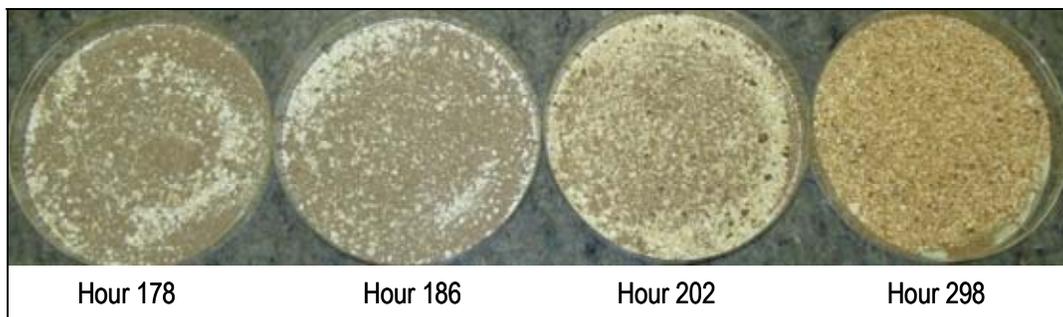


Figure 3-10. Progressive Change in Coloration of Baked Standpipe Samples.

The kaolin particles from the standpipe samples were analyzed by Energy Dispersive X-Ray Spectrometry (EDS) under a scanning electron microscope to determine if the kaolin had captured sodium. The EDS analysis was also performed on the raw kaolin for comparison, and the results are shown in Figure 3-11.

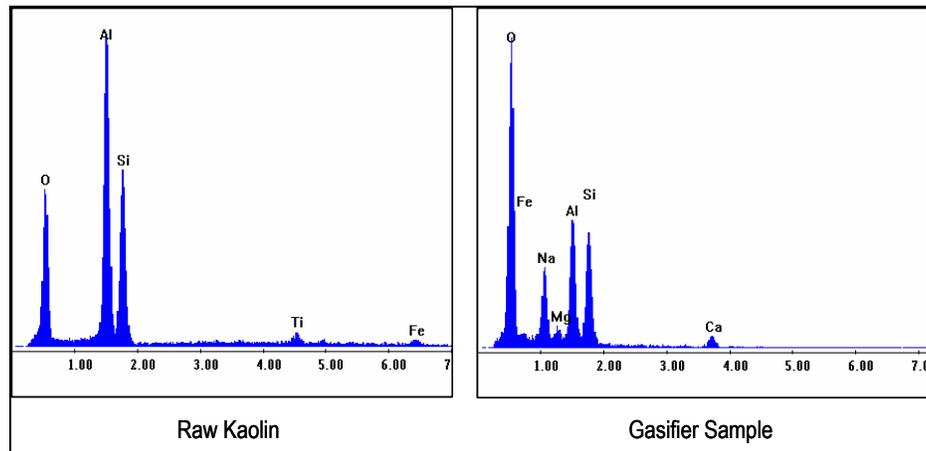


Figure 3-11. Energy-Dispersive X-Ray Spectrometry of Raw Kaolin and Kaolin Particle in Gasifier Sample.

The comparison of the EDS clearly showed that the kaolin particle in the standpipe sample from Hour 350 captured sodium. This analysis was obtained from an area of the kaolin particle surface that was not coated with ash. In cases where spectra were obtained from ash-coated surfaces, the spectra showed much higher peaks for calcium, iron, and other elements associated with the ash. In those cases, it was difficult to determine how much of the sodium was associated with the ash as opposed to the kaolin surface. However, in cases where there was no ash coating on the kaolin, there was clear evidence of sodium capture. Even in the particles that had captured significant sodium, there was no evidence of sintering between particles. Therefore, it appeared that these larger kaolin particles could capture sodium without becoming sticky and agglomerating.

### 3.3 Gasifier Performance, Gas Analyses

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<sub>2</sub>, CO, CO<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub>O, for the steady state operating periods are given in Figure 3-12. The H<sub>2</sub>, CO, CO<sub>2</sub>, and CH<sub>4</sub> 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, FTIR H<sub>2</sub>O measurements, and on a mathematical correlation based on the water-gas shift reaction equilibrium.

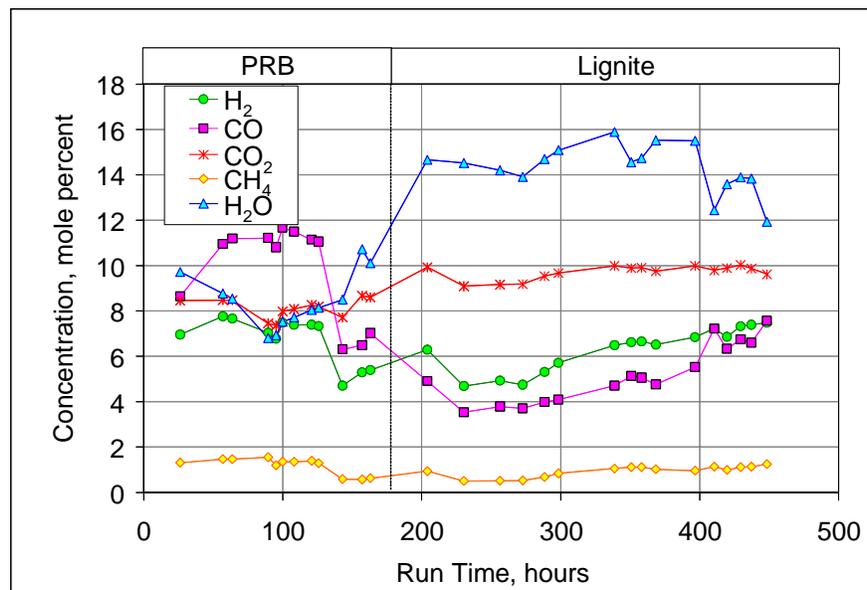


Figure 3-12. Concentrations of Major Syngas Components.

Minor constituents in the syngas include reduced sulfur compounds such as hydrogen sulfide (H<sub>2</sub>S), and reduced nitrogen compounds such as NH<sub>3</sub>. The H<sub>2</sub>S concentrations during PRB operation ranged from about 210 to 390 ppm on a wet molar basis. The higher sulfur content lignite produced a higher H<sub>2</sub>S content syngas, with H<sub>2</sub>S ranging from about 620 to 870 on a wet molar basis. A limited number of ammonia measurements were made using an FTIR analyzer, which indicated syngas ammonia concentrations with PRB operation from approximately 1,690 to 1,800 ppm on a wet molar basis. During lignite operation, the FTIR measurements ranged from about 1,570 to 1,640 ppm on a wet molar basis.

***Carbon Conversion and Syngas Heating Value.*** Figure 3-13 gives the carbon conversion values and the raw dry syngas lower heating values (LHVs) for the TC23 steady state periods. For PRB, the carbon conversion was between 95.5 and 98.7 percent and averaged 97.2 percent. With lignite operation, carbon conversion was between 90.9 and 97.6 percent and averaged 93.8 percent. The dry LHV was between 42 and 77 Btu/SCF for PRB and between 34 and 64 Btu/SCF for lignite. The syngas heating values projected for commercial operation of a Transport Gasifier are higher, since in a commercial plant, heat loss from the gasifier and nitrogen dilution would be lower than at the PSDF.

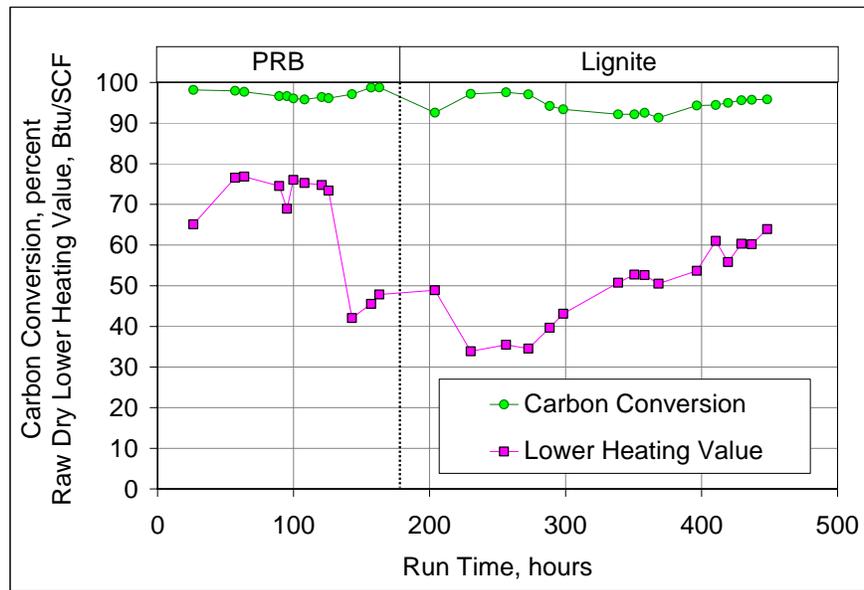


Figure 3-13. Carbon Conversion and Syngas Heating Value.

**Gasification Efficiency.** During PRB operation, the hot gasification efficiency ranged from approximately 83.8 to 90.1 percent. With high sodium lignite, the hot gasification efficiency was slightly lower, ranging from 81.2 to 86.7 percent.

### 3.4 Gasifier Parametric Testing

A number of tests were performed to establish boundary conditions of Transport Gasifier operations with high sodium lignite. The parametric testing completed included gasifier temperature, gasifier pressure/riser velocity, steam to coal ratio, and coal feed rate effects on gasifier performance. In addition, the effect of standpipe level on gasifier circulation rate was examined. 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 3-14 gives the effect of gasifier temperature on carbon conversion during lignite operation at a gasifier pressure of 185 psig, air-to-coal mass ratios between 3.2 and 3.3, and coal feed rates ranging from 3,400 to 3,600 lb/hr. As expected, the data shows a linear correlation between carbon conversion and temperature.

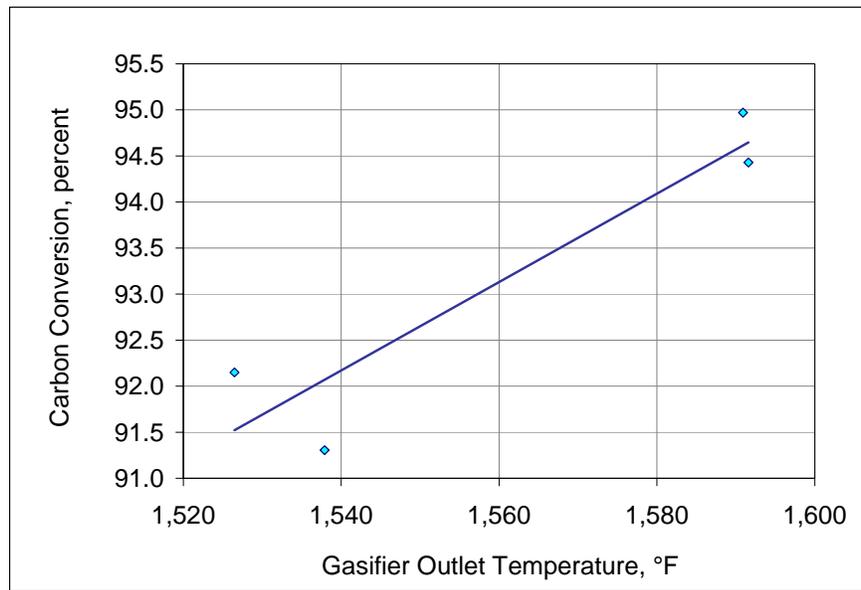


Figure 3-14. Carbon Conversion as a Function of Gasifier Temperature for Lignite Operation.

Gasifier pressure (which directly controls riser velocity) was varied to quantify its effects on gasifier performance. Figure 3-15 illustrates the effect of pressure on the syngas methane content, represented by a relative value, the methane factor. The methane factor is calculated based on the actual methane content but uses an equation to normalize the data so that inert gas dilution effects are eliminated. An additional factor is used to place the data on a zero to one scale. During the steady state periods from which the data was extracted, the air-to-coal mass ratios were maintained at about 2.9 to 3.2, the gasifier mixing zone temperature ranged from about 1,600 to 1,630°F, and carbon conversions were between 91.3 and 92.6 percent. The limited data suggest a linear relationship correlating to an increase in methane content with increasing pressure.

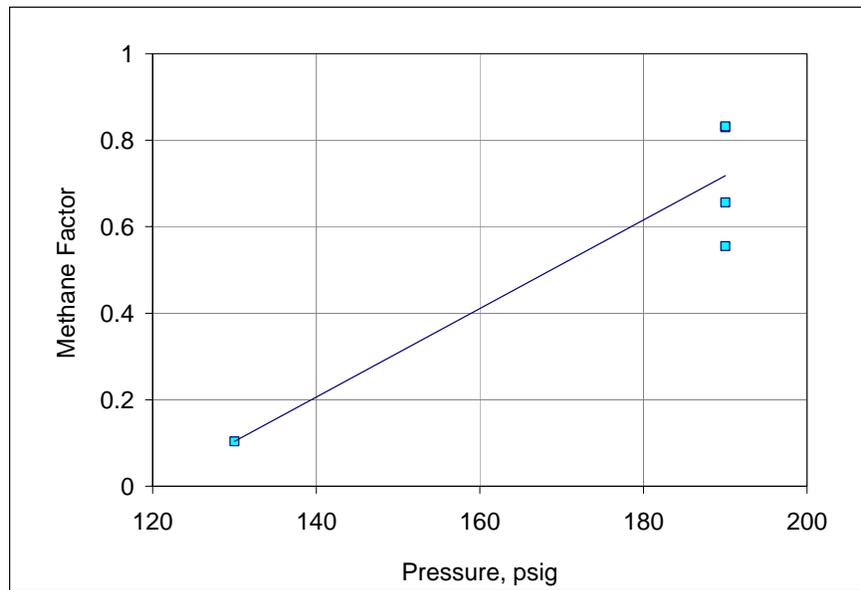


Figure 3-15. Syngas Methane Content as a Function of Gasifier Pressure for Lignite Operation.

Figure 3-16 plots the syngas hydrogen-to-carbon monoxide ratio and the steam-to-coal ratio. The curves follow the expected trend of increasing hydrogen-to-carbon monoxide ratio with increasing steam-to-coal ratio due to the water gas shift reaction. The lignite has higher hydrogen-to-carbon monoxide ratio at similar steam-to-coal ratios.

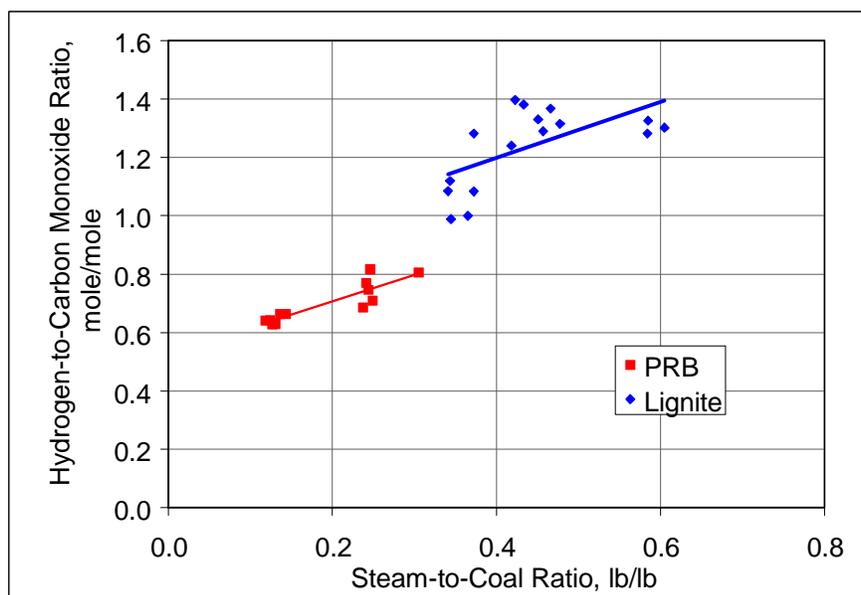


Figure 3-16. Syngas Hydrogen-to-Carbon Monoxide Ratio versus Steam-to-Coal Ratio.

Figure 3-17 shows the raw dry syngas heating value as a function of lignite feed rate. This plot included the steady state data taken when the air-to-coal mass ratio was between 2.9 and 4.1. As shown in the figure, the syngas heating value increases as the coal feed rate increases. The

increase is due to a lessened effect of nitrogen and a lower percentage of heat loss relative to the heat input.

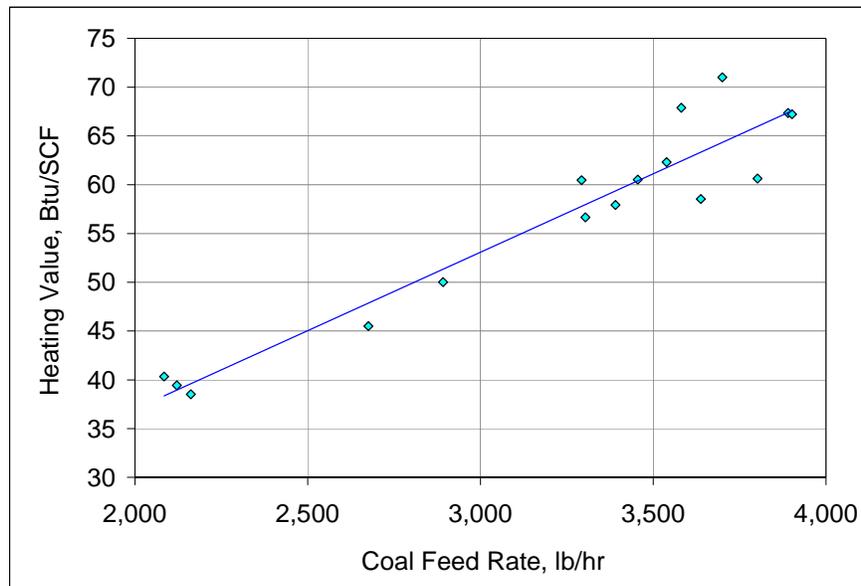


Figure 3-17. Syngas Heating Value as a Function of Lignite Feed Rate.

Figure 3-18 shows the relative solids circulation rate as a function of gasifier standpipe level during lignite operation. As expected, the data indicate a strong linear relationship.

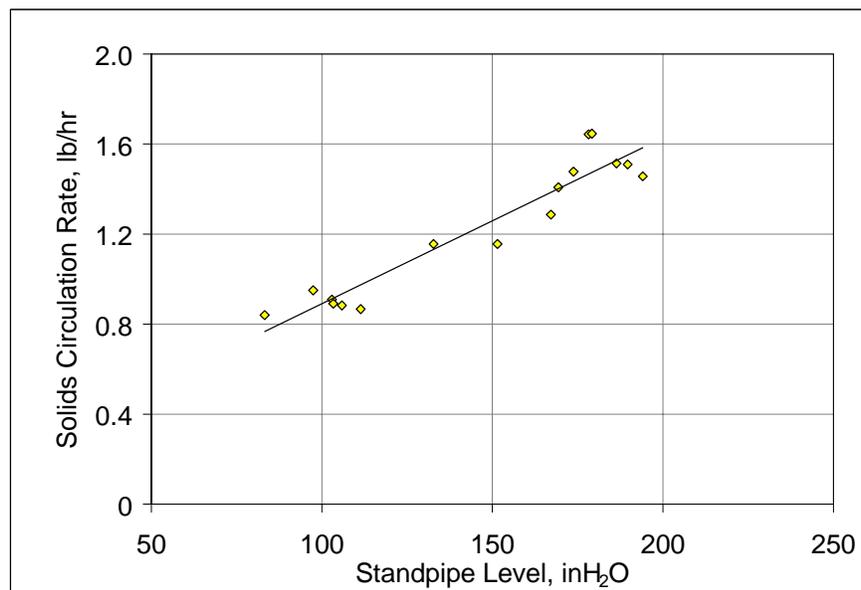


Figure 3-18. Effect of Standpipe Level on Circulation Rate for Lignite Operation.

### 3.5 Post-Test Inspections

Detailed inspections of the gasifier and related equipment were performed following the conclusion of TC23. Based on previous operations with high sodium lignite, there was a concern that solids would agglomerate in the gasifier. However, inspections confirmed that no agglomerations had formed in the gasifier during this test campaign. Figure 3-19 shows borescope photographs of the riser and lower mixing zone taken during the inspections. In general, the gasifier refractory appeared in good condition, although a portion of refractory was missing in the first stage solids separation inlet. Also, some cracks were noted in this section. The refractory in the lower standpipe, which has been in service for over 19,000 hours of solids circulation and experienced over 100 temperature cycles remains in excellent condition as shown in Figure 3-20.

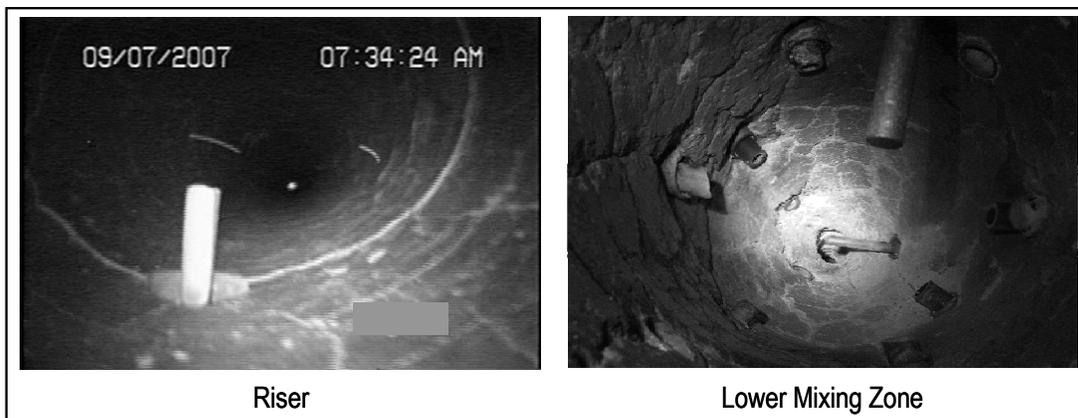


Figure 3-19. Inspection of Riser and Lower Mixing Zone.

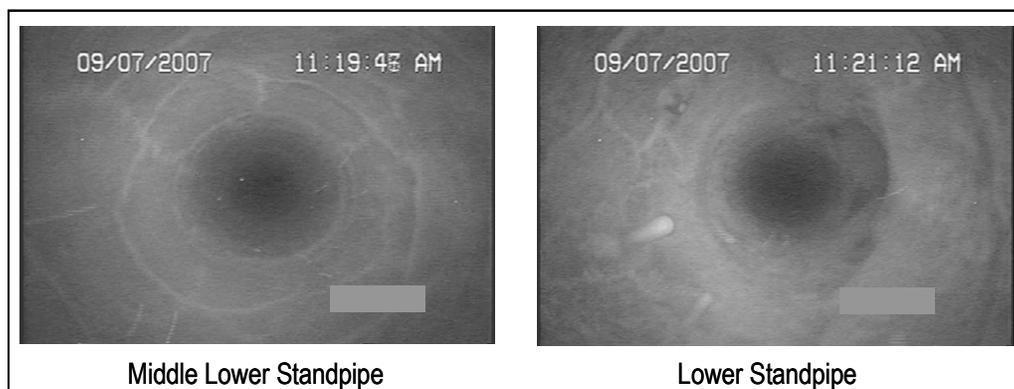


Figure 3-20. Inspection of Lower Standpipe.

During the gasifier modifications in 2006, different types of refractory were installed in various sections of the gasifier based on the operating conditions in each area to test different types of refractory. Actchem 85 VC was installed in the first stage solids separation device to evaluate its performance at these conditions. The Actchem 85 VC properties include a high erosion resistance and high coefficient of thermal expansion, which make it very resistant to wear but

susceptible to cracking. The Actchem 85 VC refractory life is heavily dependent on the number of thermal cycles and is rated for about 30 thermal cycles. Since installation in the first stage solids collection device, the Actchem 85 VC refractory has experienced approximately 15 thermal cycles. Based on the thermal cycles experienced and current refractory condition, the refractory is about halfway through its useful life. Figure 3-21 shows examples of the cracking in this refractory.

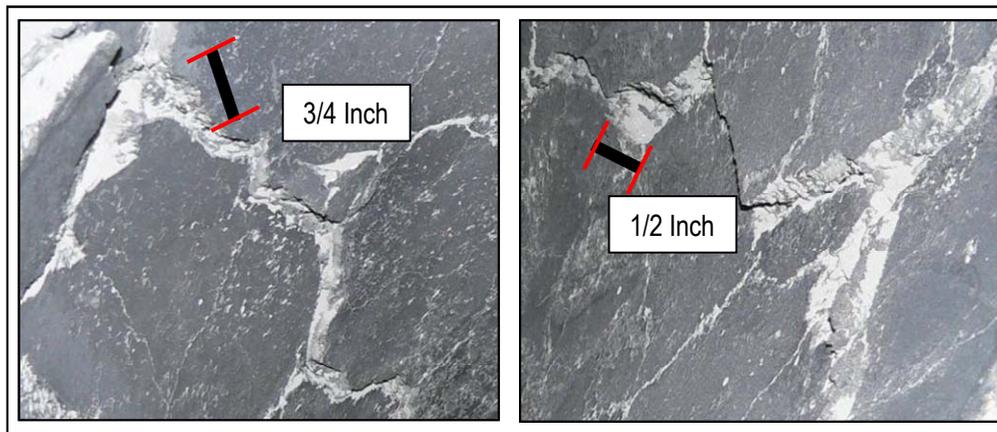


Figure 3-21. Inspection of Actchem 85 VC Refractory.

Inspections of the primary gas cooler, shown in Figure 3-22, revealed a majority of the tubes (about 60 percent) were plugged with material by the end of the test campaign, which accounted for the increases in the plugging ratio plotted in Figure 3-4. The material in the gas cooler was soft and easily removed. Some soft agglomerated material was also found in the process piping downstream of the cooler. Since the solids exiting the gasifier are small particles, about 10 to 12 microns, it is possible that the smaller particles containing sodium-based silicates agglomerated in the gas cooler as the syngas temperatures decreased. This is consistent with the findings of laboratory testing performed at the PSDF prior to the test campaign that showed some consolidation when testing the kaolin and kaolinite fine material. Samples of the material plugging the tubes were taken for additional analysis to confirm the deposition mechanism.

The tubes that remained opened showed some signs of wear. Hydrostatic testing of the cooler showed two leaking tubes. The two leaking tubes located in the outer ring of the array had cracked in the upper section of the cooler near the gas inlet.

Further inspections revealed that the water-side of the tubes in the upper section of the cooler had suffered significant corrosion. Surface pitting possibly caused from oxygen attack was noted and believed to be caused by downtime corrosion and water chemistry issues resulting from a balance of plant heat exchanger leak that allowed untreated water to enter the steam system. Additional analysis revealed high levels of sulfur on the tube outer diameter which was also related to the water chemistry issues. The lower section of the tubes where the water entered was in very good condition. Since the necessary tube repairs were extensive, all of the heat exchanger tubes were replaced.

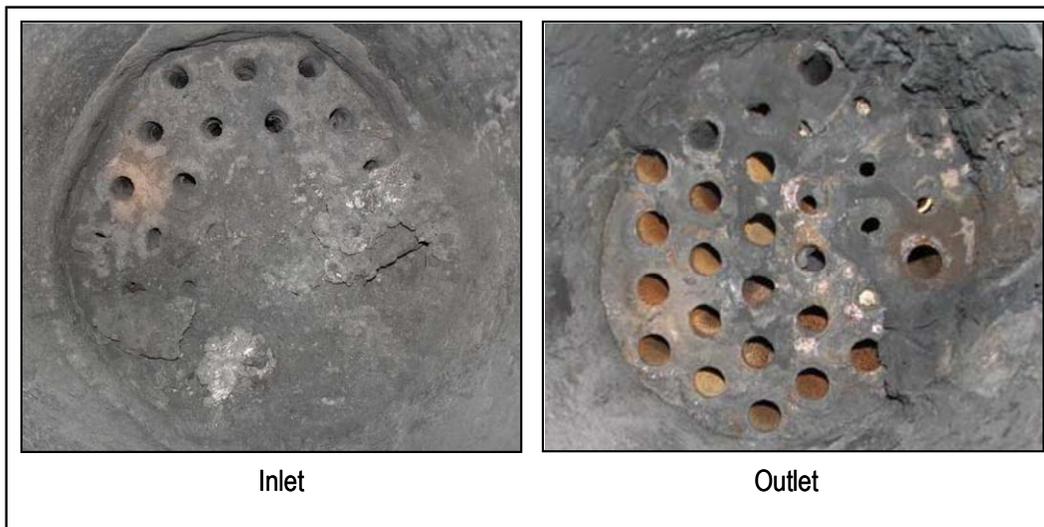


Figure 3-22. Inspection of Primary Gas Cooler Inlet and Outlet.

Figure 3-23 shows the gas cooler tube bundle after it was removed from the process. Excessive corrosion had occurred in the area of the syngas inlet and saturated steam exit. The middle section and the water inlet and syngas outlet were in acceptable condition.

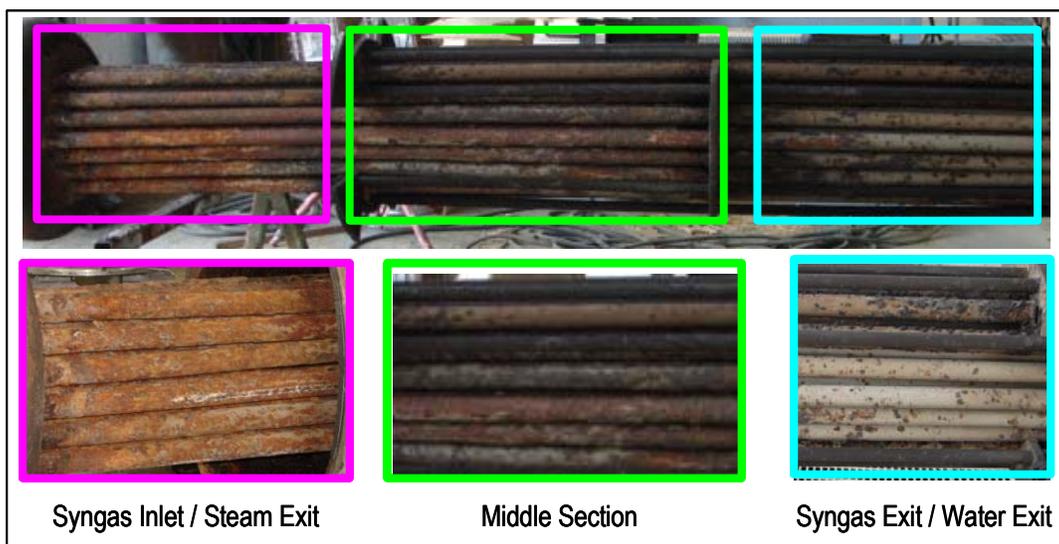


Figure 3-23. Inspection of Primary Gas Cooler Tube Bundle.

The failed tubes were analyzed to determine the root cause of failure. Analysis showed that the tube wall thickness had decreased during the last several test campaigns likely due to corrosion on the water side. As the tubes became plugged with material during the later stages of TC23, they became relatively cool, and the temperature differential between the blocked tubes and the tubesheet increased. The higher thermal stress in combination with a thinned tube wall likely caused the tubes to crack.

Inspection of the secondary syngas cooler did not show tar condensation. As preventive maintenance, the cooler was hydrostatically tested, and three tubes were found to be leaking. The leaking tubes were repaired on-site.

### 3.6 Tracer Gas Tests

A tracer gas test was performed during PRB operation to evaluate gas underflow from the first solids separation device to the standpipe, gas and solids mixing in the riser, riser velocity, and vapor evolution profiles. The tracer gas, Argon-41, was injected into the gasifier at two locations, the mixing zone and riser, at separate times under various operating conditions. The riser velocity was varied from 20 to 28 ft/s and the standpipe level measured as differential pressure was varied from 140 to 180 inH<sub>2</sub>O.

The tracer gas equipment setup, injection, and raw data acquisition was performed by a third-party contractor, Tracerco. The PSDF installed injection nozzles to connect a tracer injection apparatus to the system. Non-intrusive detectors were attached to the perimeter of the gasifier to measure tracer concentrations in the syngas. Two injections were made initially for calibration of the detection equipment. The next six injections and subsequent measurements lasted for approximately three hours. The tracer gas, isotope Argon-41, commonly used in tracer gas testing because it has a half-life of only 1.8 hours, is chemically inert and can be measured reliably with non-intrusive detectors. Radiation levels were monitored during injection of the tracer gas, and no detectable levels were observed outside of the gasifier.

## 4.0 SENSOR DEVELOPMENT

For TC23, the on-going evaluation of ceramic-tipped pressure differential indicators was discontinued. Assessment of thermowell metal and ceramic materials continued.

### 4.1 Pressure Differential Indicator Ceramic Inserts

One area of focus of the sensor development program has been low flow, pressure differential indicators fitted with ceramic inserts. Conceptually, this measurement method lowers instrument purge flow requirements and improves sensitivity. Three sets of these low flow ports were evaluated in previous test runs. Two port designs were evaluated: a low differential pressure design and a high differential pressure design. The low differential pressure design matched conventional measurements well, but the high differential pressure design often plugged due to nitrogen purge flow control difficulties. Installation of low nitrogen flow meters was investigated as a way to improve performance, but further testing of the ceramic-tipped instruments was suspended because of the high material cost and the limited potential for commercial applications.

### 4.2 Thermowell Materials

Two types of thermowell materials, HR-160 metal and ceramic, were tested during TC23 for continued evaluation of thermowell durability and longevity. There were no failed gasifier temperature measurements; however, post-test inspections revealed extensive metal loss on three thermowells in the mixing zone just above the coal feed nozzle. The tip degradation was severe, with wear to the inner sheath. These same three elements had shown some wear during TC21 when exposed to high velocities due to deposit formation in the mixing zone. Figure 4-1 is a typical example of these worn thermocouples, photographed during post-TC21 and –TC23 inspections. Metallurgical analysis of the worn HR-160 elements indicated that sulfur species may have attacked the nickel contained in the HR-160. The increased gasifier solids particle size and hardness from kaolin addition may have accelerated the thermowell tip degradation in TC23.

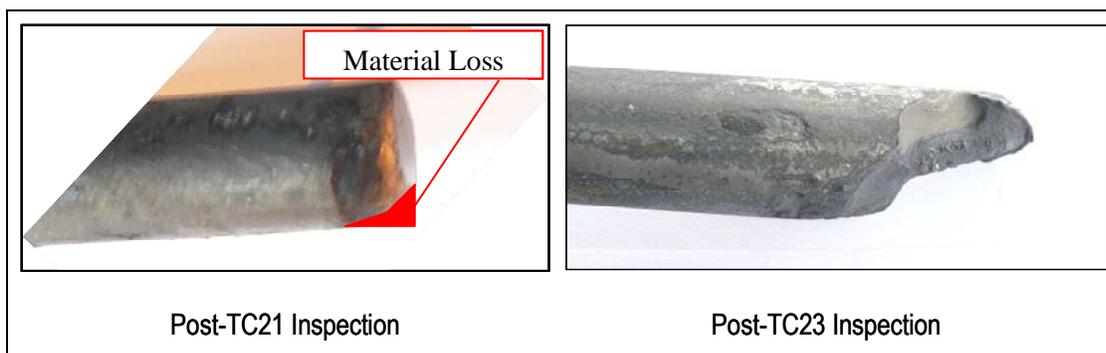


Figure 4-1. Post-TC21 and Post-TC23 Inspections of Worn HR-160 Thermowell.

All other HR-160 elements removed from the mixing zone and riser showed only minimal wear. A typical example of these elements is shown in Figure 4-2. These elements have accumulated over 2,200 hours of operation.



Figure 4-2. Inspection of HR-160 Thermowell with Minimal Wear.

Eight ceramic thermowells were tested in TC23. The ceramic thermowells have operated over 2,200 hours and show only minimal wear on the thermowell tips; however, failures incurred during removal of the thermowells continues to be a concern. Figure 4-3 shows a ceramic thermowell that was broken during removal. The tip of this element did not show significant wear.



Figure 4-3. Ceramic Thermowell Damaged during Removal.

Testing of these two types of thermowell materials will continue, but future testing will focus more on the HR-160 thermowells since they generally perform acceptably, require little maintenance, and are significantly less expensive than ceramic thermowells. A new material for thermowell application will be tested in future test campaigns as well. This material, developed by Oak Ridge National Laboratory, is a high-strength metal alloy suitable for coal gasification application. Test rods of this material, without thermocouples, will be installed in high erosion areas of the gasifier.

## 5.0 PARTICULATE CONTROL DEVICE

For TC23, the particulate characteristics and performance of the PCD with North Dakota lignite coal were quantified by particulate sampling and analyses. An equal number of Pall Dynalloy HR-160 sintered metal fiber elements and Pall iron aluminide filter elements were installed to continue long-term evaluation of these element types. On-line failsafe testing was conducted with a Pall Dynalloy metal fiber fuse failsafe device.

### 5.1 PCD Inlet and Outlet Particulate Measurements

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 are used to help understand the pressure drop characteristics of the PCD and will be used in a later section to calculate transient drag. The outlet measurements indicate the collection performance of the PCD with the installed filter elements.

The particulate concentrations measured at the PCD inlet and the corresponding mass rates, as well as the particulate concentrations measured at the PCD outlet are given in Table 5-1. Throughout the initial portion of TC23 with PRB operation, the particulate concentration at the PCD outlet remained above 0.1 ppmw (the minimum measurement resolution). Most of the particle mass collected appeared to be metallic corrosion product including the unusually high concentration of 1.86 ppmw on Run 3. Although the corrosion product did prevent quantification of particle penetration, the low mass concentration indicated that the installed filter elements provided adequate particulate collection.

Table 5-1. PCD Inlet and Outlet In-Situ Particulate Measurements.

Test Date	PCD Inlet					PCD Outlet				
	Run No.	Start Time	End Time	Particle Loading, ppmw   lb/hr		Run No.	Start Time	End Time	H <sub>2</sub> O Vapor, vol %	Particle Loading, ppmw
PRB Combustion										
8/7/07	--	--	--	--	--	1	13:30	14:30	8.3	0.46
PRB Gasification										
8/09/07	1	8:15	8:30	8820	227	2	7:30	11:30	--	0.13
8/10/07	2	8:30	8:45	8270	206	3	7:45	11:45	8.6	1.86 <sup>(1)</sup>
8/11/07	3	9:00	9:15	8300	211	4	8:45	9:45	7.5	0.16
"	4	13:30	13:45	7940	192	5	13:15	14:15	7.4	0.29 <sup>(1)</sup>
8/14/07	--	--	--	--	--	6	9:00	13:00	9.9	0.29 <sup>(1)</sup>
Lignite Gasification										
8/15/07	5	12:15	12:30	18600	404	7	8:45	14:13	15.4	0.10
8/16/07	6	9:45	9:55	23700	532	8	9:30	11:45	14.7	<0.10
8/17/07	7	8:45	9:00	12200	251	9	8:30	12:03	17.1	<0.10
8/20/07	8	9:15	9:30	6400	141	10	9:00	13:00	17.8	<0.10
8/21/07	9	8:45	9:00	19600	500	11	8:30	11:50	15.4	<0.10
8/22/07	10	9:00	9:15	21700	536	12	8:45	12:45	14.8	<0.10
8/23/07	11	10:45	11:00	21700	518	13	10:00	11:00	14.6	0.13 <sup>(3)</sup>
8/24/07	12	9:15	9:30	18900	467	14	9:00	13:00	12.7	<0.10
"	13	13:15	13:30	21400	513	--	--	--	--	--
8/25/07	14	8:45	9:00	15000	389	--	--	--	--	--
8/27/07	15	12:45	13:00	9900	261	15	10:30	14:15 <sup>(4)</sup>	15.2	<0.10 <sup>(3)</sup>

Notes:

1. Some particles are not believed to be char. No PCD leak is indicated.
2. Run paused from 9:07 to 10:30 because of coal feeder problems.
3. Failsafe injection test. Not a PCD leak.
4. Run paused from 10:46 to 11:15 because of coal feeder problems.

## 5.2 PCD Solids Analysis

Important characteristics of the PCD 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 PCD inlet in-situ samples and the PCD hopper sample (sampled from the CFAD system) used for the laboratory drag measurements. Figure 5-1 compares the differential mass percentage distributions for the average of the in-situ samples with the hopper composite samples used for the TC23 lab drag measurements. (Although the in-situ samples are a more accurate representation of the particulate entering the PCD at a given time, the quantity of particulate collected is far too small of be useful for drag measurements.) The hopper composites were blended from samples collected during the period of most stable operation with both high and low rates of kaolin addition.

Although there are some minor differences in the three distributions, these differences should not affect the flow resistance properties of the dustcake significantly. Also, there is almost no difference between the samples from high and low kaolin addition rates. Therefore, the composite hopper samples are representative of the PCD particulate.

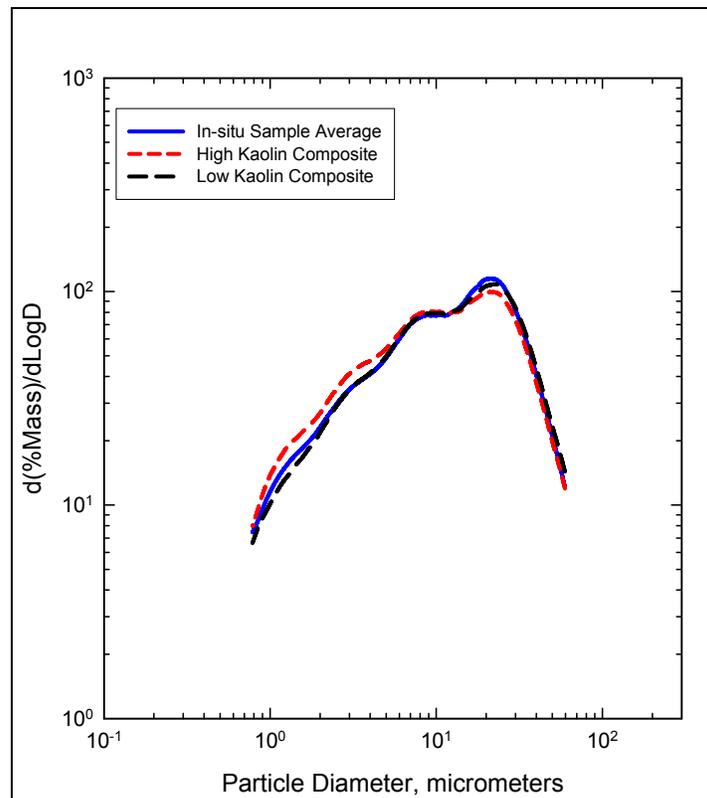


Figure 5-1. Particle Size Distributions of PCD Inlet In-Situ and Hopper Samples.

### 5.2.2 Dustcake Observations

At the conclusion of TC23, the PCD was shut down dirty, meaning that the gasifier was shut down quickly just before a cleaning sequence of the PCD was initiated. The purpose of this procedure is to allow observation of the transient dustcake. Inspection of the PCD after TC23 confirmed that both the transient and residual dustcakes were largely intact on the elements. On the top plenum, lumpy dustcakes were noted on the older iron aluminide elements. The lumpiness of the dustcake appears to be related to the roughening of the iron aluminide surface and the localized plugging that has been seen in the older iron aluminide elements that are more extensively corroded. The dustcake cross section contained several different layers with a very thin, lighter-colored layer on the surface. The surface layer was much lighter in color than the underlying ash and may have been material that was blown over after the shutdown.

On the bottom plenum, the dustcakes on the HR-160 metal fiber elements were all very smooth and contained the same layers noted on the top-plenum iron aluminide elements. The dustcake on the bottom-plenum HR-160 metal fiber elements was generally uniform, although in some areas the dustcake appeared to be thicker at the bottom of the element than at the top (see Table 5-2). On average, the dustcake on the bottom-plenum HR-160 metal fiber elements appeared to be a little thicker than the dustcake on the top-plenum iron aluminide metal powder elements. (The iron aluminide elements measured had low operating hours and did not have the corrosion and plugging problems noted above.) The difference in dustcake thickness could be related to the flow resistance of the element itself. The HR-160 metal fiber elements generally have less flow resistance than do the iron aluminide metal powder elements. This results in thicker cakes on the HR-160 elements to equalize the pressure drops between the two plenums.

Table 5-2. Dustcake Thickness Measurements.

Element Location	Element Type	PSDF No.	Mfr No.	Hrs Before TC23	Hrs After TC23	Thickness, in.	
						Top	Bottom
B08	HR160	1724	60	2526	3007	0.1178	0.1379
B14	HR160	1760	101	2217	2698	0.1327	0.1453
T08	FEAL	2034	None	2320	2801	0.0959	0.1037
T14	FEAL	2040	None	1801	2282	0.1044	0.1307

### 5.2.3 Particulate Physical Properties and Chemical Compositions

This section discusses the physical properties and chemical compositions of the in-situ samples collected at the PCD inlet, the PCD hopper samples used for the laboratory drag measurements, and the dustcake samples.

***In-situ Samples.*** Table 5-3 and Table 5-4 give the physical properties and chemical compositions of the in-situ samples collected at the PCD inlet and the hopper samples selected for laboratory drag measurements. As noted in the tables, Runs 1 through 4 were performed with PRB coal, and Runs 5 through 15 with the high-sodium lignite and kaolin sorbent. Despite the large

addition of kaolin, the data in Tables 5-3 and 5-4 do not appear to be significantly different from previous tests with high-sodium lignite. This result suggests that very little of the kaolin was carried over to the PCD, which seems reasonable given the large particle size of the kaolin.

Past observations have shown an increase in the specific surface area of the gasification ash with increasing non-carbonate carbon content (NCC). The TC23 data on surface area and NCC are added to previous data in Figure 5-4, which graphically illustrates this effect.

**Composite Hopper Sample.** For the lab drag measurements, two composite hopper samples were prepared using individual hopper samples from steady state periods with low and high rates of kaolin addition. As shown in Tables 5-3 and 5-4, the physical properties and chemistry of the composite hopper sample are similar to those of the in-situ samples, suggesting that the composite hopper samples were representative samples for the laboratory drag measurements. Comparison of the two composite hopper samples also showed very little difference in properties, again suggesting that very little of the kaolin was carried over to the PCD.

Table 5-3. Physical Properties of In-Situ Samples and Samples Used for Lab Measurements.

Sample ID	Run No.	Sample Date	Bulk Density g/cc	True Density g/cc	Uncompacted Bulk Porosity %	Specific Surface Area m <sup>2</sup> /g	Mass Median Diameter μm	Loss on Ignition Wt %
<i>In-Situ Samples - PRB Coal</i>								
AB23763	1	08/09/07	0.27	2.44	88.9	152	9.2	36.81
AB23764	2	08/10/07	0.26	2.60	90.0	159	14.0	26.30
AB23765	3	08/11/07	0.27	2.28	88.2	212	12.8	47.29
AB23766	4	08/11/07	0.20	2.44	91.8	306	12.4	46.01
<i>In-Situ Samples - High-Sodium North Dakota Lignite</i>								
AB23772	5	08/15/07	0.37	2.44	84.8	132	12.0	28.85
AB23917	6	08/16/07	0.39	2.50	84.4	84	12.6	23.57
AB23918	7	08/17/07	0.44	2.69	83.6	55	10.6	11.15
AB23919	8	08/20/07	0.45	2.57	82.5	86	18.9	21.11
AB23952	9	08/21/07	0.36	2.30	84.3	164	13.5	35.91
AB23976	10	08/22/07	0.35	2.32	84.9	156	14.7	35.15
AB23996	11	08/23/07	0.32	2.45	86.9	148	11.0	31.25
AB24021	12	08/24/07	0.36	2.65	86.4	120	10.3	19.20
AB24022	13	08/24/07	0.33	2.45	86.5	162	13.9	28.12
AB24023	14	08/25/07	0.34	2.46	86.2	185	11.5	32.01
AB24087	15	08/27/07	0.29	2.56	88.7	178	12.7	29.54
<i>Samples Used for Lab Drag Measurements</i>								
AB24160	NDL -Low Kaolin	8/22-23/2007	0.37	2.49	85.1	143	13.0	34.43
AB24159	NDL - High Kaolin	8/25-26/2007	0.30	2.54	88.2	138	11.2	25.06

Table 5-4. Chemical Composition of In-Situ Samples and Sample Used for Lab Measurements.

Sample ID	Run No.	Sample Date	CaCO <sub>3</sub> Wt %	CaS Wt %	CaO Wt %	Non- Carbonate Carbon Wt %	Inerts (Ash/Sand) Wt %	Loss on Ignition Wt %
<i>In-Situ Samples - PRB Coal</i>								
AB23763	1	08/09/07	3.09	1.65	13.37	36.04	45.85	36.81
AB23764	2	08/10/07	3.00	1.54	17.76	28.24	49.45	26.30
AB23765	3	08/11/07	4.45	2.50	9.87	44.97	38.20	47.29
AB23766	4	08/11/07	3.68	1.73	10.69	43.56	40.33	46.01
<i>In-Situ Samples - High-Sodium North Dakota Lignite</i>								
AB23772	5	08/15/07	3.18	1.56	11.43	28.72	55.11	28.85
AB23917	6	08/16/07	2.95	1.71	8.92	24.15	62.27	23.57
AB23918	7	08/17/07	1.43	0.45	16.51	14.23	67.38	11.15
AB23919	8	08/20/07	2.45	0.91	11.76	22.01	62.87	21.11
AB23952	9	08/21/07	2.18	1.71	10.42	34.94	50.74	35.91
AB23976	10	08/22/07	3.30	2.20	8.86	34.20	51.44	35.15
AB23996	11	08/23/07	3.18	1.58	10.03	31.12	54.09	31.25
AB24021	12	08/24/07	1.95	1.36	10.53	21.07	65.08	19.20
AB24022	13	08/24/07	3.14	2.20	8.01	28.42	58.23	28.12
AB24023	14	08/25/07	3.09	2.56	8.40	31.83	54.13	32.01
AB24087	15	08/27/07	4.43	1.56	17.05	29.27	47.69	29.54
<i>Samples Used for Lab Drag Measurements</i>								
AB24160	NDL -Low Kaolin	8/22-23/2007	2.50	2.03	11.36	33.80	50.31	34.43
AB24159	NDL - High Kaolin	8/25-26/2007	2.57	2.32	11.65	26.59	56.87	25.06

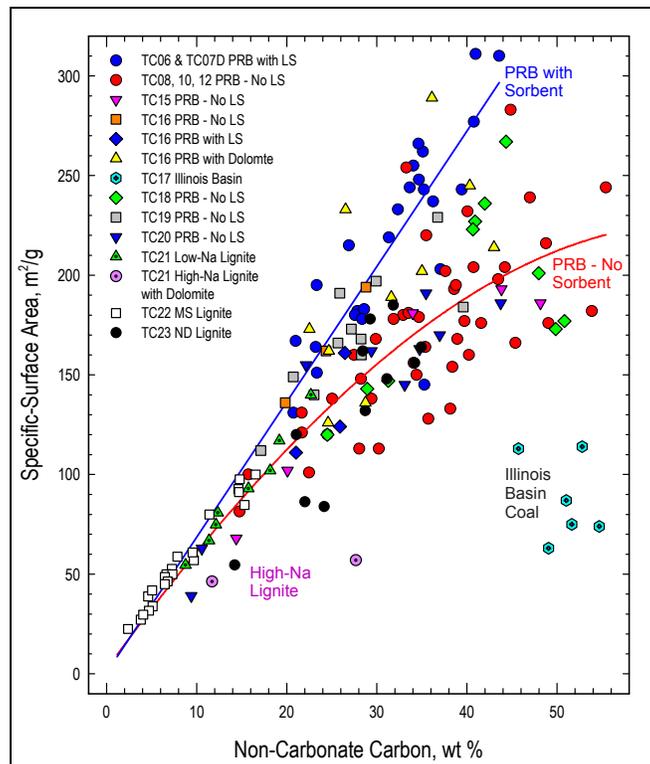


Figure 5-2. Effect of Carbon Content on Specific Surface Area of Gasification Ash.

**Dustcake Samples.** Tables 5-5 and 5-6 give the physical properties and chemical composition of the dustcake samples taken after TC23. The samples included separate samples of the residual and transient dustcakes from both the top and bottom plenums. All of the samples had similar physical properties, except that the residual cakes had a finer mean particle size than the transient cakes. This trend has been observed in previous test campaigns and was attributed to fine-particle enrichment in the residual dustcake. That is, the finer particles, which tend to be more tightly bonded than the larger particles, are preferentially retained in the dustcake, while the more loosely held large particles are blown out by the prolonged back pulsing of the residual dustcake. Roughening of the element surface by corrosion and wear may also result in greater retention of fine particles within the residual dustcake.

Table 5-5. Physical Properties of Dustcake Samples.

Sample ID	Sample Location	Bulk Density, g/cc	TRUE Density, g/cc	Uncompacted Bulk Porosity, %	Specific Surface Area, m <sup>2</sup> /g	Mass Median Diameter, microns	Loss on Ignition Wt %
AB24107	Top Plenum Residual	0.31	2.54	87.8	147	8.3	23.43
AB24106	Bottom Plenum Residual	0.31	2.58	88.0	144	9.1	23.99
AB24108	Top Plenum Transient	0.32	2.58	87.6	140	10.8	22.81
AB24109	Bottom Plenum Transient	0.32	2.66	88.0	136	13.2	22.53

Table 5-6. Chemical Composition of Dustcake Samples.

Sample ID	Sample Location	CaCO <sub>3</sub> , Wt %	CaS, Wt %	CaO, Wt %	Non-Carbonate Carbon, Wt %	Inerts (Ash/Sand), Wt %	Loss on Ignition, Wt %
AB24107	Top Plenum Residual	2.82	0.68	13.79	23.66	59.05	23.43
AB24106	Bottom Plenum Residual	3.36	0.68	13.55	23.90	58.51	23.99
AB24108	Top Plenum Transient	3.66	1.01	13.02	22.66	59.65	22.81
AB24109	Bottom Plenum Transient	2.45	1.12	13.85	22.11	60.47	22.53

### 5.3 PCD Pressure Drop Performance

Transient PCD Drag. The pressure 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 dustcake, 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 that is normalized to 1 ft/min face velocity, 1 lb/ft<sup>2</sup> areal particulate loading, and gas viscosity of air at 70°F. The result is a fundamental parameter that describes the flow resistance of the collected dustcake.

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 transient drag calculations are shown in Table 5-7. The calculated transient drag at PCD conditions is listed under the column heading “PCD.” The corresponding value of transient drag normalized to the viscosity of 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 are also comparable to other test campaigns that operated at different temperatures. The comparison of these values are presented in a later section. The drag values for TC23 were reasonably low, and did not cause operational problems with the PCD.

Table 5-7. Transient Drag Determined from PCD Pressure Drop and from Lab Measurements.

Run No.	$\Delta P/\Delta t$ , inwc/min	$\Delta(AL)/\Delta t$ , lb/ft <sup>2</sup> /min	FV, ft/min	MMD, $\mu\text{m}$	NCC, %	Drag, inwc/(lb/ft <sup>2</sup> )/(ft/min)		
						PCD	PCD@RT	Lab
PRB Coal								
1	3.15	0.018	4.93	9.2	36.0	174	115	—
2	2.04	0.016	4.79	14.0	28.2	124	72	—
3	3.91	0.017	5.58	12.8	45.0	233	135	—
4	2.84	0.015	4.43	12.4	43.6	186	108	—
North Dakota Lignite Coal								
5	3.81	0.032	6.04	12.0	28.7	118	69	65
6	4.42	0.042	6.36	12.6	24.2	104	61	62
7	0.88	0.020	4.88	10.5	14.2	44	26	71
8	2.38	0.011	5.22	18.9	22.0	211	123	44
9	3.80	0.040	5.33	13.5	34.9	95	56	59
10	3.77	0.043	5.09	14.7	34.2	88	52	55
11	3.46	0.041	4.95	11.0	31.1	84	49	70
12	4.42	0.037	4.82	10.3	21.1	119	68	73
13	4.86	0.041	4.62	13.9	28.4	119	68	57
14	5.28	0.031	5.16	11.5	31.8	170	97	67
15	1.66	0.021	5.09	12.7	29.3	80	44	62
Avg Lig	3.52	0.033	5.23	12.9	30.2	112	65	62
Lab drag data calculated from linear regression to MMD and NCC of lab drag samples.								

Nomenclature:

$\Delta P/\Delta t$  = rate of pressure drop rise during particulate sampling run, inwc/min.

$\Delta(AL)/\Delta t$  = rate of increase in areal loading during sampling run, lb/min/ft<sup>2</sup>.

FV = average PCD face velocity during particulate sampling run, ft/min.

MMD = mass-median diameter of in-situ particulate sample,  $\mu\text{m}$ .

NCC = non-carbonate carbon. LOI = Loss On Ignition.

RT = room temperature, 77°F (25°C).

Normalized PCD transient drag is plotted as a function of carbon content in Figure 5-3. As seen in previous test campaigns, transient drag increases with increasing carbon content in the gasification ash. The drag data for the TC23 particulate is higher than typically seen with lignite fuel. The data on Figure 5-3 fall into the middle of the PRB results rather than down with TC21 with the previous North Dakota lignite coal. The higher drag values are partially driven by higher carbon contents than are typical of the lignite ashes. If the regression to the Mississippi lignite test is extrapolated to higher carbon contents, it passes roughly through the middle of the TC23 data. The match to TC21 lignite data is not so good, but this graph suggests that the higher drag values for TC23 are not completely out of line for higher carbon lignite ashes. This correlation shows a lot of scatter in the data, because it does not take into account the effect of particle size, which will be considered in a later section.

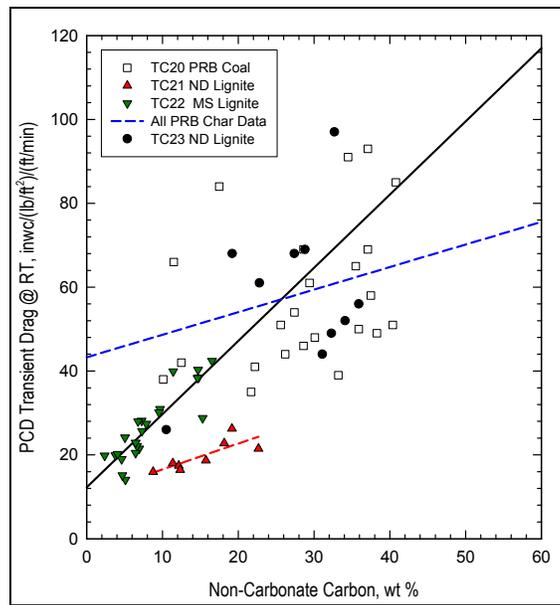


Figure 5-3. PCD Transient Drag versus Carbon Content of In-Situ Samples.

**Baseline Pressure Drop Analysis.** Figure 5-4 plots the PCD baseline pressure drop from TC23 as well as the pressure drop values for recent test campaigns. These pressure drop values were normalized for temperature and gas velocity. The plot indicates that the baseline pressure drop generally increased throughout TC23 and was higher in TC23 than in recent test campaigns. Reasons for the higher pressure drop include the higher particulate mass carryover from the gasifier, higher particulate drag, and the use of the aged, high pressure drop iron aluminide filter elements.

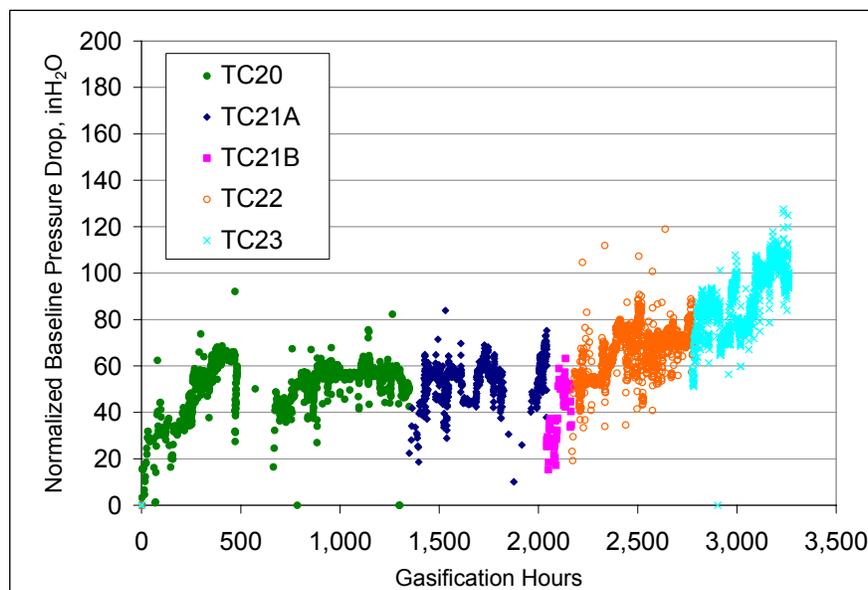


Figure 5-4. Normalized PCD Baseline Pressure Drop from TC20 through TC23.

**Lab Drag Measurements.** To investigate the characteristics of the TC23 particulate, drag measurements were made in the laboratory flow resistance test device on the composite hopper samples described previously. This 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 5-5 with normalized drag plotted against the mass median particle diameter (MMD) of the collected dustcake. The actual lab measured data points are indicated by the triangles and squares, while the solid lines are linear regressions to the data to illustrate the linearity of the results. The solid circle symbols in Figure 5-5 are the values of PCD transient drag calculated for each of the in-situ samples from Table 5-7. The PCD data points fall around the laboratory drag measurements showing better agreement than usual.

Historically, the most accurate model of dustcake drag relates the drag of particulate samples to both the MMD of the dustcake and to the non-carbonate carbon (NCC) or loss-on-ignition (LOI) of the sample. Since the lab measurements for the two samples (high and low kaolin) were so similar, a single regression to all of the lab data was used. The result of the regression is shown in the equation below:

$$\text{Drag} = 10^{(2.680 - (0.816 * \text{Log}(\text{MMD}) + 0.00394 * \text{NCC})}, \text{ with an } r^2 = 0.97.$$

The results of regression predictions for each individual value of PCD transient drag are shown in the rightmost column of Table 5-7. These calculations use the MMD and NCC of each in-situ sample to predict the transient drag of the PCD during that test. While the agreement between the laboratory predictions and actual PCD data vary for individual values, the average agreement for the TC23 data is excellent.

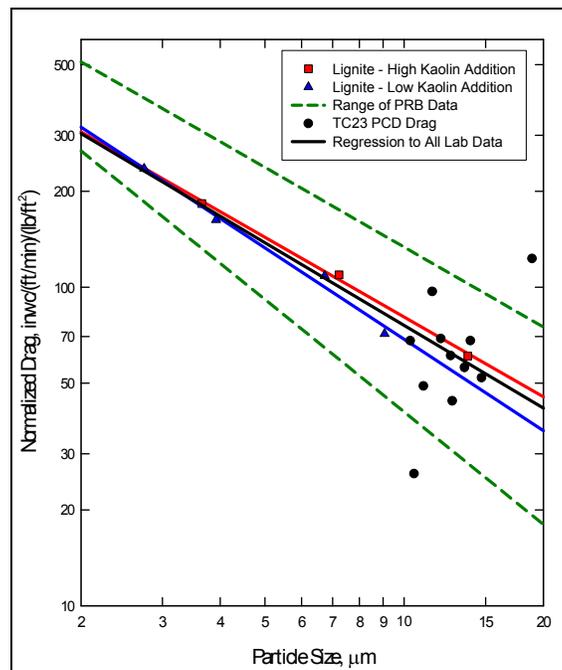


Figure 5-5. Lab-Measured Drag as a Function of Particle Size.

Comparison of Lab Measurements with Transient Drag. Average laboratory and PCD drag values for all gasification test runs are summarized in Table 5-8. The comparison shows excellent overall historical agreement (average difference of about 10 percent), even though the difference is much higher for certain test campaigns. For TC23, the difference was -4.7 percent, which is excellent agreement. The results for all gasification test campaigns are plotted in Figure 5-6 and continue to show that the data points are scattered around the perfect agreement line. The average values of TC23 drag measured in the laboratory and for the actual PCD are the highest ever obtained for lignite coal. These relatively high values are probably caused by the higher than usual carbon contents of the ash samples. However, even these drag values are not considered high relative to PRB coal and PCD operational problems would not be anticipated.

Table 5-8. Average Drag Values Determined from PCD and Lab Measurements.

Run	Coal	Average Transient Drag Determined from PCD Performance, inwc/(lb/ft <sup>2</sup> )/(ft/min)	Average Drag Determined from RAPTOR Lab Measurements, inwc/(lb/ft <sup>2</sup> )/(ft/min)	Difference from Mean Value*, %
GCT2	PRB	29	21	-33.5
GCT3	PRB	80	93	14.5
GCT4	PRB	66	57	-15.2
TC06	PRB	89	81	-9.6
TC07	PRB	48	50	4.3
TC08	PRB	47	50	7.3
TC09	Hiawatha	29	23	-21.8
TC10	PRB	45	58	25.2
TC11	Falkirk Lignite	16	36	76.2
TC12	PRB	58	61	4.7
TC13	Freedom Lignite	34	39	13.6
TC14	PRB	47	42	-13.0
TC15	PRB	55	76	33.3
TC16	PRB + Limestone	49	52	4.8
TC16	Lignite + Dolomite	26	42	47.1
TC17	IL Basin	25	19	-27.8
TC18	PRB	59	82	32.6
TC19**	PRB	64	72	11.8
TC20**	PRB	78	108	32.3
TC21**	ND Lignite	19	32	51.0
TC22**	MS Lignite	27	40	38.8
TC23**	ND Lignite	65	62	-4.7
<i>Average</i>		48	54	12.3
* D = (R1-R2)/(R1+R2)/2*100				
** Technique modified to use carbon content of lab drag sample				

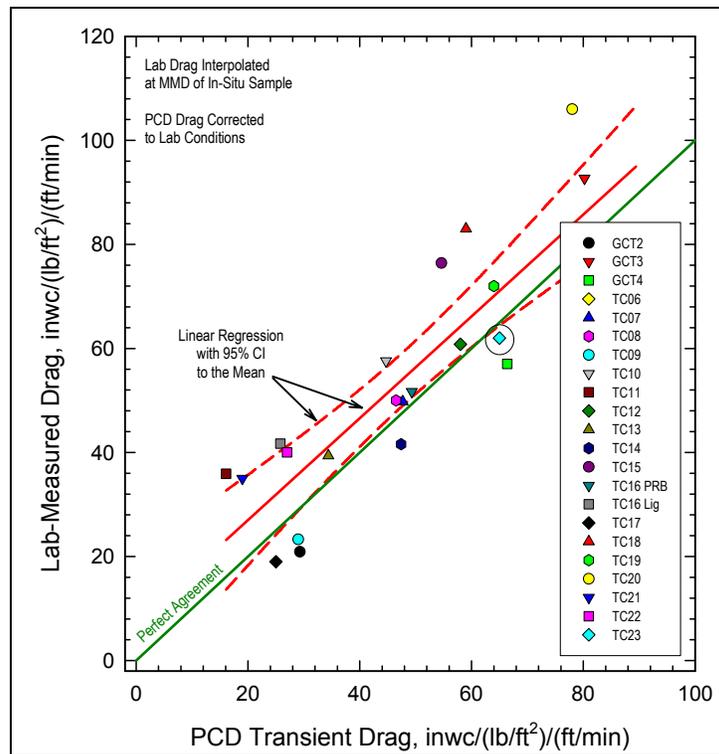


Figure 5-6. Comparison of PCD Transient Drag with Laboratory Measurements.

#### 5.4 Filter Element Evaluation

Following TC23, a complete set of measurements was made on the elements that were removed from the PCD to determine the effect of exposure hours on pressure drop. All of the Dynalloy elements were removed, as these will be replaced with a finer fiber version in the next test campaign. A selected subset of iron aluminide (FEAL) elements were removed for testing.

The pressure-drop, face-velocity relationship was measured on each of the filter elements both with the residual dustcake and after pressure washing to remove all particulate. The data are plotted as a function of gasification exposure hours for the two types of elements in Figure 5-7 and Figure 5-8.

The FEAL elements continued to show the trend of increasing pressure drop with time seen previously. This is true for both clean and dirty elements. Inspection of the clean elements also indicated that the degree of corrosion has increased and is probably responsible for the increase in pressure drop.

The Dynalloy filter elements showed an increase in pressure drop with time when dirty, but were completely restored by pressure washing. This apparent trend may result from the higher drag with the TC23 gasification ash.

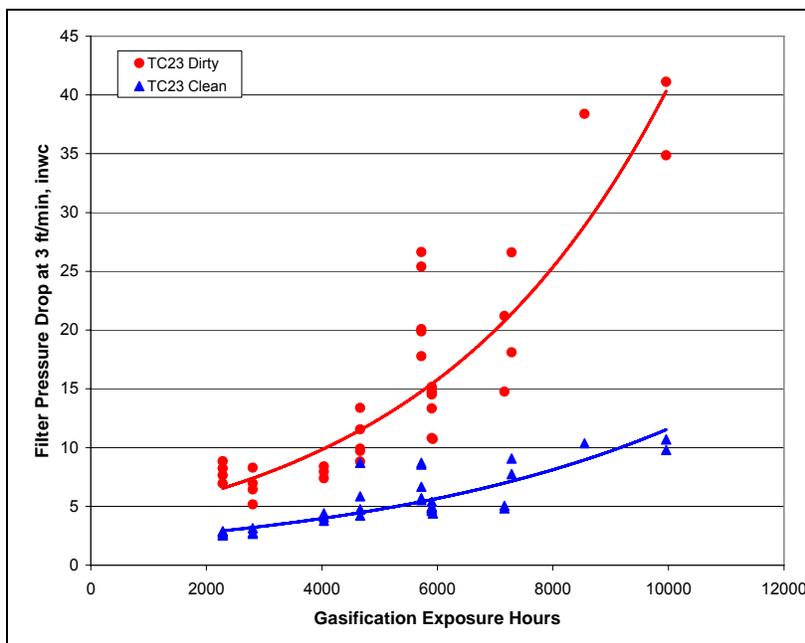


Figure 5-7. Pressure Drop versus Exposure Hours for Iron Aluminide Filter Elements.

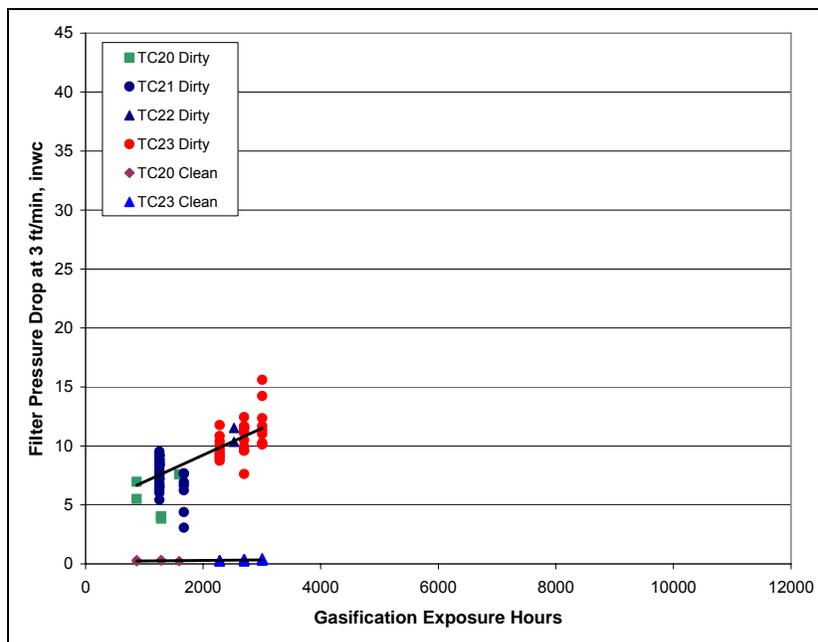


Figure 5-8. Pressure Drop versus Exposure Hours for Coarse Fiber Dynalloy HR-160 Filter Elements.

## 5.5 On-Line Failsafe Testing

During TC23, the valve-type failsafe tester that was first described in the TC19 report was used to simulate the effect of a minor filter element failure on a Pall prototype reversed-media, metal-fiber fuse. This type of fuse was previously tested with a high leak rate in TC20. To simulate a small leak, a 0.250 inch orifice was installed above the valve to limit the particulate flow to the failsafe. A lower inlet particulate loading might be expected to plug the failsafe more slowly than a higher loading. That is, a failsafe may prove better protection from a large breach of filter element media than for a pinhole. This effect has been observed in the cold-flow model with sintered fiber failsafes.

The inlet valve to the failsafe was opened just prior to Outlet Run 13. Although the indicated mass loading during that test was slightly elevated (0.13 ppmw), microscopic examination did not show a significant increase in particles on the sample filter relative to the filter from Run 12. Ignition of a portion of the Run 12 sample filter indicated that a significant amount of the mass on the filter was corrosion product, not gasification ash that would have penetrated the failsafe. If the failsafe did contribute to the outlet particulate concentration during Outlet Run 13, it was not the full amount of 0.13 ppmw, but would have been a smaller increment added to the background level. Therefore, the failsafe was considered effective in plugging with a small simulated leak.

## 6.0 ADVANCED SYNGAS CLEANUP

TC23 marked the initial testing of several new syngas cleanup technologies. These included testing of water-gas shift reactions with a catalytic filter element and a fixed bed reactor, direct oxidation of H<sub>2</sub>S in a fixed bed reactor, and CO<sub>2</sub> capture in a batch reactor. The initial phase of testing was conducted in off-line mode with bottled gases. Observations from the off-line and on-line tests were qualitative in scope.

### 6.1 Water-Gas Shift Reaction Testing

For water-gas shift reaction testing, a superheated steam line was installed along with appropriate instrumentation and controls. The catalytic element and the fixed bed were arranged in series, with the outlet stream routed to the CO<sub>2</sub> capture reactor. The approximate composition of the Sud-Chemie T-2822 shift catalyst used for the water-gas shift testing is shown in Table 6-1.

Table 6-1. Composition of Sud-Chemie T-2822 Shift Catalyst.

Component	Weight Percent
Aluminum Oxide	50—70
Magnesium Oxide	15—35
Molybdenum (III) Oxide	5—15
Cobalt Oxide	1—10
Calcium Oxide	3—7

**Catalytic Filter Element.** For water-gas shift testing, the T-2822 water-gas shift catalyst was pulverized and sieved into a particle size range of 180 to 500 microns for packaging in an iron aluminide filter element. This testing was conducted during the initial portion of TC23 when the gasifier was operating on PRB coal. Testing with the catalytic filter element showed a need for increased catalyst material due to difficulties controlling the low gas flow rate. Pressure typically ranged from 150 to 200 psig, and temperatures varied from 500 to 600°F, with a short period of testing done at temperatures up to 800°F. The syngas flow ranged from 6 to 30 lb/hr, and the steam flow was varied from 0 to 6 lb/hr.

**Fixed Bed Reactor.** Fixed bed reactor testing of water-gas shift was also conducted during gasifier operation with PRB coal and employed the T-2822 catalyst in pellet form. Operating pressures ranged from 110 to 190 psig with temperatures of 550 to 800°F. Syngas flow through the fixed bed reactor ranged from 15 to 30 lb/hr while steam flow rates varied between 0 and 18 lb/hr. Approximately 22 hours of testing with the fixed bed water-gas shift reactor was completed, and this preliminary testing gave results of 40 to 88 percent shift conversion, with higher rates achieved at higher temperatures.

### 6.2 Direct Oxidation of H<sub>2</sub>S

Direct oxidation of H<sub>2</sub>S was performed off-line with bottled gases (nitrogen, hydrogen sulfide, and sulfur dioxide) in preparation for on-line testing with syngas. The primary objective of this

test was to investigate bulk sulfur removal efficiency by converting H<sub>2</sub>S at low concentrations to elemental sulfur using sulfur dioxide (SO<sub>2</sub>).

The oxidation catalyst used was BASF DD-431 activated alumina in 6 mm diameter spherical form. Off-line testing was conducted at 200 psig pressure and gas flow rates of 11.5 to 12 lb/hr. The first test was performed at a reactor bed temperature of about 475°F and achieved conversions up to about 88 percent. During the second test, the reactor bed temperature was maintained at 417°F, and the H<sub>2</sub>S conversion was slightly higher, at about 93 percent.

TC23 testing of H<sub>2</sub>S oxidation employed the same DD-431 catalyst used in off-line testing and took place using syngas during the high sodium lignite portion of the test campaign. One objective of the test was to ensure that high H<sub>2</sub>S conversions achieved during off-line testing could be achieved with actual syngas containing low H<sub>2</sub>S concentrations. Another test objective was to observe how a stoichiometric amount of SO<sub>2</sub> selectively reacts with H<sub>2</sub>S in the presence of CO and H<sub>2</sub>. Levels of COS were monitored to ensure that additional amounts of COS were not formed.

The on-line testing took place for about 40 hours. Operating conditions included pressures from 110 to 200 psig, temperatures of 260 to 430°F, and a syngas flow rate of 30 lb/hr. Bottle gas containing 1 percent SO<sub>2</sub> and 99 percent N<sub>2</sub> was fed at rates from 0 to 3 lb/hr. During the testing, the reactor inlet concentration of H<sub>2</sub>S generally ranged from 0.07 to 0.10 percent on a dry basis.

The first part of the direct oxidation on-line test was performed at temperatures up to 550°F. It was observed during this test that H<sub>2</sub>S concentration at the outlet of the reactor increased with the increase of SO<sub>2</sub> flow, indicating that SO<sub>2</sub> was reacting with H<sub>2</sub> present in the syngas, forming additional H<sub>2</sub>S. No oxidation reaction of H<sub>2</sub>S with SO<sub>2</sub> to form elemental sulfur was observed.

The second part of the direct oxidation on-line test was demonstrated at a lower temperature of about 280°F. It was noticed in this test that the H<sub>2</sub>S concentration at the outlet of the reactor was unchanged, and ammonia present in the syngas was significantly reduced from the reactor inlet to the outlet. Direct oxidation of H<sub>2</sub>S was observed only when excess SO<sub>2</sub> flow was used.

### 6.3 CO<sub>2</sub> Capture

For CO<sub>2</sub> capture testing, a syngas line was installed with instrumentation and controls to measure and regulate syngas flow to the CO<sub>2</sub> reactor. Also, syngas cooler was installed upstream of the CO<sub>2</sub> reactor.

Carbon dioxide capture from syngas was performed for a few hours with syngas from the fixed bed, water gas shift reactor. The initial commissioning test with syngas was short due to problems associated with the condensate removal system in the inlet syngas line. The batch reactor operated at approximately 110°F. The limited data showed a decrease in CO<sub>2</sub> concentration.

### 6.4 Inspections

The pulverized Sud-Chemie water gas shift catalyst was removed from the catalytic filter element, and the pelleted shift catalyst was drained from the fixed bed reactor. Both the

pulverized catalyst and the pelleted catalyst had changed color from pale green to black. Samples of the used catalysts were sent to Sud-Chemie for analysis.

The BASF DD431 catalyst was also removed from the direct H<sub>2</sub>S oxidation fixed bed reactor after about 40 hours of testing. The catalyst shape used was 6 mm diameter spheres and the color had changed from white to grayish black. The used catalyst was sent to BASF for analysis. According to BASF, the sulfur content had increased to about 12 percent, higher than the 3 to 4 percent increase typically seen with oxidation catalysts.

## 7.0 SUPPORT EQUIPMENT

The recycle gas compressor supplied syngas for gasifier aeration for 372 hours during TC23. The system operated well with no major problems. There was one compressor related trip caused by a faulty vibration probe. The probe was removed from service and replaced during the outage. The compressor was restarted within 4 hours of the trip and operated well through the remainder of the test campaign. Steady state operating conditions at the recycle gas compressor outlet as well as the recycle syngas flow rate to the gasifier are shown in Figure 7-1. When recycled syngas was used to replace nitrogen aeration, the raw syngas lower heating value increased about 10 percent during both PRB and lignite operations, comparable to previous testing results during PRB operations.

The control trip logic for the recycle gas compressor was modified prior to TC23 to increase the availability of the recycle gas system. Previously, all gasifier and coal feeder trips would also trip the recycle gas compressor. Generally, coal feeder trips have a short duration, less than 5 minutes, and therefore do not impact operation of the recycle gas compressor. After completing a thorough design hazard review, the logic was changed to eliminate compressor trips due to coal feeder trips and certain gasifier trips.

As a result of these modifications, the compressor availability was more than doubled, increasing from about 40 percent in recent test campaigns to over 80 percent in TC23. The higher availability increased test data available for analysis by shortening the time required to re-establish steady state conditions following coal feeder and certain gasifier trips. In addition nitrogen costs were reduced by over \$20,000. Based on operations in TC23, a trip condition related to the main air compressor discharge pressure was identified as another trip condition that will be eliminated to further improve availability.

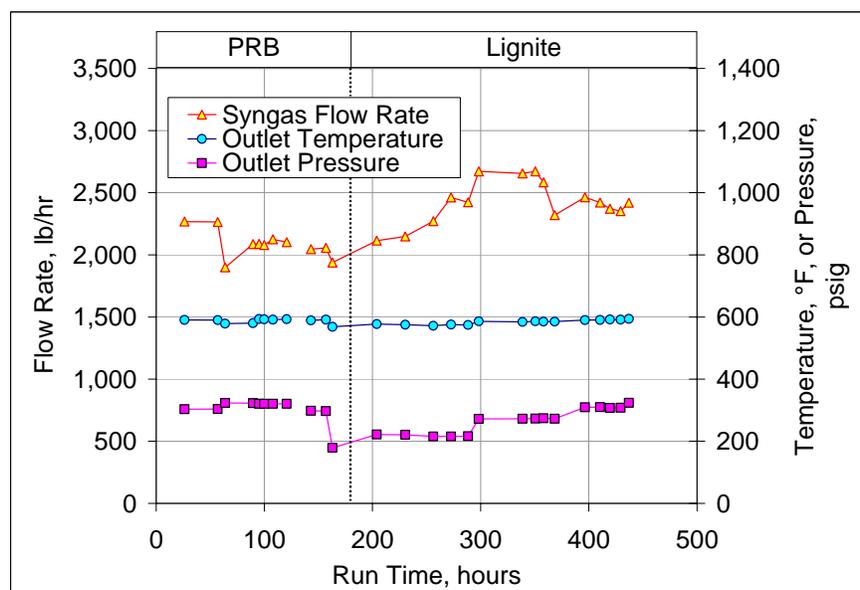


Figure 7-1. Recycle Gas Compressor Operating Conditions.

## 8.0 CONCLUSIONS

The major focus of test campaign TC23 was characterization of the gasifier operation and performance with North Dakota Freedom Mine high sodium lignite. To prevent the agglomerations experienced previously, initial operation of TC23 was performed using PRB coal so that the start-up sand was replaced with gasification ash prior to lignite feed, and a kaolin additive was fed with the lignite. The gasification process was operated for a total of 481 hours in TC23, with over 300 hours of operation with high sodium lignite. In addition to characterizing operation and performance of the modified gasifier and related equipment with the high sodium lignite, test objectives included testing of coal feeders, hot gas filter element and failsafes, instrumentation enhancements, and advanced syngas cleanup technologies.

Lessons Learned. The following list shows key lessons learned from TC23 operation.

- The lignite was processed in two separate coal mills, which resulted in a larger variation in moisture content than seen with the PRB, with was processed in only one mill. During lignite operation, one mill was operating at a lower gas mass flow through the system, resulting in a lower drying capacity and thus a higher coal moisture content than with the second mill.
- Initially, material plugging in the discharge line caused several coal feeder trips a day. Increasing the coal feed transport velocity was effective in reducing the number of trips significantly.
- The use of kaolin proved successful in eliminating agglomeration within the gasifier; however, fine, tightly-adhering ash deposited in the primary gas cooler, and the subsequent loss of heat transfer became an operational issue as the test campaign progressed.
- Although the HR-160 thermowell material has shown to be somewhat susceptible to corrosion by sulfur, overall this material has shown acceptable durability and is not prone to breakage like ceramic material.
- Testing of Dynalloy HR-160 and iron aluminide PCD filter elements showed continued high collection efficiency, although some corrosion has continued to be a concern with the iron aluminide elements.
- The prototype reversed-media failsafe proved effective in preventing small particulate leaks when tested on-line with the valve-activated failsafe tester.
- Initial testing of various syngas cleanup technologies, including CO<sub>2</sub> capture and water-gas shift conversions, showed positive trends and was useful in directing future testing.
- Modifications to the recycle gas compressor control logic proved useful in preventing unnecessary trips. The improved availability of the compressor resulted in significant operational cost savings since nitrogen was not needed for gasifier aeration during times of recycle gas use.

## 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 TC23, 18 gasification test campaigns were completed, each nominally 250 to 1,500 hours in duration, for a total of about 10,600 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 TC23. The table lists the duration, 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 Date	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 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 CFAD commissioning
TC15	April 2004	200	PRB	Improved oxygen feed distribution
TC16	July 2004	835	PRB, Freedom Lignite	Fuel cell testing High pressure O <sub>2</sub> -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	388	Freedom Lignite	First lignite test following the gasifier modifications
TC22	March 2007	543	Mississippi Lignite	First lignite test following the gasifier modifications
TC23	August 2007	481	PRB, Freedom Lignite	High sodium lignite testing

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

## APPENDIX B STEADY STATE OPERATING PERIODS AND MAJOR OPERATING PARAMETERS

TC23 consisted of 28 steady state operating periods. These periods are given in Table B-1, along with the major operating parameters for each period. The steady state periods are defined based on maintaining gasifier operating conditions within defined ranges.

All of the steady state periods were in air-blown gasification mode, the first 12 periods (TC23-1 through TC23-12) with PRB operation, and the last 16 periods (TC23-13 through TC23-28) with high sodium lignite operation. Recycle syngas was used for gasifier aeration in all operating periods except for TC23-1 and TC23-10. The coal feed rates were calculated from the feeder weigh cells, and the air, steam, nitrogen, and recycle syngas flow rates were taken from flow indicators. The PCD solids rates were determined from the in-situ sampling at the PCD inlet, and the ash removal rates for CCAD were determined by a system ash balance.

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

Steady State Operating Period	Start Time (2007)	End Time (2007)	Run Time Hours	Gasifier Mixing Zone Temp., °F	Gasifier Outlet Pressure, psig	Coal Feed Rate, lb/hr	Kaolin Feed Rate, lb/hr	Air Feed Rate, lb/hr	Steam Feed Rate, lb/hr	Nitrogen Flow Rate, lb/hr	Recycle Syngas Flow Rate, lb/hr	Syngas Rate, lb/hr	PCD Inlet Temp., °F	Gasifier Solids Removal Rate, lb/hr	PCD Solids Removal Rate, lb/hr
TC23-1	8/8 18:15	8/8 16:15	26	1,670	190	3,610	0	12,220	1,100	6,880	0	24,390	780	50	230
TC23-2	8/10 1:00	8/9 23:00	57	1,680	200	3,780	0	13,090	940	4,960	1,860	23,710	810	60	210
TC23-3	8/10 7:45	8/10 4:30	64	1,690	200	3,780	0	13,180	900	4,750	1,850	23,540	810	100	220
TC23-4	8/11 9:30	8/11 8:00	89	1,680	180	4,070	0	13,340	530	6,820	1,780	25,830	810	90	230
TC23-5	8/11 15:07	8/11 13:00	95	1,700	210	3,600	0	12,670	460	6,740	1,960	24,560	810	100	200
TC23-6	8/11 19:52	8/11 17:30	100	1,690	210	3,690	0	12,600	440	4,860	1,970	22,650	800	70	230
TC23-7	8/12 4:00	8/11 23:00	108	1,690	210	3,660	0	12,850	450	4,920	1,970	23,020	800	70	240
TC23-8	8/12 16:45	8/12 15:00	121	1,690	210	3,580	0	12,500	510	4,850	1,990	22,550	800	80	210
TC23-9	8/12 21:45	8/12 19:45	126	1,700	210	3,750	0	12,840	510	4,890	1,980	23,020	810	70	230
TC23-10	8/13 15:00	8/13 12:45	143	1,690	190	2,190	0	9,810	530	7,210	0	21,260	780	80	130
TC23-11	8/14 5:00	8/14 3:00	157	1,710	190	2,210	0	9,840	540	5,120	1,930	19,150	780	60	130
TC23-12	8/14 11:00	8/14 8:30	163	1,710	190	2,270	0	10,000	550	4,930	1,930	19,080	790	80	130
TC23-13	8/16 4:00	8/16 1:45	204	1,530	130	3,300	300	9,690	1,230	5,160	1,860	20,700	740	260	430
TC23-14	8/17 6:15	8/17 5:00	230	1,560	150	2,160	110	8,810	1,260	5,060	1,990	19,950	740	30	280
TC23-15	8/18 8:15	8/18 4:45	256	1,550	150	2,080	130	8,370	1,260	4,700	2,030	18,840	730	0	270
TC23-16	8/19 0:37	8/18 22:00	273	1,550	150	2,120	100	8,560	1,240	4,800	2,130	19,340	740	0	290
TC23-17	8/19 16:22	8/19 14:15	288	1,530	160	2,680	110	9,040	1,210	4,610	2,260	20,140	750	0	360
TC23-18	8/20 2:15	8/20 0:15	298	1,510	160	2,890	100	9,020	1,220	4,650	2,260	20,260	740	0	390
TC23-19	8/21 18:37	8/21 15:45	339	1,530	190	3,640	130	10,740	1,570	5,160	2,360	23,280	810	0	490
TC23-20	8/22 6:37	8/22 2:00	351	1,530	190	3,460	130	10,500	1,580	5,060	2,390	22,780	810	0	470
TC23-21	8/22 14:07	8/22 11:30	358	1,520	190	3,290	140	10,190	1,570	5,070	2,430	22,270	810	0	450
TC23-22	8/23 0:22	8/22 21:45	368	1,540	190	3,390	130	10,600	1,580	5,180	2,370	22,970	820	0	460
TC23-23	8/24 4:30	8/24 2:30	396	1,670	190	3,800	330	11,500	1,590	4,900	2,200	23,790	870	0	540
TC23-24	8/24 18:22	8/24 14:15	410	1,680	210	3,580	390	11,280	1,310	4,560	2,320	22,570	860	310	480
TC23-25	8/25 3:30	8/25 0:45	419	1,690	210	3,540	360	11,190	1,320	4,560	2,300	22,600	860	330	430
TC23-26	8/25 13:22	8/25 11:15	429	1,680	210	3,900	370	11,790	1,330	4,530	2,250	23,450	880	380	380
TC23-27	8/25 21:00	8/25 18:45	437	1,700	210	3,890	360	11,690	1,340	4,680	2,250	23,460	880	390	360
TC23-28	8/26 8:15	8/26 6:15	448	1,690	220	3,700	340	11,560	1,270	4,780	2,300	23,100	890	390	330

APPENDIX C MATERIAL AND ENERGY BALANCES

The material and energy balances showed reasonable accuracy given the diversity of the measurements used for their calculation. A gasifier mass balance for the TC23 steady state operating periods is shown 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 generally showed agreement within a 10 percent error range.

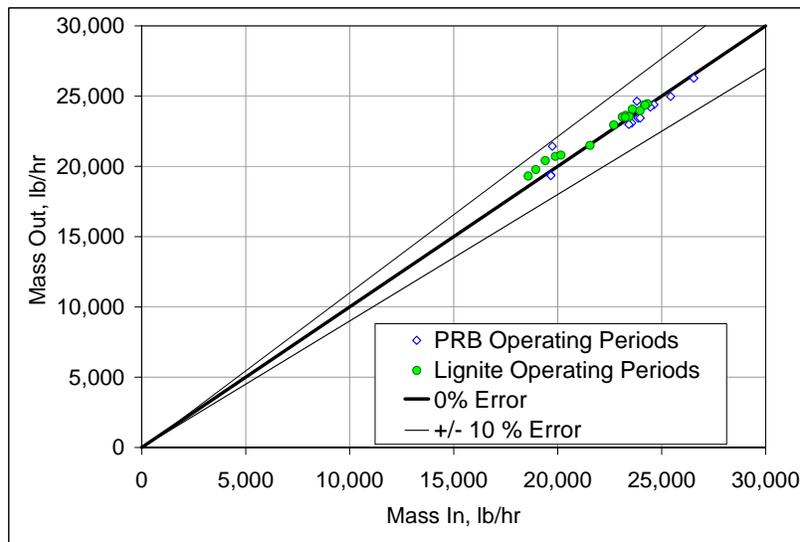


Figure C-1. Mass Balance.

The overall energy balance for the gasifier (assuming a 3.5 MMBtu/hr heat loss) is plotted in Figure C-2 for the steady state operating periods. This balance verifies the accuracy of the gasification efficiencies, and shows agreement within about a 25 percent error range.

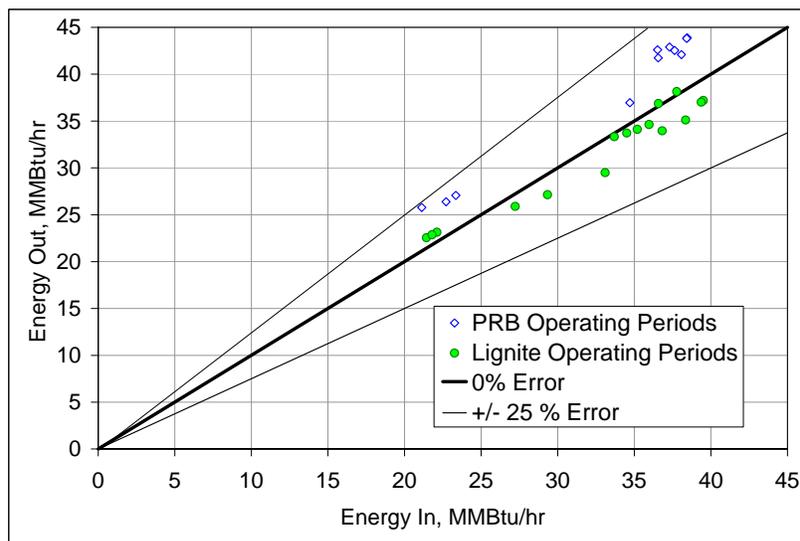


Figure C-2. Energy Balance.

The carbon balance, which documents the accuracy of the carbon conversions, is given for the steady state periods in Figure C-3. The data showed good agreement within a 12 percent error range.

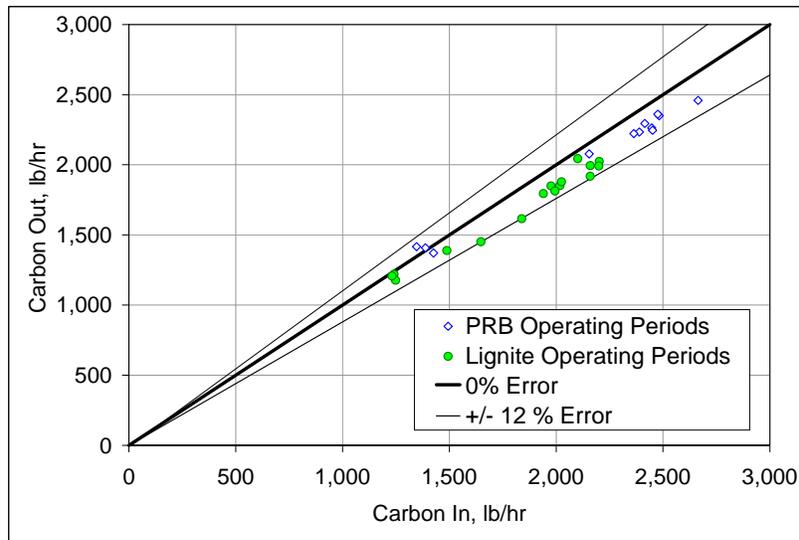


Figure C-3. Carbon Balance.

The sulfur balance supports the accuracy of the sulfur removal efficiencies and is plotted in Figure C-4 for the steady state operating periods. The balance showed reasonable agreement within a 30 percent error range with three outliers corresponding to periods of PRB operation.

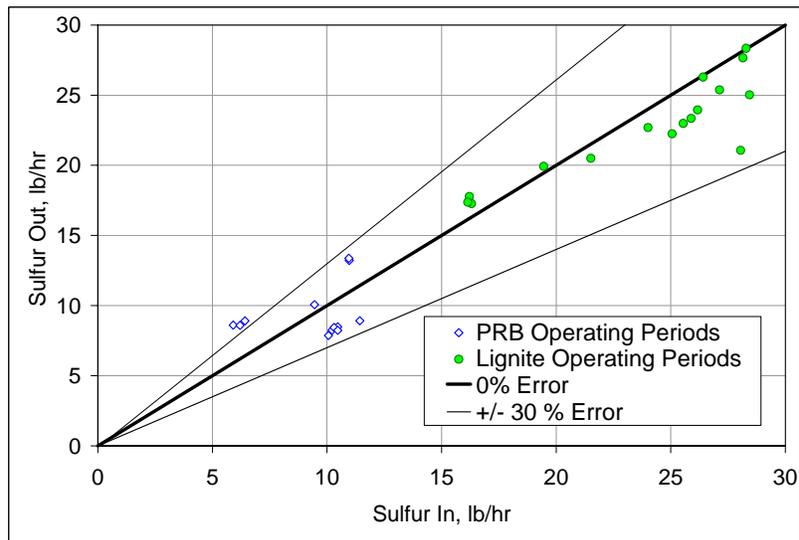


Figure C-4. Sulfur Balance.

APPENDIX D LIST OF ABBREVIATIONS AND UNITS

Abbreviations

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

Units

Btu—British thermal units	MMBtu—million British thermal units
°F—degrees Fahrenheit	mol—mole
ft—feet	µm—microns or micrometers
ft <sup>3</sup> —cubic feet	MW—megawatts
g/cm <sup>3</sup> or g/cc—grams per cubic centimeter	ppm—parts per million
hr— hours	ppmv—parts per million by volume
inH <sub>2</sub> O—inches of water	ppmw—parts per million by weight
in—inches	psi—pounds per square inch
inwc—inches of water column	psig—pounds per square inch gauge
lb—pounds	s or sec—second
min—minutes	SCF—standard cubic feet
mm—millimeters	wt—weight