

LIGNITE TESTING IN AN ADVANCED HIGH-TEMPERATURE, HIGH-PRESSURE TRANSPORT REACTOR GASIFIER

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LIGNITE TESTING IN AN ADVANCED HIGH-TEMPERATURE, HIGH-PRESSURE TRANSPORT REACTOR GASIFIER

EXECUTIVE SUMMARY

The objective of the proposed scope of work is to evaluate the performance of lignite fuels in a highly efficient advanced transport reactor integrated gasification combined-cycle (IGCC) system. Specific technical issues include determining the effects of transport reactor development unit (TRDU) operating conditions on carbon conversion and product gas yields and quality while monitoring for the increased ash agglomeration and deposition potential of the lignite fuels. Variable operating conditions include air or oxygen/coal, steam/coal, sorbent/coal ratios, and the operating temperature of the mixing zone of the gasifier. A specific objective of this test was to operate the TRDU in both air-blown and oxygen-blown mode on the three North Dakota lignite coals.

TRDU test campaigns conducted in air-blown mode during the week of February 7–12, 2000, generated 126 hours of coal feed and 120 hours of operation in coal gasification mode on the Kinneman Creek seam lignite from the BNI Mine at Center, North Dakota. A second air-blown test was conducted from February 26 to March 3, 2000, which generated an additional 71 hours of coal feed and 66 hours of gasification on a run-of-mine lignite from the Falkirk Mine near Washburn, North Dakota, and an additional 35 hours of coal feed and 33 hours of gasification on a lignite from the Freedom Mine near Beulah, North Dakota. After the modification of the TRDU loop seal and the completion of two oxygen-blown shakedown tests under the concurrent U.S. Department of Energy (DOE) program, another oxygen-blown lignite gasification test campaign was completed in the weeks of June 12, 2001 through June 21, 2002. This oxygen-blown gasification test of the same three lignites tested previously resulted in 70.5 hours of gasification testing on the Center lignite, 45.5 hours on the Falkirk lignite, and 60 hours of gasification on the Freedom lignite. These tests were completed with the system gases and fly ash passing through the hot-gas filter system during these test campaigns.

Comparable carbon conversions have been achieved at similar oxygen/coal ratios for both air-blown and oxygen-blown operation. This figure also shows the calculated corrected heating values for both the dry and wet (containing steam) product gas streams. Since hot-gas cleanup is utilized, the unconverted steam and coal moisture injected into the gasifier will remain in the fuel gas entering the gas turbine. When the air-blown and oxygen-blown fuel gas heating values are compared for the wet product gas streams, it is apparent that only a slight improvement in product gas heating entering the gas turbine is achieved with oxygen-blown operation. In order to keep the gas turbine firing temperature down to prevent thermal NO_x formation, typically large amounts of nitrogen or steam are injected into the gas turbine combustor such that the fuel gas heating is typically not much greater than 115 Btu/scf as fired. In essence, the transport reactor has either injected the nitrogen (in the form of air) or steam into the gasifier instead of into the gas turbine combustor to keep the fuel gas heating value at the desired level. However, if chemicals or fuel production are being considered where conventional cold-gas cleanup technology would be utilized to remove the water vapor from the fuel gas stream, significantly higher fuel gas heating values can be achieved with oxygen-blown operation because of the lack of the nitrogen diluent.

The pilot-scale TRDU located at the EERC was successfully operated under both air-blown and oxygen-blown operating conditions on three different North Dakota lignite fuels. Significantly higher product gas heating values were achieved under oxygen-blown conditions when compared on a dry basis. However, when compared on a wet basis, the air-blown and oxygen-blown operation both provided a fuel gas of comparable heating value considering the significantly higher steam flows which must be injected to keep the process temperatures below ash-melting temperatures. For strictly power production, air-blown operation makes more economic sense, since the high capital and operating costs associated with an air separation unit (ASU) are not needed. If the plant also wants to consider chemical and fuel production, oxygen-blown operation is required in order to reduce the size of the subsequent unit operations. No problems with sodium-based bed material agglomeration and deposition were detected with these fuels, even though some lignites were considered to be high-sodium fuels. Hot-gas filter operation and performance was excellent with no operating problems encountered with these fuels.

Before beginning the construction of a commercial transport reactor, a longer-duration proof-of-concept test on the selected lignite feedstock should be conducted on the larger-scale Power Systems Development Facility (PSDF) located at the Southern Company Services (SCS) facility in Wilsonville, Alabama. The economics of a transport reactor need to be determined especially in light of a potential requirement to install a selective catalytic reduction (SCR) unit in the heat recovery steam generator of the combined cycle for NO_x BACT (best available control technology) control.

LIGNITE TESTING IN AN ADVANCED HIGH-TEMPERATURE, HIGH-PRESSURE TRANSPORT REACTOR GASIFIER

1.0 OBJECTIVES

The objective of the proposed scope of work is to evaluate the performance of lignite fuels in a highly efficient advanced transport reactor integrated gasification combined-cycle (IGCC) system. Specific technical issues include determining the effects of TRDU operating conditions on carbon conversion and product gas yields and quality while monitoring for the increased ash agglomeration and deposition potential of the lignite fuels. Variable operating conditions include air or oxygen/coal, steam/coal, sorbent/coal ratios and the operating temperature of the mixing zone of the gasifier.

A specific objective of this test was to operate the transport reactor development unit (TRDU) in both air-blown and oxygen-blown mode on the three North Dakota lignite coals as selected by the participants in the “Lignite Testing in an Advanced Transport Reactor Gasifier” project. This report will define the operating conditions that provide acceptable performance and identify various operating problems for these fuel and sorbent combinations. The four major tasks which were to be completed are described below.

2.0 TASKS

2.1 Task 1 – Evaluation of Air-Blown TRDU Performance Using ND Lignite

Task 1 assumes the completion of 10 days of pilot-scale TRDU system operation in air-blown gasification generating at least 200 hours of testing on three selected lignite fuels. The fuel gas will pass through the hot-gas filter system operating at 900° to 1000°F and with a filter face velocity of 4 feet per minute. Each test will consist of nominally 8 to 12 hours of natural gas firing to preheat the reactor and filter system followed by the desired coal-fired steady-state test periods of specified length, typically 12 hours. Fuel selections will be based on availability and ash deposition properties such as ash composition and ash fusion temperature. Final selections will be made in concurrence with the North Dakota Industrial Commission (NDIC) technical project monitor. Any ash deposits collected during the first test period will be characterized to determine chemical composition and relative strength. Specific analyses to be completed include x-ray fluorescence (XRF), scanning electron microscopy (SEM) point count, and SEM morphology. Fuel gas composition (carbon dioxide, carbon monoxide, hydrogen, hydrogen sulfide, and methane along with other trace species) will be measured by on-line gas chromatography and reported with the fuel gas quantity to determine a conversion efficiency. The gas-phase constituents (carbon monoxide, carbon dioxide, hydrogen, hydrogen sulfide, and oxygen) also will be monitored continuously using on-line instrumentation at the exit of the TRDU quench system. Gas-phase constituent data will be reported on a concentration basis and a heating value basis. Particulate sampling will be completed at the inlet and outlet of the hot-gas filter system. Sampling at the inlet of the hot-gas filter system will document mass loading and particle-size distribution. Sampling at the outlet of the hot-gas filter system will document the collection efficiency of the ceramic filters and show whether acceptable

turbine inlet levels are achieved. Particulate emissions will be reported on a mass per unit volume and parts per million by weight basis.

Composite samples of coal, bed material, and hot-gas filter ash will be collected for routine analyses. One composite coal sample will be analyzed for each period of operation. Analyses will include ultimate, proximate, Btu, dry sieve, ash fusion (reducing), and XRF analyses. Samples of LASH (limestone ash) bed material will be taken every 4 hours and analyzed for loss on ignition (LOI) and particle size along with selected XRF analyses. Hot-gas filter samples will also be collected every 4 hours and analyzed for LOI and particle size along with selected XRF analysis. Samples of ash from other locations in the system, such as the dipleg, will also be collected. Analysis of these samples will depend on system performance observations and initial data analysis.

A detailed test plan documenting test objectives, planned operating conditions, data to be collected, sampling requirements, and sample analyses to be completed will be prepared in advance for each period of TRDU operation. This experiment operating specification (EOS) will be reviewed with the NDIC technical project monitor prior to each period of operation. Special emphasis will be placed on the collection of data to determine the performance of the TRDU mixing zone at various temperatures and velocities with regard to product gas quality and ash deposition properties under reducing conditions. Deliverables include a pretest kickoff meeting to familiarize all involved parties with the TRDU and its capabilities. The initial test plan will be developed at this meeting. Deliverables also include a detailed report summarizing the test data within 3 months of the test completion date, followed by a review meeting at the EERC to present these results.

2.2 Task 2 – Oxygen-Blown TRDU Operation Using a ND Lignite

Under the current DOE program, the TRDU loop seal will be modified from a J-leg to an L-valve. The current DOE program will pay for the loop seal modifications and two oxygen-blown gasification tests. It is expected to take 9 months to complete the loop seal modifications and the two DOE-funded oxygen-blown gasification tests. This will result in a minimum 9-month delay between the completion of the first air-blown gasification test and the second oxygen-blown gasification test. The lignite test should be conducted after the loop seal modifications have been completed and both 200-hour gasification tests have been completed in order to reduce the project risk to the project sponsors from system operation under the new configuration.

For budgeting purposes, it was assumed the TRDU would be heated on natural gas for 12 hours until transitioned to air-blown gasification for approximately 24 hours. This will allow a direct comparison between the air-blown data generated with the current J-leg loop seal and the new loop seal. After each subsequent 24-hour period, the oxygen concentration would be increased until either an upper temperature limit is reached in the mixing zone or full 100% oxygen-blown gasification conditions are achieved, with the test being continued until the desired 200-hour test period is completed. Again, up to three different lignite fuels could be investigated. This oxygen-blown gasification test would again be completed with the hot-gas filter system operating at 1000°F and a filter face velocity of 4 feet per minute. An upper limit on operating temperature in the mixing zone would be selected based on any ash deposition observations made during the previous air-

blown gasification test and would be made in concurrence with the NDIC technical project monitor and project sponsors.

Conditions during the Task 2 period of operation will be modified based on the Task 1 observations and may include changes in sorbents or even the use of a different lignite. Ash deposits collected during the second test period will be characterized to determine chemical composition and relative strength. Specific analyses to be completed include XRF, SEM point count, and SEM morphology. Fuel gas composition (carbon dioxide, carbon monoxide, hydrogen, hydrogen sulfide, and methane along with other minor species) will be measured by on-line gas chromatography and reported with the fuel gas quantity to determine a conversion efficiency. The gas-phase constituents (carbon monoxide, carbon dioxide, hydrogen, hydrogen sulfide, and oxygen) also will be monitored continuously using on-line instrumentation at the exit of the TRDU quench system. Gas-phase constituent data will be reported on a concentration basis and a heating value basis. Particulate sampling will be completed at the inlet and outlet of the hot-gas filter system. Sampling at the inlet of the hot-gas filter system will document mass loading and particle-size distribution. Sampling at the outlet of the hot-gas filter system will document the collection efficiency of the ceramic filters and show whether acceptable turbine inlet levels are achieved. Particulate emissions will be reported on a mass per unit volume and parts per million by weight basis.

Composite samples of coal, bed material, and hot-gas filter ash will be collected for routine analyses. One composite coal sample will be analyzed for each period of operation. Analyses will include ultimate, proximate, Btu, dry sieve, ash fusion (reducing), and XRF analyses. Samples of LASH bed material will be taken every 4 hours and analyzed for LOI and particle size along with selected XRF. Hot-gas filter samples will also be collected every 4 hours and analyzed for LOI and particle size along with selected XRF analysis. Samples of ash from other locations in the system such as the dipleg will also be collected. Analysis of these samples will depend on system performance observations and initial data analysis.

A detailed test plan documenting test objectives, planned operating conditions, data to be collected, sampling requirements, and sample analyses to be completed will be prepared in advance for each period of TRDU operation. This EOS will be reviewed with the NDIC technical project monitor prior to each week of operation. Special emphasis will be placed on the collection of data to determine the performance of the TRDU mixing zone at various temperatures and velocities with regard to product gas quality and ash deposition properties under reducing conditions. Deliverables would include a Task 2 pretest meeting to familiarize all involved parties with the recent results from the TRDU loop seal changes and operation in an oxygen-blown mode. This will enable an initial Task 2 test plan to be developed at this meeting. Deliverables would also include a detailed report summarizing the Task 2 test data within 3 months of the test completion date, followed by a review meeting at the EERC to present these results.

2.3 Task 3 – Gas Turbine Combustion Modeling

As part of this project, GE will perform, at its expense, computer modeling to determine the suitability of a transport reactor fuel gas to fire a GE gas turbine in a combined-cycle system. This modeling will use the fuel gas flow rate, composition, temperature, and pressure from the TRDU

tests after adjustment to a commercial-scale IGCC plant as inputs for the model. Output from the model would include pollutant emission rates, peak firing temperatures, gas turbine output, and load-following capability.

2.4 Task 4 – Economic Projections for Transport Reactor Gasifiers

Another part of the project cost share consists of Great Rivers Energy (GRE) performing, at its expense, an economic assessment for a transport reactor IGCC system operating on lignite as compared to a natural gas combined-cycle system. This analysis will determine the natural gas fuel price at which this IGCC technology is competitive. Deliverables for these two tasks would include a summary of the findings at the review meetings and a written summary included in the final project report.

3.0 PROJECT DESCRIPTION

The TRDU has an exit gas temperature of up to 980°C (1800°F), a gas flow rate of 325 scfm, and an operating pressure of 120–150 psig. The TRDU system can be divided into three sections: the coal feed section, the TRDU, and the product recovery section. The TRDU proper, as shown in Figure 1, consists of a riser reactor with an expanded mixing zone at the bottom, a disengager, primary cyclone, standpipe, and dipleg. The standpipe collects solids from the disengager and is connected to the mixing section of the riser by an L-valve transfer line which utilizes steam to move the solids back to mixing zone. Additional solids are collected by the primary cyclone into the dipleg that returns these solids into the standpipe through a seal pot. All of the components in the system are refractory-lined and designed mechanically for 150 psig and an internal temperature of 1090°C (2000°F). Table 1 summarizes the operational performance for the TRDU under the previous test program utilizing the J-leg loop seal (1).

For oxygen-blown operation, the TRDU was modified under a concurrent DOE-funded program, in which the TRDU loop seal was changed to allow more solids circulation through the mixing zone. Higher solids circulation rates will dissipate more of the heat release in the mixing zone. The loop seal was changed from a J-leg to an L-valve configuration which allowed the length of the mixing zone to be increased substantially for increased solids residence time. In addition, the diameters of the standpipe, dipleg, and L-valve return legs were increased to reduce the amount of wall friction and gas bubble holdup caused by the small inside diameters of these sections. Another modification was to install a seal pot on the bottom of the dipleg to allow the bed material height in the standpipe to be operated independently of the level in the dipleg without having the primary cyclone performance spoiled by gas bypassing the dipleg when the solids level drops below the dipleg solids return point.

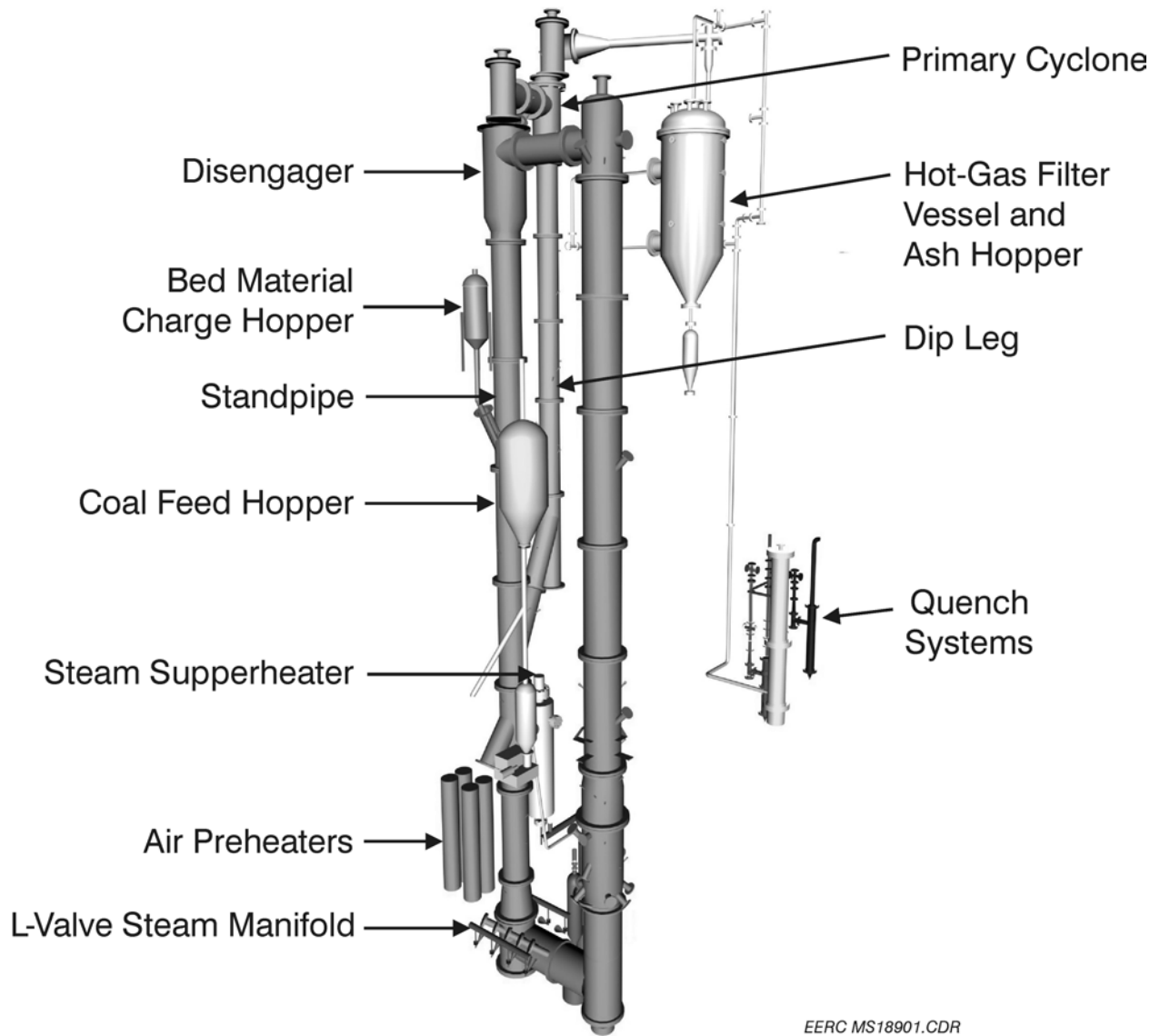


Figure 1. EERC transport reactor development unit with L-valve modifications.

Table 1. TRDU Design and Actual Operating Conditions

Parameter Conditions Coal	P056 &			
	Design Gasification Illinois No. 6	P057 Gasification Wyodak	P056 Gasification Illinois No. 6	P057 Gasification SUFCo
Moisture Content, %	5	20.0	8.5	9.5
Pressure, bar	9.3	9.3	9.3	9.3
Steam:Coal Ratio, lb/lb coal	0.34	0.29	0.39	0.14 to 0.41
Air:Coal Ratio, lb/lb coal	4.0	2.69	2.59	3.34–3.45
Ca:S Mole Ratio, sorbent	1.5	2.0	2.0	2.0
Coal Feed Rate, lb/hr	198	276.6	232.5	220
J-leg Zone, °C, avg.	993	800	901	866–876
Mixing Zone, °C, avg.	1010	850	935	920–950
Riser, °C, avg.	1010	840	923	894–914
Standpipe, °C, avg.	993	790	856	828–860
Dipleg, °C, avg.		600	576	555–591
TRDU Outlet, °C, avg.		795	870	856–877
Carbon Conversion, %	>80	89	76	72–87
Carbon in Bed, %, Standpipe	20 to 40	6 to 15	6 to 15	5 to 20
Riser Velocity, ft/s	31.3	30	24	25–31
Standpipe Velocity, ft/s	0.1	0.4 to 0.5	.45	0.4–0.45
Circulation Rate, lb/hr	30,000	3000 to 6000	4000	2650–4200
HHV of Fuel Gas, act., Btu/scf, cor., Btu/scf	100	62–75 105–117	61 113	52–75 93–130

The premixed coal and limestone feed to the transport reactor can be admitted through three separate nozzles, which are at varying elevations. Two of these nozzles are located near the top of the mixing zone (gasification), and the remaining one is near the bottom of the mixing zone (combustion). During operation of the TRDU, feed is admitted through one predetermined nozzle at a time. The coal feed is measured by an rpm-controlled metering auger. Oxidant is fed to the reactor through two pairs of nozzles at varying elevations within the mixing zone. For the combustion mode of operation, additional nozzles are provided in the riser for feeding secondary air. Hot solids from the standpipe are circulated into the mixing zone, where they come into contact with the nitrogen and the steam being injected into the J-leg. This feature enables spent char to contact steam prior to the fresh coal feed. This staged gasification process is expected to enhance the process efficiency. Gasification or combustion and desulfurization reactions are carried out in the riser as coal, sorbent, and oxidant (with steam for gasification) flow up the reactor. The solids circulation into the mixing zone is controlled by the solids level in the standpipe.

The riser, disengager, standpipe, and cyclones are equipped with several internal and skin thermocouples. Nitrogen-purged pressure taps are also provided to record differential pressure across the riser, disengager, dipleg, and the cyclones. The data acquisition and control system scans the data points every one-half second and is saving the process data every 30 seconds. The bulk of entrained solids leaving the riser is separated from the gas stream in the disengager and circulated back to the riser via the standpipe. A solids stream is withdrawn from the standpipe via an auger to maintain the system's solids inventory. Gas exiting the disengager enters a primary cyclone. Gas exiting this

cyclone enters a jacketed-pipe heat exchanger before entering the hot-gas filter vessel (HGFV). The cleaned gases leaving the HGFV enters a quench system before being depressurized and vented to a flare.

The quench system uses a sieve tower and two direct-contact water scrubbers to act as heat sinks and remove impurities. All water and organic vapors are condensed in the first scrubber, with the second scrubber capturing entrained material and serving as a backup. The condensed liquid is separated from the gas stream in a cyclone that also serves as a reservoir. Liquid is pumped either to a shell-and-tube heat exchanger for reinjection into the scrubber or down to the product receiver barrels.

3.1 Hot-Gas Filter Vessel

The filter design criteria are summarized in Table 2, and a schematic is given in Figure 2. This vessel is designed to handle all of the gas flow from the TRDU at its expected operating conditions. The vessel is approximately 48-in. ID and 185 in. long and is designed to handle gas flows of approximately 325 scfm at temperatures up to 815°C (1500°F) and 150 psig. The refractory has a 28-in. ID with a shroud diameter of approximately 22 in. The vessel is sized such that it could handle candle filters up to 1.5 m long; however, mostly 1-m candles have been utilized in the 540°C (1000°F) gasification tests to date. Candle filters are 2.375-in. OD with 4-in. center line-to-center line spacing.

The total number of candles that can be mounted in the current geometry of the HGFV tube sheet is 19. This enables filter face velocities as low as 2.5 ft/min to be tested using 1-m candles, although most tests have been conducted using 12 to 13 candles, providing a face velocity between 4 to 4.5 ft/min. The openings for the removed candles have been blanked off. This program has tested Industrial Filter & Pump (IF&P) Fibrosic and REECER candles, silicon carbon-coated and silicon oxide ceramic fiber candles from the 3M company, along with sintered metal (iron aluminide) and Vitropore silicon carbide ceramic candles from Pall Advanced Separation Systems Corporation, and granular SiC candles from U.S. Filter/Schumacher. Candle filter fail-safes from Westinghouse Science and Technology Center have also been tested.

The ash letdown system consists of two sets of alternating high-temperature valves with a conical pressure vessel to act as a lock hopper. Additionally, a preheat natural gas burner attached to a lower inlet nozzle on the filter vessel can be used to preheat the filter vessel separately from the TRDU. The hot gas from the burner enters the vessel via a nozzle inlet separate from the dirty gas.

The high-pressure nitrogen backpulse system is capable of backpulsing up to four sets of four or five candle filters with ambient-temperature nitrogen in a time-controlled sequence. The pulse length and volume of nitrogen displaced into the filter vessel is controlled by regulating the pressure (up to 800 psig) of the nitrogen reservoir and the solenoid valves used to control the timing of the gas pulse. Figure 1 also shows the filter vessel location and process piping in the EERC gasifier tower.

Table 2. Design Criteria and Actual Operating Conditions for the Pilot-Scale Hot-Gas Filter Vessel

Operating Conditions	Design	Actual
Inlet Gas Temperature	540°–980°C	520°–580°C
Operating Pressure	150 psig	120 psig
Volumetric Gas Flow	325 scfm	350 scfm
Number of Candles	19 (1 or 1.5 meter)	13 (1 meter)
Candle Spacing	4 in. \varnothing to \varnothing	4 in. \varnothing to \varnothing
Filter Face Velocity	2.5–10 ft/min	4.5 ft/min
Particulate Loading	<10,000 ppm	<7000 ppm
Temperature Drop Across HGFV	<30°C	25°C
Nitrogen Backpulse System Pressure	up to 800 psig	250 to 350 psig
Backpulse Valve Open Duration	up to 1-s duration	½-s duration

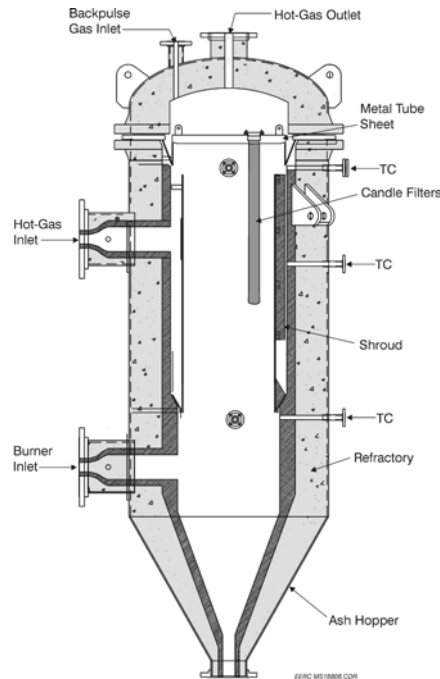


Figure 2. EERC hot-gas filter system.

Since all the filter tests are to be completed in the 540°–650°C (1000°–1200°F) range, a length of heat exchanger was used to drop the gas temperature to the desired range. In addition, sample ports both upstream and downstream of the filter vessel have been utilized for obtaining particulate and hazardous air pollutant (HAP) samples.

3.2 High-Pressure and High-Temperature Sampling System

The high-pressure and high-temperature sampling system (HPHTSS) was designed and constructed to extract dust-laden flue gas isokinetically from either an oxidizing or reducing environment. The maximum gas temperature at which the sample probe can be operated is specified as 815°C (1500°F) for the HPHTSS. The maximum working pressure of the gas stream for the HPHTSS is specified as 150 psig.

The probe for the HPHTSS is a 3/8-in.-OD and 1/8-in.-ID 304 stainless steel tube. The probe can be used for only one sampling test. The key to the sampling system is the use of a vessel designed to withstand high-pressure and high-temperature conditions to enclose the low-pressure sampling devices.

The principle of operation is to pressurize the outside of the sampling device (i.e., multicyclone assembly or backup filter) with nitrogen at a slightly higher gas pressure than the system pressure of the flue gas. The pressure differential between the nitrogen gas within the pressure vessel and the flue gas within the sampling device is maintained at less than 5 psig.

If the HPHTSS is operating in a reducing environment where the presence of organic vapors is a possibility, the pressure vessel is capable of operating at temperatures as high as 540°C (1000°F) and maintaining nitrogen gas pressures up to 150 psig. This will prevent the heavier organic vapors from condensing while passing through the particulate sampling assembly. Electric resistance heaters are used to heat the pressure vessel to specified temperatures. This operating temperature also allows vapor-phase trace species to be maintained in the vapor phase through the backup filter.

Once the process gas exits the sampling assembly, the gas pressure is reduced through a throttling valve to approximately atmospheric pressure. The throttling valve will also act as the flow control valve for the sampling system. A second throttling valve was installed in series in the event that the primary throttling valve fails to close.

After the throttling valve, the process gas is cooled through a set of impingers to remove moisture and organic vapors if present. A set of up to six impingers may be used in this sampling system. These impingers are rated for 200 psig at 120°C (250°F) maximum operating conditions. The impingers are made of 304 stainless steel, with the interior surfaces coated with Teflon. The Teflon-coated surfaces allow the HPHTSS to be used for collecting the vapor-phase trace metal species.

The dry gas is then metered through a rotameter and dry-gas meter to measure total flow before it is vented out of the stack.

4.0 ACCOMPLISHMENTS

TRDU test campaigns conducted in air-blown mode during the week of February 7–12, 2000, generated 126 hours of coal feed and 120 hours of operation in coal gasification mode on the Kinneman Creek seam lignite from the BNI Mine at Center, North Dakota. A second air-blown test was conducted from February 26 to March 3, 2000, which generated an additional 71 hours of coal feed and 66 hours of gasification on a run-of-mine lignite from the Falkirk Mine near Washburn, North Dakota, and an additional 35 hours of coal feed and 33 hours of gasification on a lignite from the Freedom Mine near Beulah, North Dakota. After the modification of the TRDU loop seal and the completion of two oxygen-blown shakedown tests under the concurrent DOE program, another oxygen-blown lignite gasification test campaign was completed the weeks of June 12, 2001, through June 21, 2002. This oxygen-blown gasification test of the same three lignites tested previously resulted in 70.5 hours of gasification testing on the Center lignite, 45.5 hours on the Falkirk lignite, and 60 hours of gasification on the Freedom lignite. These tests were completed with the system gases and fly ash passing through the hot-gas filter system during these test campaigns.

4.1 TRDU Fuel Analysis

The fuels tested in the TRDU during this test campaign include Kinneman Creek seam lignite from the BNI mine at Center, North Dakota; lignite from the Falkirk Mine near Washburn, North Dakota; and two lignites (including a higher sodium) from the Freedom Mine near Beulah, North Dakota. Table 3 shows the proximate, ultimate, and XRF analysis of all the fuels. The Center lignite was initially mixed with the Plum Run dolomite (PRD), used for previous tests, and then the Montana limestone (MLS) as sorbent materials. The MLS is a locally available candidate sorbent material that could be used for commercial gasification of lignite. Both the Falkirk and Freedom lignites were blended with MLS. All fuels were premixed with the sorbent before testing in the TRDU. The sorbents were mixed with the respective coals to provide a Ca/S ratio of approximately 1.5 or less on a sorbent-only basis for the fuels being gasified.

4.2 TRDU Operation

4.2.1 Task 1 – TRDU Air-Blown Gasification Tests P064 and P065

The TRDU was operated at average temperatures ranging from 793° to 894°C at various air/fuel ratios and reactor velocities. Table 4 summarizes the range of operational performance for the TRDU during these test periods. Table 5 summarizes the optimum operating conditions achieved with each lignite. In general, similar actual and corrected fuel gas heating values were achieved with all three lignites. The dry product gas produced was 4.2% to 6.5% CO and 7.1% to 9.2% H₂, 12.0% to 13.8% CO₂, 0.9% to 1.4% CH₄, with the balance being N₂ and other trace constituents. The moisture in the fuel gas averaged 18% to 19%. The H₂S concentration ranged from 446 to 1088 ppm and averaged 850 ppm. Coal feed rates ranged from 302 to 492 lb/hr (137 to 223 kg/hr), and the gasifier pressure averaged 120 psig (8.6 bar). Calculated recirculation rates ranged from 950 to 3115 lb/hr (430 to 1412 kg/hr).

Table 3. North Dakota Lignite and Sorbent Analyses

Proximate Analysis, as run, wt%	-10-mesh Center Lignite	-10-mesh Falkirk Lignite	-10-mesh Freedom Lignite	-10-mesh Hi-Na Freedom Lignite	-35-mesh PRD	-35-mesh MLS
Moisture	35.0	36.2	33.8	28.3	NA ¹	NA
Volatile Matter	32.1	30.0	31.0	31.8		
Fixed Carbon	26.6	24.5	24.3	29.6		
Ash	6.3	9.3	10.9	10.3		
Ultimate Analysis, MF, wt%						
Carbon	61.88	58.59	57.74	59.77		
Hydrogen	4.43	4.08	3.72	3.54	NA	NA
Nitrogen	2.27	2.14	1.94	1.18		
Sulfur	1.27	1.72	4.70	1.50		
Oxygen	20.53	18.81	15.48	19.69		
Ash	9.62	14.66	16.42	14.32		
Ash Composition, % as oxides						
Calcium, CaO	20.9	16.3	23.1	16.3	66.6	73.6
Magnesium, MgO	6.6	4.9	9.2	7.4	27.5	0.4
Sodium, Na ₂ O	0.8	3.7	5.7	8.9	0.3	0.0
Silica, SiO ₂	20.9	29.3	18.8	30.3	2.7	25.3
Aluminum, Al ₂ O ₃	9.3	10.5	9.7	15.0	1.0	0.0
Ferric, Fe ₂ O ₃	9.5	10.2	11.6	6.0	1.3	0.0
Titanium, TiO ₂	0.6	0.5	0.4	0.6	0.0	0.0
Phosphorus, P ₂ O ₅	0.1	0.1	0.2	0.3	0.0	0.0
Potassium, K ₂ O	0.3	1.4	0.5	0.9	0.3	0.3
Sulfur, SO ₃	28.4	23.0	20.8	14.1	0.4	0.4 0.0
High Heating Value						
Moisture-Free, Btu/lb	10,200	9820	9600	10017	NA	NA
As-Received, Btu/lb	6620	6260	6350	7179	NA	NA

¹ Not applicable.

The recirculating bed material particle size for Test P064 was approximately 200 μm and was decreasing with time down to approximately 100 μm while on Center lignite with PRD. After the MLS was switched to, the bed material particle-size distribution started increasing to approximately 300 μm. The particle-size distribution for the filter ash was approximately 12 μm but ranged from 8 up to almost 20 μm at the end of the test period because of a partial obstruction of the dipleg. The circulating bed material for Test P065 with the Falkirk lignite started at approximately 150 μm and gradually increased to approximately 300 μm of the course of the 71 hours of testing. After the TRDU was restarted on fresh sand for the Freedom lignite test, the bed material particle size remained relatively constant at 150 μm. The filter vessel particle size averaged approximately

Table 4. TRDU Range of Air-Blown Operating Conditions

Parameter	P064	P065	P065
Conditions	Gasification	Gasification	Gasification
Coal	Center	Falkirk	Freedom
Moisture Content, %	35.0	36.2	33.8
Pressure, psig	120	120	120
Steam:Coal Ratio	0.22–0.29	0.19–0.28	0.20–0.26
Air:Coal Ratio	1.97–2.54	1.95–2.47	1.99–2.44
Ca:S Ratio, mole, total including ash	2.32–2.49	1.71	0.8–1.05
Coal and Sorbent Feed Rate, lb/hr	352–468	302–492	360–428
Avg. Mixing Zone Temp, °C, avg.	793–894	809–853	814–847
HHV of Fuel Gas, Act., Btu/scf	49–61	49–62	50–61
HHV of Fuel Gas, Cor., Btu/scf	105–125	110–123	108–133
Conversion, %	70–93	75–93	69–87
Carbon in Bed, %, standpipe	7.0–32	10.5–23.9	12.5–27.2
Riser Velocity, ft/s	32.6–38.8	29.1–40.5	33.5–36.8
Standpipe Velocity, ft/s	0.39–0.49	0.42–0.45	0.42–0.46
Circulation Rate, lb/hr	950–3030	1555–3115	1870–2910
Duration, hr	126	71	30.5
Time	00:04–06:00	12:40–11:50	05:35–12:05
Date	2/8/00–2/12/00	2/27/00–3/01/00	3/02/00–3/03/00

15 μm on both the Falkirk and Freedom lignites. Figures 3 and 4 show the particle-size distributions for selected samples taken during the air-blown and oxygen-blown gasification tests.

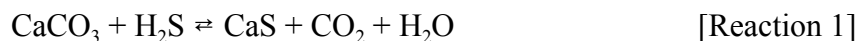
4.2.2 Task 2 – Oxygen-Blown Gasification Test P068

The TRDU was operated at average temperatures ranging from 792° to 828°C at various air/fuel ratios and reactor velocities. Table 6 summarizes the range of operational performance for the TRDU during these test periods. Table 7 summarizes the optimum operating conditions achieved with each lignite. In general, similar actual and corrected fuel gas heating values were achieved with all three lignites. The actual dry product gas produced was 4.7% to 7.4% CO and 12.7% to 20.8% H₂, 20.8% to 29.7% CO₂, 1.9% to 3.1% CH₄, and 0.20% to 0.35% ethane with the balance being N₂ and other trace constituents. The moisture in the fuel gas exiting the transport reactor ranged from 45.9% to 55.7% under oxygen-blown conditions. The H₂S concentration ranged from 2000 to 3700 ppm and averaged 3370 ppm under full oxygen-blown operating conditions. The sulfur retention was less than 33% under these operating conditions. This low level of sulfur capture was a result of the

Table 5. TRDU Optimum Operating Conditions

Parameter	P064	P065	P065
Conditions	Gasification	Gasification	Gasification
Coal	Center	Falkirk	Freedom
Pressure, psig	120	120	120
Steam:Coal Ratio	0.22	0.23	0.23
Air:Coal Ratio	1.97	2.08	2.15
Ca:S Ratio, mole, total including ash	2.32	1.71	1.05
Coal and Sorbent Feed Rate, lb/hr	456	428	409
Avg. Mixing Zone Temp, °C	812	845	814
Avg. J-Leg Temp, °C	739	748	735
Avg. Riser Temp, °C	739	760	737
Avg. Standpipe Temp, °C	713	730	705
Avg. Dipleg Temp, °C	499	526	554
Conversion, %	89.5	82.9	87.1
Product Gas HHV, Btu/scf act.	60	60	61
Product Gas HHV, Btu/scf cor.	125	123	133
Carbon in Bed, %, Standpipe	26.3	16.3	20.2
Riser Velocity, ft/s	37.0	36.5	36.8
Standpipe Velocity, ft/s	0.40	0.44	0.42
Circulation Rate, lb/hr	1760	1580	1965

high water and carbon dioxide partial pressures generated by oxygen-blown operation greatly reducing the equilibrium concentration of calcium sulfide that will form according to the reaction:



Coal/sorbent feed rates ranged from 413 to 586 lb/hr (187 to 265 kg/hr), and the gasifier pressure averaged 100 psig (7.9 bar). Calculated recirculation rates ranged from 950 to 7650 lb/hr (430 to 3470 kg/hr).

The recirculating bed material particle size for Test P068 was approximately 150 to 300 μm with the MLS. The circulating bed material with the Falkirk lignite was approximately 180 μm and increased to approximately 400 μm while on the Freedom coal with the MLS. After the TRDU was restarted on fresh sand for the high-sodium Freedom lignite test with the PRD, the bed material particle size remained relatively constant at 150 μm . The particle-size distribution for the filter ash for all coals was approximately 15 μm but ranged between 8 μm up to almost 20 μm . Figures 3 and

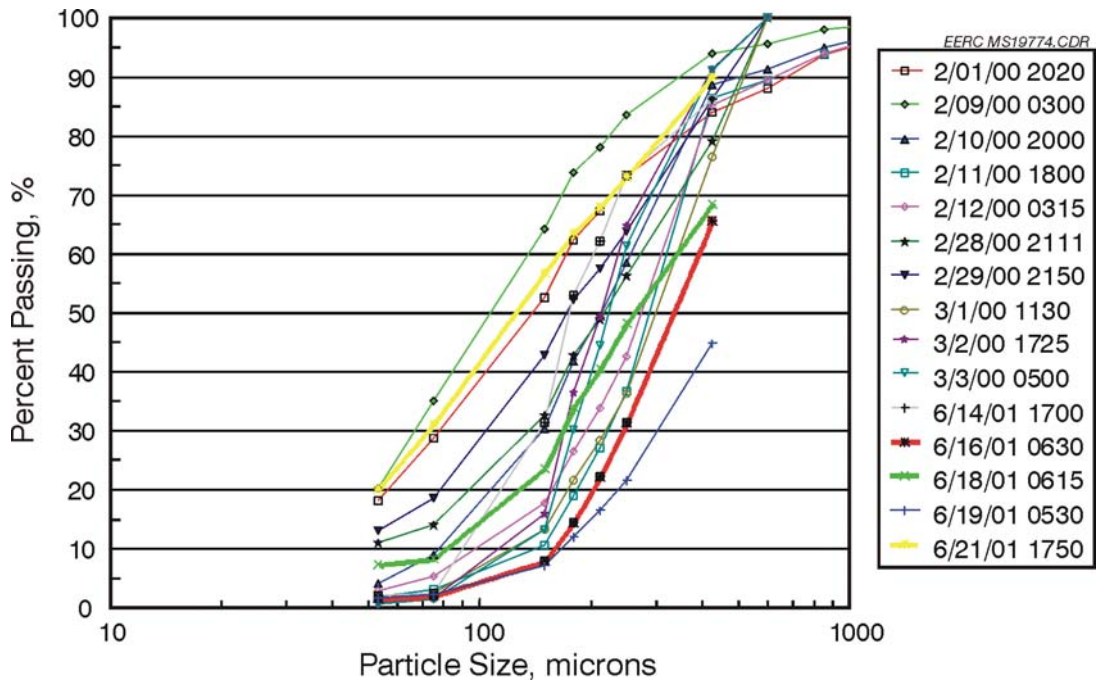


Figure 3. Particle-size distributions of selected standpipe samples.

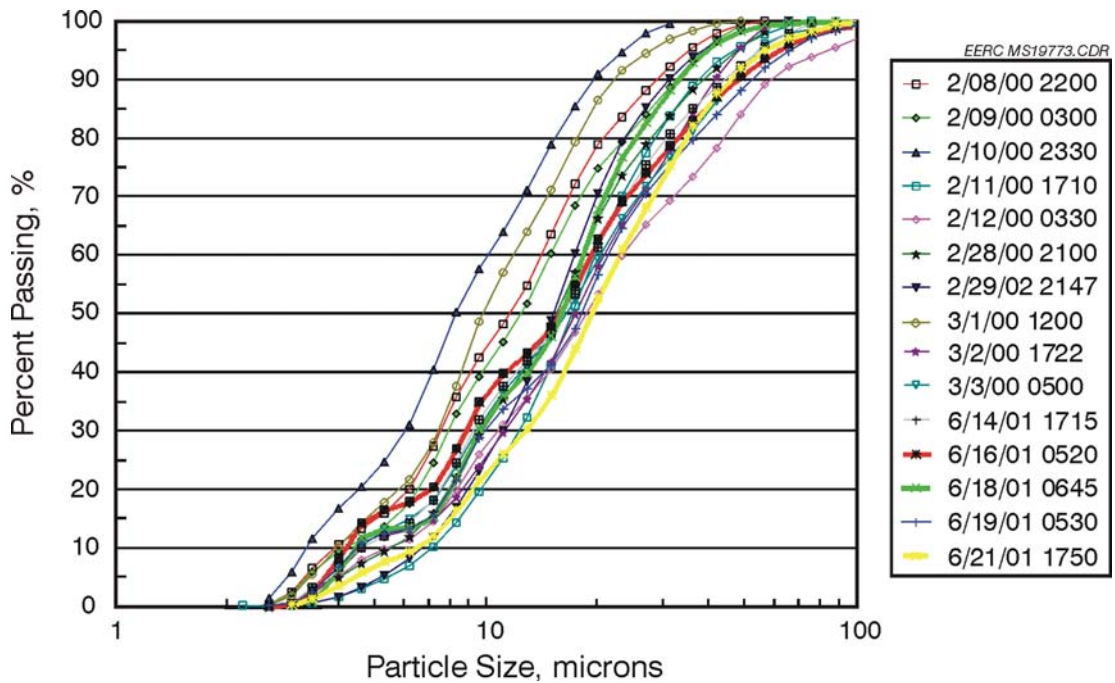


Figure 4. Particle-size distribution of selected hot-gas filter samples.

Table 6. TRDU Range of Oxygen-Blown Operating Conditions

Parameter	P068	P068	P068
Conditions	Gasification	Gasification	Gasification
Coal	Center	Falkirk	Freedom
Moisture Content, %	35.0	36.2	28.3–33.8
Pressure, psig	100	100	85–100
Steam:Coal Ratio	0.80–1.01	0.79–0.95	1.05–1.43
O ₂ :Coal Ratio	0.41–0.51	0.40–0.48	0.49–0.61
Ca:S Ratio, mole, total including ash	1.61	1.52	1.2–3.5
Coal and Sorbent Feed Rate, lb/hr	440–567	487–586	413–531
Avg. Mixing Zone Temp, °C, avg.	808–828	796–811	792–816
HHV of Fuel Gas, act., Btu/scf	79–128	112–121	90–118
HHV of Fuel Gas, cor., Btu/scf	220–239	211–236	214–232
Conversion, %	79–90	80–87	64–90
Carbon in Bed, %, Standpipe	6–26	6–25	5–7
Riser Velocity, ft/s	41.6–45.0	50–53	48–51
Standpipe Velocity, ft/s	0.35	0.35	0.35
Circulation Rate, lb/hr	3250–7650	4000–5000	950–2550
Duration, hr	77	46	67

4 also show the particle-size distributions for selected standpipe and filter samples collected during the oxygen-blown tests. These figures indicate that there was not a significant difference in particle-size distributions between air-blown and oxygen-blown operation.

Correction of the raw product gas stream is necessary because of the high level of dilution caused by the nitrogen purges in the system and by the high heat losses as a percentage of the coal feed experienced by a pilot-scale system. These corrections assume that the purges would either be small enough to be inconsequential or where significant amounts of purge gas are required, a compressor would recycle syngas instead of injecting nitrogen. Heat losses were corrected from approximately 20% of the coal feed heat input to approximately 0.25% of the coal feed heat input. Comparing the corrected product gas compositions, the air-blown fuel gas composition would be 15%–17% H₂, 9%–12% CO, 2.0%–3.0% CH₄, and 15%–17% CO₂, as compared with a corrected fuel gas composition of 35%–39% H₂, 13%–14% CO, 4.5%–6.0% CH₄, and 38%–41% CO₂. The high hydrogen and carbon dioxide concentrations under oxygen-blown conditions are the result of the water-gas shift reaction (Reaction 2 shown below) being driven to form the products on the right-hand side of the reaction by the high steam partial pressure in the gasifier product gas stream. This high hydrogen and carbon dioxide product gas stream would make an excellent gas stream for hydrogen separation and for CO₂ separation and possible sequestration under a Vision 21 project.

Table 7. TRDU Optimum Oxygen-Blown Operating Conditions

Parameter	P068	P068	P068
Conditions	Gasification	Gasification	Gasification
Coal	Center-6	Falkirk-2	Hi-Na Freedom-3
Pressure, psig	100	100	85
Steam:Coal Ratio	1.01	0.92	1.05
O ₂ :Coal Ratio	0.50	0.47	0.49
% Sorbent in feed, wt%	8	10	20
Coal and Sorbent Feed Rate, lb/hr	457	502	531
Avg. Mixing Zone Temp, °C	812	811	809
Avg. L-Valve Temp, °C	700	637	580
Avg. Riser Temp, °C	728	738	712
Avg. Standpipe Temp, °C	748	756	718
Avg. Dipleg Temp, °C	440	456	515
Conversion, %	85.0	85.3	81.5
Product Gas HHV, act., Btu/scf	114	116	116
Product Gas HHV, cor., Btu/scf	234	233	232
Carbon in Bed, %, standpipe	10.7	12.2	10.4
Riser Velocity, ft/s	42.5	42.4	48.8
Standpipe Velocity, ft/s	0.35	0.35	0.35
Circulation Rate, lb/hr	5200	4000	950



Figure 5 compares the carbon conversion and product gas heating values achieved as a function of the O₂/coal weight ratio for the various steady-state operating periods identified during both the air-blown and oxygen-blown tests. Comparable carbon conversions have been achieved at similar oxygen/coal ratios for both air-blown and oxygen-blown operation. This figure also shows the calculated corrected heating values for both the dry and wet (containing steam) product gas streams. Since hot-gas cleanup is utilized, the unconverted steam and coal moisture injected into the gasifier will remain in the fuel gas entering the gas turbine. When the air-blown and oxygen-blown fuel gas heating values are compared for the wet product gas streams, it is apparent that only a slight improvement in product gas heating entering the gas turbine is achieved with oxygen-blown operation. In order to keep the gas turbine firing temperature down to prevent thermal NO_x formation, typically large amounts of nitrogen or steam are injected into gas turbine combustor such that the fuel gas heating is typically not much greater than 115 Btu/scf as fired. In essence, the transport reactor has either injected the nitrogen (in the form of air) or steam into the gasifier instead

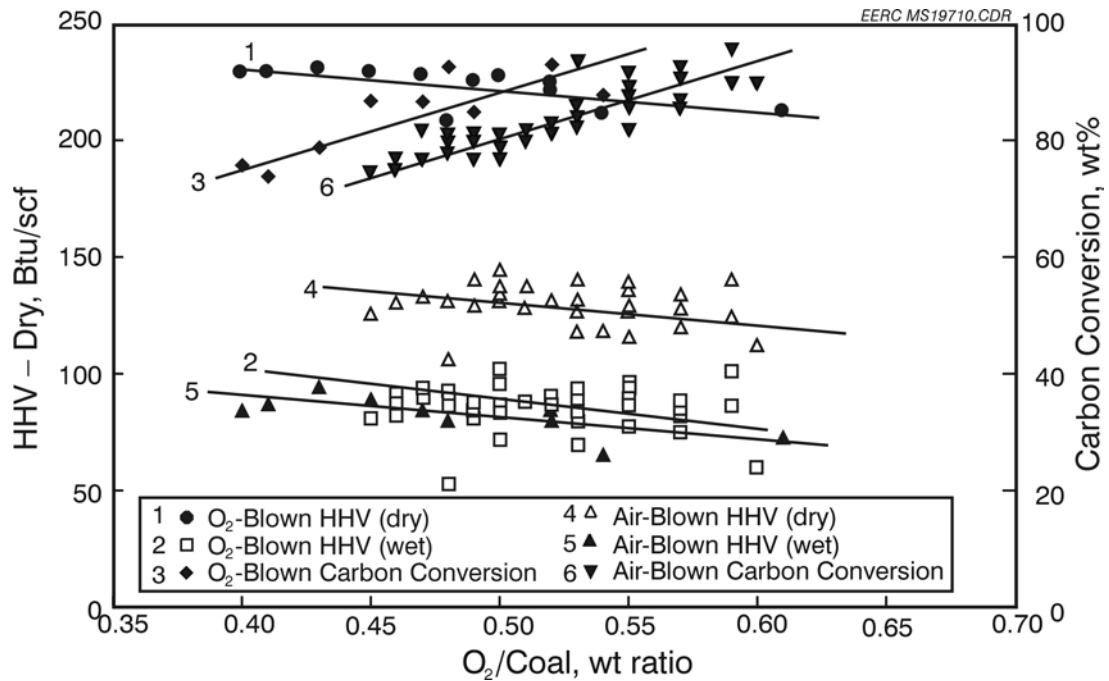


Figure 5. TRDU performance under air-blown and oxygen-blown operation.

of into the gas turbine combustor to keep the fuel gas heating value at the desired level. However, if chemicals or fuel production is being considered where conventional cold-gas cleanup technology would be utilized to remove the water vapor from the fuel gas stream, significantly higher fuel gas heating values can be achieved with oxygen-blown operation because of the lack of the nitrogen diluent.

4.3 TRDU Ash Chemistry

Tables 8 through 11 show the elemental analyses for steady-state standpipe, primary cyclone, and filter samples collected toward the end of each coal test period under air-blown operating conditions. These analyses indicates that the standpipe material still contained some significant levels of the startup silica sand while the filter ash samples were representative of the coal ash/sorbent mixture. Figures 6 and 7 show the ash chemistry for several standpipe samples collected over the duration of Tests P064 and P065, respectively. Figure 8 and 9 show the ash chemistry for the filter ash samples collected during these same tests. These analyses show that the start-up silica sand bed material is displaced primarily with calcium and magnesium from the dolomite sorbent until the sorbent was switched to the MLS. At this point, the calcium concentration increased even higher, and the magnesium content in the circulating bed material decreased substantially. The remaining ash constituents closely follow ash concentrations from the coal ash. Very little sodium was measured in the standpipe samples from the Center Kinneman Creek seam coal; however, sodium concentrations increased to approximately 3% with the Falkirk lignite and increased to approximately 4% with the higher- sodium Freedom lignite. Whether the sodium levels would have

Table 8. XRF Chemical Composition of Center Lignite TRDU Steady-State Samples, air-blown Test P064

Element, wt%	Center	Center	Center
	Coal Ash w/ 8 wt% PRD	Standpipe	Filter
Si	15.6	38.9	18.5
Al	6.3	2.6	8.1
Fe	10.6	4.6	10.3
Ti	0.5	0.2	0.7
P	0	0	0
Ca	38.8	37.1	44.1
Mg	15.2	12	10.2
Na	0.4	0	0.6
K	0.6	0.6	0.7
S	11.9	4	6.8
Total	99.9	100.0	100.0

Table 9. XRF Chemical Composition of Center Lignite TRDU Steady-State Samples, air-blown Test P064

Element, wt%	Center	Center	Center
	Coal Ash w/ 6.5 wt% MLS	Standpipe	Filter
Si	16.2	22.1	19.3
Al	7.9	2	8.4
Fe	16	5.8	10
Ti	0.7	0.3	0.7
P	0.1	0	0
Ca	32.2	60.2	44.5
Mg	6.9	4.5	7.1
Na	0.8	0	0.9
K	0.6	0.4	0.6
S	18.6	4.7	8.5
Total	100.0	100.0	100.0

continued to climb until bed material agglomeration problems would have resulted cannot be entirely ruled out. Sodium also seemed to be preferentially released to the smaller particle sizes in the dipleg and filter ash.

Table 10. XRF Chemical Composition of Falkirk Lignite TRDU Steady-State Samples, air-blown Test P065

Element, wt%	Falkirk Coal Ash w/ 4 wt% MLS	Falkirk Standpipe Agglomerate	Falkirk Standpipe	Falkirk Dipleg	Falkirk Filter
Si	24.9	26.5	29.2	34.8	23.6
Al	8.8	6.3	8.4	9.9	11.2
Fe	7.8	4.4	5.2	6.6	9.7
Ti	0.5	0.3	0.4	0.5	0.6
P	0.1	0.1	0.1	0.1	0.2
Ca	34.8	53.0	49.6	37.7	39.5
Mg	4	2.2	2	2.8	6.6
Na	3.5	2.6	2.4	3.9	3
K	1.8	2.0	1.9	2	1.5
S	13.8	2.5	0.7	1.7	4.2
Total	100.0	99.9	99.9	100.0	100.1

Table 11. XRF Chemical Composition of Freedom Lignite TRDU Steady-State Samples, air-blown Test P065

Element, wt%	Freedom Coal Ash w/ 7 wt% MLS	Freedom Standpipe Agglomerate	Freedom Standpipe	Freedom Filter
Si	15.3	26.5	29.2	13.1
Al	9	6.3	3.1	7.2
Fe	14.2	4.4	5.4	8.3
Ti	0.5	0.3	0.2	0.4
P	0.2	0.1	0	0.1
Ca	28.7	53.0	52	48
Mg	9.7	2.2	2.3	8.7
Na	7.4	2.6	3.4	3.7
K	0.7	2.0	0.6	0.6
S	14.5	2.5	3.7	9.8
Total	100.2	99.9	99.9	99.9

Tables 12 through 15 show the XRF analysis of representative samples from the oxygen-blown gasification tests of the North Dakota lignites in the TRDU. Coal and steady-state standpipe and filter ash compositions are shown in Figures 10 and 11 for the oxygen-blown lignite tests. These

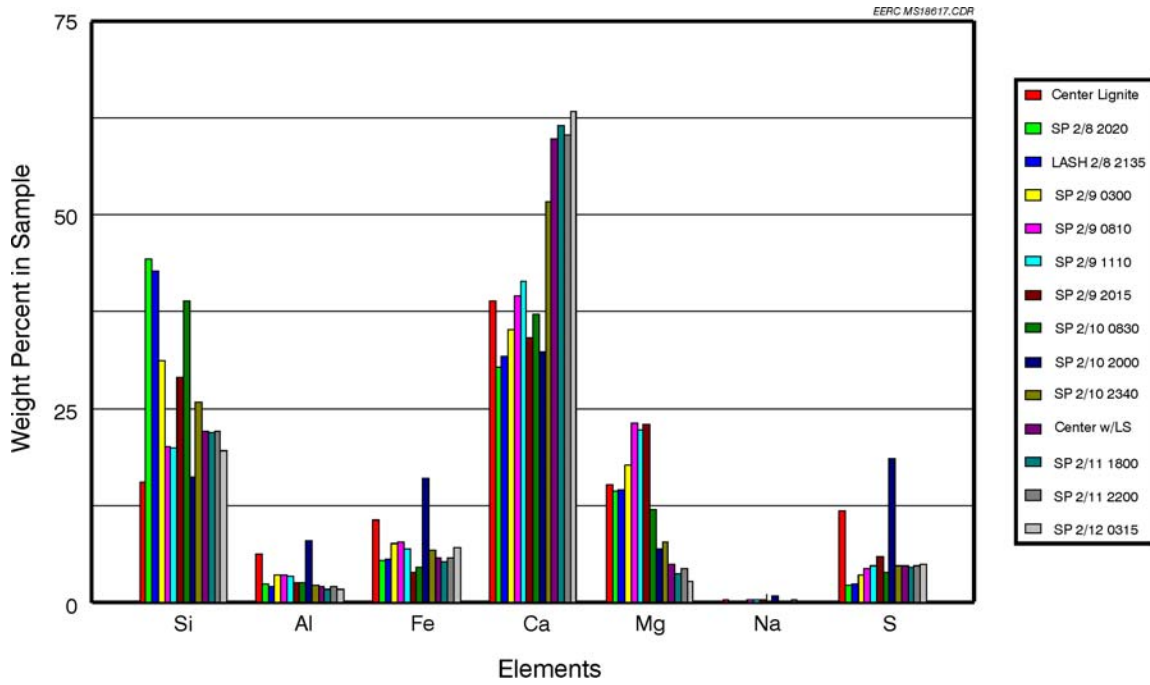


Figure 6. Standpipe samples, Test P064.

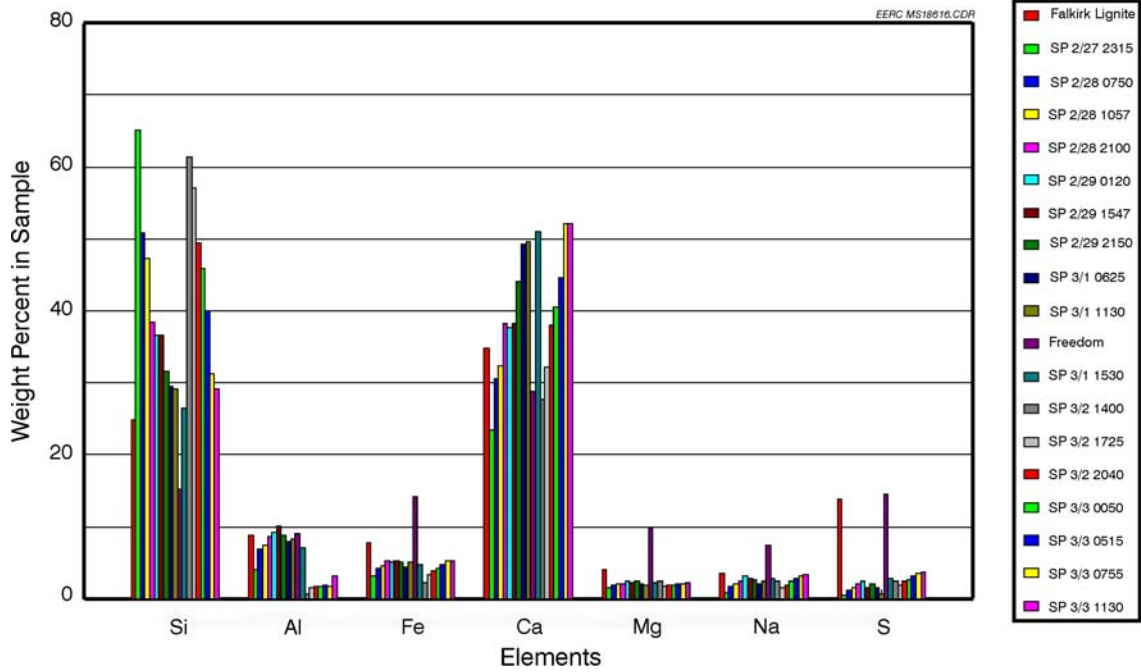


Figure 7. Standpipe samples, Test P065.

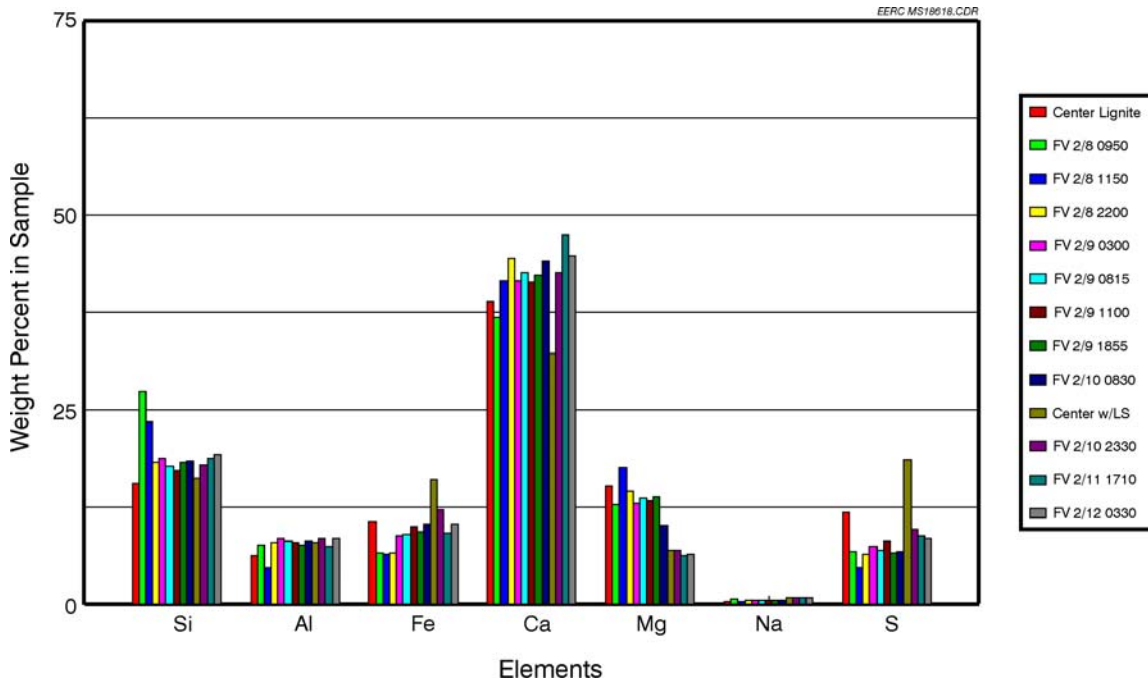


Figure 8. Filter vessel samples, Test P064.

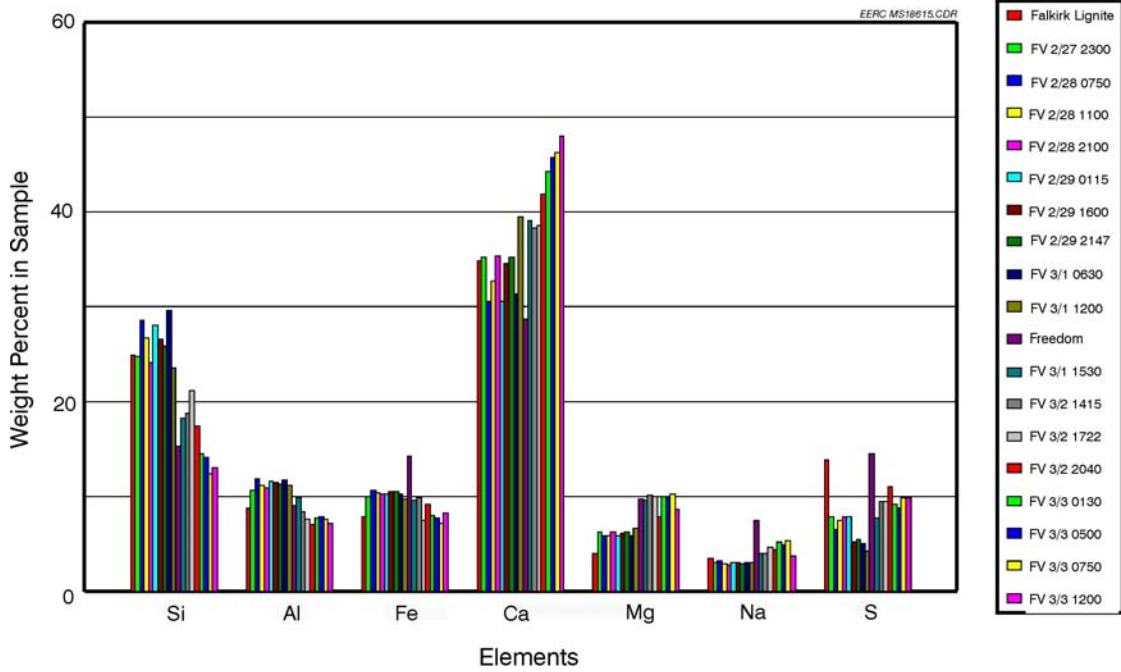


Figure 9. Filter vessel samples, Test P065.

Table 12. XRF Chemical Composition of Center Lignite TRDU Steady-State Samples, oxygen-blown Test P068

Element, wt%	Center	Center	Center
	Coal Ash w/ 8 wt% MLS	Standpipe	Filter
Si	16.2	26.4	19.7
Al	7.9	2.4	10.1
Fe	16	6.1	10.1
Ti	0.7	0.3	0.7
P	0.1	0.1	0.1
Ca	32.2	56.0	39.3
Mg	6.9	2.2	6.8
Na	0.8	05.0	7.9
K	0.6	0.5	0.9
S	18.6	1.1	4.4
Total	100.0	100.1	100.0

Table 13. XRF Chemical Composition of Falkirk Lignite TRDU Steady-State Samples, oxygen-blown Test P068

Element, wt%	Falkirk	Falkirk	Falkirk	Falkirk
	Coal Ash w/ 10 wt% MLS	Standpipe	Dipleg	Filter
Si	24.9	22.9	33.4	29.9
Al	8.8	6.1	5.3	11.5
Fe	7.8	4.9	5.3	9.0
Ti	0.5	0.4	0.4	0.6
P	0.1	0.1	0.1	0.1
Ca	34.8	56.5	47.9	35.8
Mg	4	3.9	2.6	6.2
Na	3.5	2.2	3.2	3.6
K	1.8	1.6	1.3	2.0
S	13.8	1.4	0.5	1.3
Total	100.0	100.0	100.0	100.0

Table 14. XRF Chemical Composition of Freedom Lignite TRDU Steady-State Samples, oxygen-blown Test P068

Element, wt%	Freedom Coal Ash w/ 20 wt% MLS	Freedom Standpipe	Freedom Dipleg	Freedom Filter
Si	15.3	11.6	38.5	13.2
Al	9	0.6	1.7	8.7
Fe	14.2	0.7	2.2	10.2
Ti	0.5	0.1	0.1	0.5
P	0.2	0.0	0.1	0.1
Ca	28.7	83.6	49.8	42.8
Mg	9.7	1.6	2.8	11.2
Na	7.4	0.8	2.8	7.0
K	0.7	0.2	0.5	0.6
S	14.5	0.9	1.4	5.7
Total	100.2	100.1	99.9	100.0

Table 15. XRF Chemical Composition of High Sodium Freedom TRDU Steady-State Samples, oxygen-blown Test P068

Element, wt%	Hi Na Freedom Coal Ash w/ 20% PRD	Hi Na Freedom Mixing Zone Deposit	Hi Na Freedom Standpipe	Hi Na Freedom Dipleg	Hi Na Freedom Filter
Si	10.9	25.2	16.4	17.5	10.3
Al	4.2	6.7	4.9	2.4	6.4
Fe	4.9	6.1	5.1	3.5	4.6
Ti	0.5	0.4	0.3	0.2	0.4
P	0.1	0.0	0.1	0.0	0.2
Ca	48.6	56.7	42.7	47.6	47.1
Mg	22.2	2.7	25.0	27.7	26.5
Na	2.2	1.8	3.2	1.9	2.8
K	0.7	0.3	0.9	0.4	0.5
S	5.8	0.1	1.4	0.5	1.2
Total	99.9	99.9	100.0	100.2	100.1

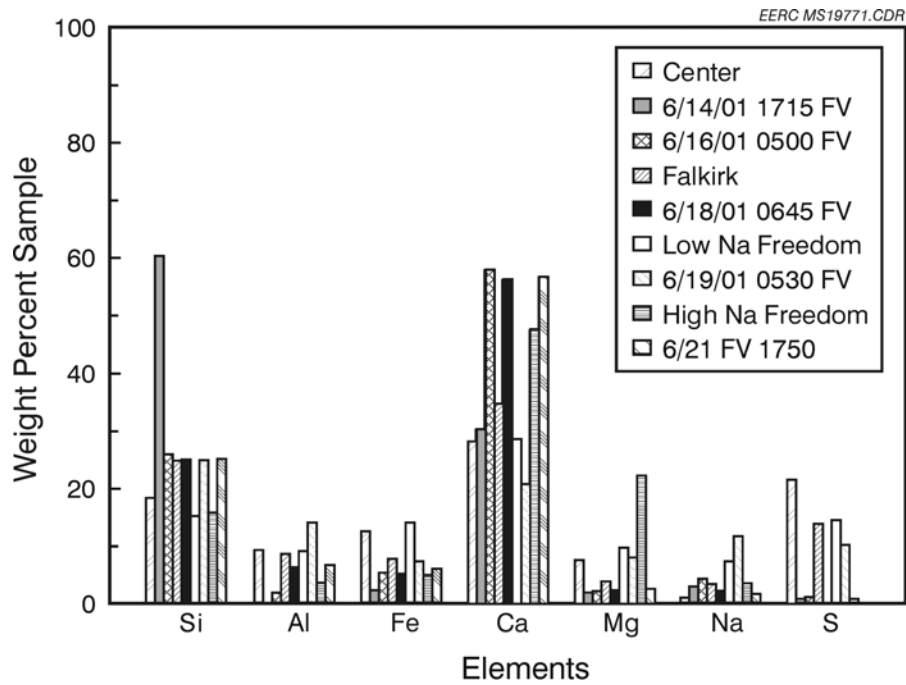


Figure 10. Standpipe ash chemistry for oxygen-blown lignite tests.

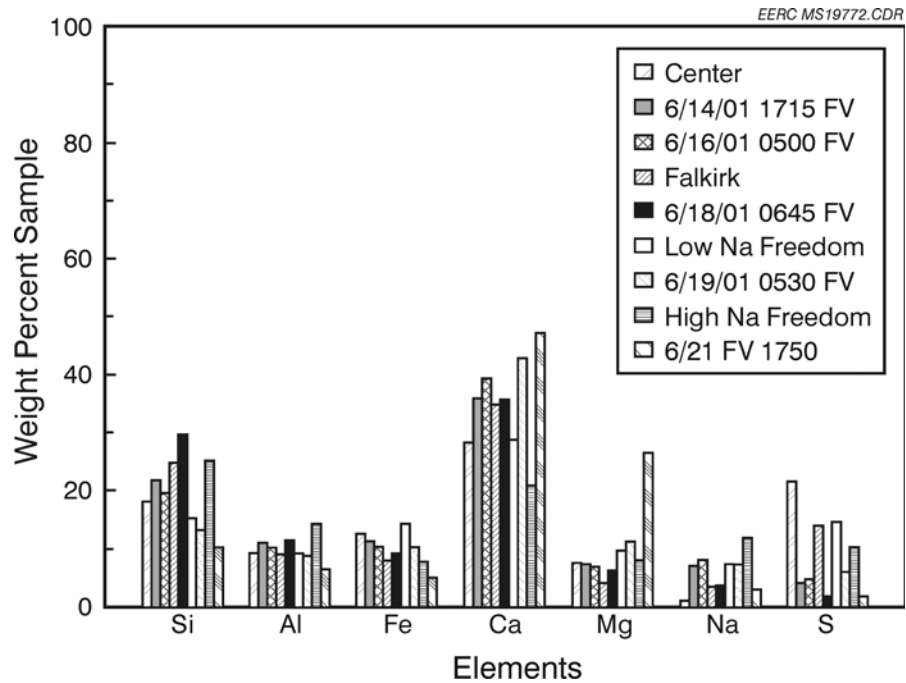


Figure 11. Filter ash chemistry for oxygen-blown lignite tests.

tables and figures all indicate that while there is less sulfur in the ash samples because of less sulfur capture with the calcium-based sorbent, the remaining ash chemistry exhibited by the standpipe and filter ash samples is very similar under both air-blown and oxygen-blown operating conditions.

4.4 TRDU Deposit Formation

Test P064 using the Center lignite from the Kinneman Creek seam did not produce any deposits in the TRDU. The North Dakota air-blown lignite test using the Falkirk and Freedom Mine coals generated an agglomerate that prevented the return flow of solids back down the standpipe to the J-leg and mixing zone, necessitating a system shutdown to clear the deposit. The agglomerate occurred within 3 hours of switching from the Falkirk to the Freedom Mine lignites; thus the agglomerate was primarily the result of the Falkirk coal ash; however, an interaction with the Freedom lignite coal ash cannot be dismissed. Table 16 and Figures 12–14 show the SEM morphology of the outer coating of the bed material particles. Except for two points, there did not appear to be significant levels of sodium in the layer but possibly calcium or iron aluminosilicates. A number of points also contained elevated levels of sulfur, possibly suggesting that the presence of lower-melting-point sulfide compounds could have been involved in agglomerating the bed material.

During the oxygen-blown lignite tests, a few small ash nodules were found adhering to the refractory in the mixing zone at the end of the test. An XRF analysis of these nodules is also shown in Table 16 and in Figure 10. This analysis indicates that these nodules were not very high in sodium and appeared to be enriched in iron, silica, and alumina, indicating that the formation of a low-melting iron aluminosilicate. The lack of magnesium in the nodules suggests that the nodules might ever have formed before the PRD was fed at the end of the oxygen-blown tests.

4.5 Hot-Gas Filter Operation

Tables 17 and 18 show the steady-state operating conditions on the hot-gas filter system achieved for the lignite tests under both air-blown and oxygen-blown operating conditions, respectively. The HGFV was held at an average temperature between 400° and 500°C.

The candles were backpulsed over 846 times during Test P064 and over 638 times during Test P065 with no major candle failures. The same candles were backpulsed 1154 times during the oxygen-blown tests. From the backpulse signature data, the filter vessel was backpulsed at 30- to 40-in. H₂O above the just-cleaned baseline. As the baseline climbed initially from 20-in. H₂O to 40- to 50-in. H₂O, the filter vessel differential pressure trigger was increased from 60-in. H₂O to 70 and finally to 80-in. H₂O.

Backpulse operating parameters initially were a 380 psig reservoir pressure with a ½-second pulse duration which was increased ¾ sec during the test. An increase in pulse duration did not appear to provide any significantly improved backpulse performance. The mechanical operation of the N₂ backpulse system and the filter vessel ash letdown system presented no operational problems. During the oxygen-blown test, a backpulse reservoir pressure of 360 psig with a ½-second pulse duration was utilized throughout the test.

Table 16. SEM Morphology Analysis of TRDU Disengager/Standpipe Agglomerate, Falkirk Lignite, Test P065 (Figure 12)

SEM Point No.:	XRFA	1	2	3	4	5	6	7	8	9	10
Description:	Bulk	Layer	Neck	Fill	Fill	Fill	Fill	Layer	Fill	Fill	Fill
Normal O ₂ -Free Element, wt%											
Na	2.6	0.0	0.0	0.4	0.3	3.7	12.2	0.6	0.1	5.1	1.1
Mg	2.2	0.0	0.0	0.0	1.5	2.0	1.5	0.0	1.0	0.4	1.8
Al	6.3	0.0	0.0	0.7	2.7	6.2	1.4	1.7	5.6	2.3	5.5
Si	26.5	19.6	19.6	16.2	17.1	30.7	63.0	23.5	15.7	82.8	23.6
P	0.1	0.2	0.2	0.1	0.0	0.0	0.0	0.1	0.2	0.0	0.2
S	2.5	0.8	0.8	2.8	1.0	0.0	0.3	0.4	1.0	0.0	0.6
Cl	ND ¹	0.0	0.0	0.6	0.2	0.0	0.2	0.1	0.1	0.0	0.2
K	2.0	0.0	0.0	0.2	0.3	0.2	5.3	0.0	0.2	1.9	0.0
Ca	53.0	79.2	79.2	78.8	66.7	43.8	7.1	71.9	74.0	1.7	61.6
Fe	4.4	0.0	0.0	0.2	10.0	10.2	7.0	0.9	2.0	4.6	5.2
Ba	ND	0.0	0.0	0.0	0.0	2.9	2.0	0.6	0.0	0.0	0.0
Ti	0.3	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.2	1.2	0.1
Total	99.9	99.8	99.8	100.0	100.0	100.0	100.0	99.8	100.1	100.0	99.9

¹ Not determined.

Table 16 (continued) (Figure 13)

SEM Point No.:	11	12	13	14	15	16	17	18	19
Description:	Layer	Neck	Fill	Fill	Fill	Fill	Layer	Fill	Fill
Normal O ₂ -Free Element, wt%									
Na	0.0	0.9	0.0	0.5	0.3	0.0	0.5	0.0	0.0
Mg	0.3	0.4	23.2	0.0	2.0	2.8	0.7	0.0	4.8
Al	0.2	0.0	24.4	2.0	9.4	2.1	1.8	0.4	9.5
Si	0.1	0.3	1.4	18.4	9.0	0.0	10.3	0.1	6.7
P	0.2	0.0	0.2	0.4	0.0	0.0	0.3	0.0	0.0
S	37.0	0.5	1.5	0.9	4.8	34.7	10.1	30.6	3.7
Cl	0.0	0.0	0.5	0.0	2.7	0.0	0.0	0.0	0.3
K	0.2	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.0
Ca	52.8	96.0	42.6	77.8	69.3	55.2	68.9	34.5	64.5
Fe	8.7	1.8	6.1	0.0	1.6	5.2	7.0	34.4	9.8
Ba	0.4	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
Ti	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.7
Total	99.9	99.9	100.0	100.0	100.0	100.0	99.9	100.0	100.0

Table 16 (continued) (Figure 14)

SEM Point No.:	20	21	22	23	24	25	26	27	28	29	30
Description:	?	Layer	Neck	Fill	Fill	Fill	Fill	Layer	Fill	?	Fill
Normal O ₂ -Free Element, wt%											
Na	0.0	0.4	0.0	0.0	1.5	0.2	0.1	0.5	0.0	0.1	1.5
Mg	0.6	2.6	3.7	0.3	3.8	0.0	0.4	5.5	0.8	0.0	1.4
Al	0.7	1.8	3.3	0.4	8.2	4.5	4.8	3.3	0.3	1.6	3.5
Si	12.7	12.8	8.0	0.2	18.2	10.9	9.8	7.1	0.0	3.3	19.0
P	0.2	0.7	0.3	0.1	0.2	0.0	0.2	0.6	0.3	0.0	0.2
S	11.8	7.3	8.5	0.4	0.2	12.1	9.4	6.2	1.5	1.2	0.5
Cl	0.2	1.2	0.1	0.4	0.0	0.1	0.2	3.2	0.9	0.4	0.0
K	0.0	0.2	0.2	0.4	0.2	0.0	0.4	0.1	0.2	0.0	0.0
Ca	73.2	70.5	63.8	96.5	28.9	71.7	68.4	58.9	95.6	92.2	56.5
Fe	0.6	2.6	11.9	1.2	34.3	0.4	6.5	14.5	0.0	0.0	3.5
Ba	0.0	0.0	0.4	0.0	4.1	0.0	0.0	0.0	0.4	0.0	1.3
Ti	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	1.2	12.6
Total	100.0	100.1	100.2	99.9	100.0	99.9	100.2	99.9	100.	100.0	100.0

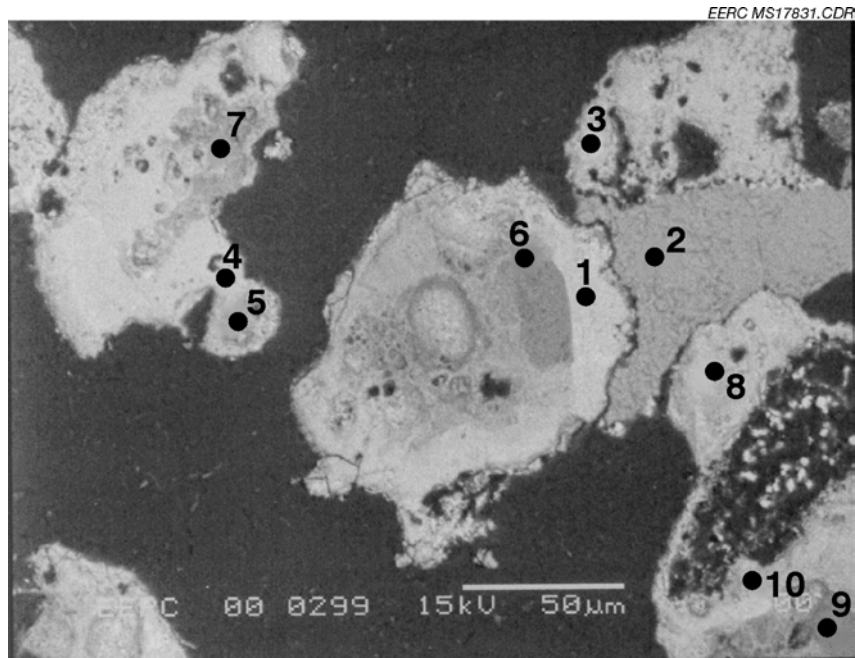


Figure 12. SEM micrograph of mixing zone deposit from Gasification Test P065 on North Dakota lignite coal showing Points 1–10.

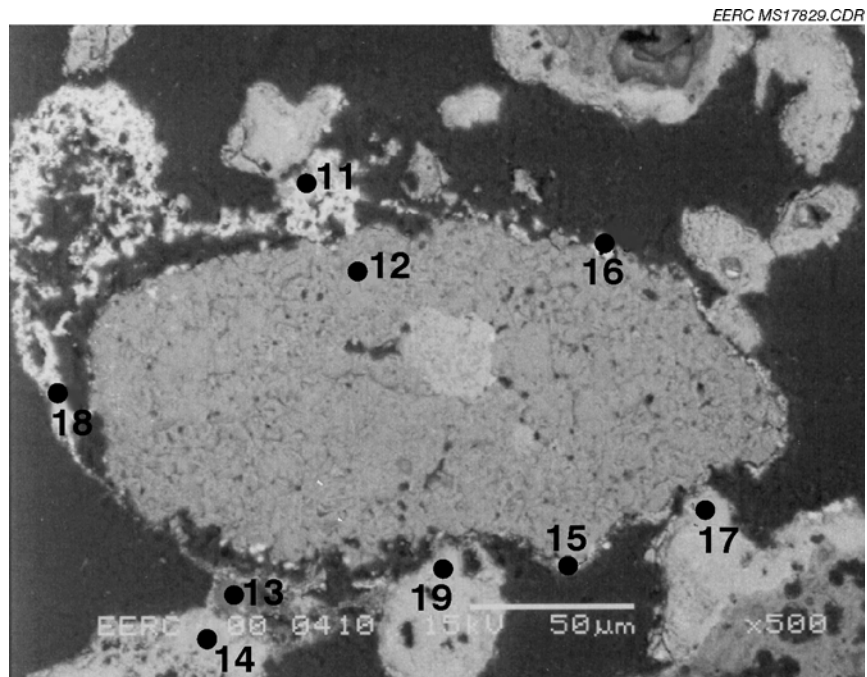


Figure 13. SEM micrograph of mixing zone deposit from Gasification Test P065 on North Dakota lignite coal showing Points 11–19.

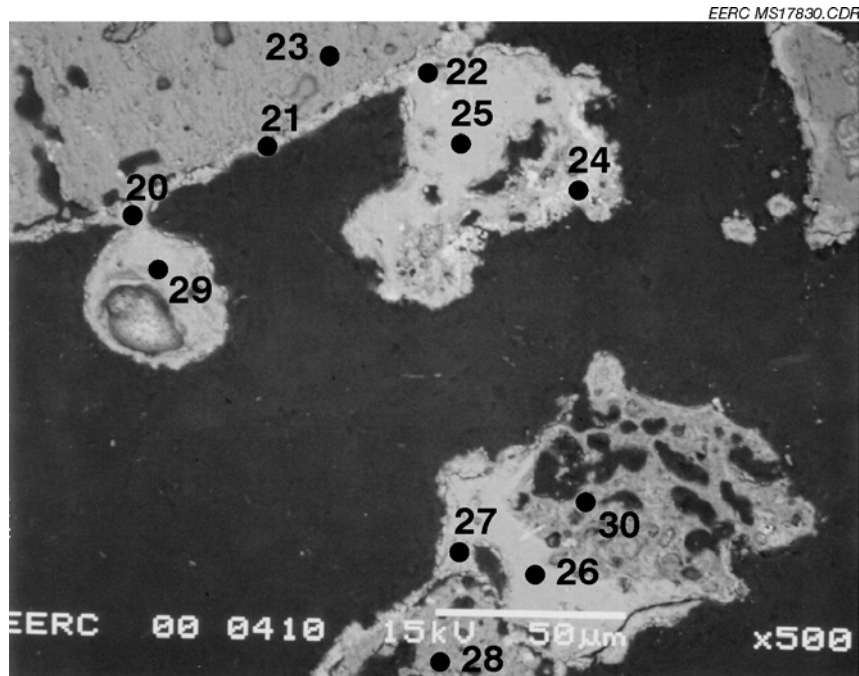


Figure 14. SEM micrograph of mixing zone deposit from Gasification Test P065 of North Dakota lignite coal showing Points 20–30.

Table 17. Operating Conditions for Air-Blown Tests P064 and P065 on the Hot-Gas Filter System

Operating Conditions	Center	Falkirk	Freedom
Inlet Gas Temperature, °C	450–500	450	500
Operating Pressure, psig	120	120	120
Volumetric Gas Flow, scfm	430	405	425
Number of Candles	14 (1 meter)	14	14
Candle Spacing, in. \varnothing to \varnothing	4	4	4
Filter Face Velocity, ft/min	4.2	3.9	4.0
Particulate Loading, inlet, ppm	<20,000	<15,000	<15,000
Particulate Loading, outlet, ppm	0.7	1.2	0.7
Temperature Drop Across HGFV, °C	26	26	27
Nitrogen Backpulse Pressure, psig	380	380	380
Backpulse Valve Open Duration, sec	$\frac{1}{2}$ and $\frac{3}{4}$	$\frac{1}{2}$ and $\frac{3}{4}$	$\frac{3}{4}$

Table 18. Operating Conditions for Oxygen-Blown Test P068 on the Hot-Gas Filter System

Operating Conditions	Center	Falkirk	Freedom
Inlet Gas Temperature, °C	425–452	450	400–450
Operating Pressure, psig	100	100	85–100
Volumetric Gas Flow, scfm	407–485	400–417	415–507
Number of Candles	14 (1 meter)	14	14
Candle Spacing, in. ⌀ to ⌀	4	4	4
Filter Face Velocity, ft/min	4.8 - 5.7	4.75	5.3–5.9
Particulate Loading, inlet, ppm	6000–18,000	<10,000	<10,000
Particulate Loading, outlet, ppm	1.0	1.0	1.0
Temperature Drop Across HGFV, °C	13–19	15	9–15
Nitrogen Backpulse Pressure, psig	360	360	360
Backpulse Valve Open Duration, sec	½	½	½

Similar to other tests, a rapid buildup of pressure drop across the filters results in a pulse frequency of about 8 to 10 minutes. The average particulate loading going into the HGFV was approximately 10,000 to 20,000 ppm, with a d_{50} of approximately 12 to 15 μm . The outlet loading was typically 1 ppm or less over the course of both tests. Carbon in the filter ash ranged from 35% to 50% depending on the operating conditions such as air/fuel ratio and also had a low bulk density of approximately 20 lb/ft^3 . The small size, the lack of the cohesiveness seen in other filter ashes, and the low density of the ash suggest that a high percentage of the filter cake is reentrained back onto the filters after they are backpulsed.

The filter ash is approximately the same size as the ash from the particulate samples indicating no agglomeration of filter ash on the surface of the candle filter. Figures 9 and 10 show the chemical composition of the major species of the filter ash collected throughout both test campaigns. In less than 24 hours after entering gasification, the filter ash is at steady-state with the coal ash/sorbent mixture and does not change with increasing operating time but will change with changing sorbent or coal ash chemistry. For instance, when the sorbent was changed from the PRD to the MLS, the magnesium content of the filter ash decreased. The sodium in these filter ashes also increased slightly with a change to the higher sodium lignites but did not increase to the levels in the coal ash. These ashes are comprised primarily of 35 to 45 wt% Ca, 15 to 25 wt% Si, and up to approximately 6 wt% Na with close to 10 wt% S in the filter ash. These results show that the majority of the sulfur is removed in the filter ash. Sulfur levels in the filter ash decreased significantly under oxygen-blown operation because of the decreased sulfur capture reported earlier.

Another concern about the utilization of calcium-based sorbents for sulfur control is the potential to form solid materials that are high in reactive calcium sulfides. Reactive sulfide in the standpipe LASH was analyzed to be less than 117 ppm and the filter ash was less than 5 ppm. The reactive sulfide concentrations were even less (<1.0 ppm) for oxygen-blown tests because of the sorbent's diminished capacity for sulfur at high steam and carbon dioxide partial pressures. Reactive

sulfide levels above 500 ppm are considered hazardous waste under the EPA reactivity category. Oxidation of these solid materials in a combustor to convert the CaS to CaSO₄ would be required in this case. Economic studies on the transport reactor always have assumed both a circulating fluid-bed gasifier and a combustor would be operated for utilizing the remaining fuel value from the gasifier solids. This “second-generation” combined cycle would also convert any reactive sulfide species to calcium sulfate, making the sulfur nonhazardous.

4.6 Task 5 – GE Combustion Turbine Modeling of a Lignite-Fired Transport Reactor Gasification Combined-Cycle Plant

Tables A-1 and A-2 are the gas turbine combustion modeling results generated by GE for a 6FA gas turbine operating on both air-blown and oxygen-blown fuel gas from a lignite-fired transport reactor gasifier. These results show that the fuel gas mixtures are combustible in a lean premix-type burner; however, the NO_x emissions due to the conversion of the fuel-bound nitrogen will be significantly higher than desired. From air-blown operation, the NO_x formed via the thermal formation mechanism is very low at less than 25 ppmv @ 15% O₂ (~ 0.023 lb/MMBtu of fuel gas), while the NO_x formed via the chemical conversion of nitrogen containing species such as ammonia and HCN is high at approximately 330 ppmv at 15% O₂ (~2.057 lb/MMBtu of fuel gas). For oxygen-blown operation, the NO_x formed via the thermal formation mechanism is also very low at less than 25 ppmv @ 15% O₂ (~ 0.012 lb/MMBtu of fuel gas) while the NO_x formed via the chemical conversion of nitrogen containing species such as ammonia and HCN is even higher at approximately 475 ppmv @ 15% O₂ (~2.597 lb/MMBtu of fuel gas). These calculations assume that 100% of the fuel-bound nitrogen is converted in the dry low-NO_x (DLN) burner. While no actual operating data were generated on the combustion of nitrogen-containing fuel gases in the Piñon Pine 6FA gas turbine, actual conversion rates were expected to be between 30% to 50% for this type of combustor. Correction of these NO_x emission rates to this level of NH₃ conversion to NO_x would result in actual NO_x emissions of 0.64 to 1.05 lb/MMBtu for air-blown operation and 0.80 to 1.32 lb/MMBtu for oxygen-blown operation. Utilization of cold-gas cleanup with a water scrubber would alleviate the ammonia conversion issue, since the water scrubbers can remove all of the ammonia. Installing SCR technology in the heat recovery steam generator (HRSG) and living with the ammonium bisulfate deposition in the HRSG that will occur with the reaction of the ammonia slip and the sulfur dioxide in the flue gas has been considered as an option. Cost of electricity increases on the order of 0.15¢/kWh have been projected for the use of SCR on a 150-MW gas turbine power plant.

The need still exists to investigate the potential for other technology to remove ammonia from the hot or warm fuel gas (without the need for cold-gas water scrubbers) by the use of ammonia decomposition catalysts such as nickel, ruthenium, or an iron-based catalyst investigated by other researchers (1–3) or by the use of rich-quench-lean (RQL)-type combustors which were being developed by various gas turbine manufacturers in the past (4, 5). However, these gas turbine manufacturers have not commercialized these combustors and are not currently pursuing their development.

4.7 Task 6 – Economic Assessment of a Natural Gas-Fired Combined-Cycle Power Plant in North Dakota

Great River Energy performed a study of a baseload natural gas-fired combined-cycle power plant located at a greenfield site in North Dakota. This plant was sized to have a net plant capacity of 443.5 MW using two GE 7FA combustion turbines and one steam turbine with a heat rate of 7151 Btu/kWh. The plant was assumed to have an 80% capacity factor with a project life of 30 years and a start-up date of January 2004. The turn-key project costs are \$239,000,000, with an additional \$10,000,000 for a natural gas line and connection assuming the plant is located within 10 miles of a major high-pressure gas line. Construction loan interest generated at 8% over 20 months adds an additional \$18,000,000 to give a total project installed cost of approximately \$267 million dollars, resulting in an installed total cost of \$602/kW. As a comparison, an average turn-key price of \$185.5 million for a S207FA combined-cycle plant has been given in the 2000–2001 Gas Turbine World Handbook. This plant has 2 Frame 7FA gas turbines with a single 196-MW three-pressure steam turbine system with reheat. This cost only includes the bare minimum and does not include extensive buildings (as would be required in North Dakota), spare equipment, and other indirect costs such as interest during construction, permitting, insurance, taxes, freight, overhead, and contingency funds. Given these extra costs, the \$267 million is probably accurate for a total installed cost estimate. Transmission line improvements are not included in the project cost but would be needed for any type of power plant installed in North Dakota.

Project economics were generated assuming an 80%/20% project debt-to-equity ratio with a 20-year note at 9% interest and a 20-year depreciation term. Fixed O&M costs were assumed to be \$5.50/kW-year and variable O&M costs were \$3.00/MWh. Natural gas was priced at \$3.00/MMBtu. Both the CPI and natural gas escalation rates were assumed to be 2.5%/year. Given these assumptions, an energy price of \$32.3/MWh breaks even over the 20-year debt repayment term and has a 8.9% return over the 30-year life of the project. This project would not have a positive cash flow until 2010 (or the seventh year of operation) and would not show a profit until 2015 (or the 12th year of operation). At a rate of \$35.6/MWh, the project has a 20% return on equity and would have a positive cash flow of over \$7 million in the very first year. The project would show a profit (including depreciation charges) after the third year of operation. These economics also showed that the fuel (natural gas) costs were 83% to 84.5% of the total plant operating costs. This demonstrates the significant economic risk natural gas-fired plants are susceptible to with volatile fuel prices.

5.0 CONCLUSIONS

The pilot-scale TRDU located at the EERC was successfully operated under both air-blown and oxygen-blown operating conditions on three different North Dakota lignite fuels. Significantly higher product gas heating values were achieved under oxygen-blown conditions when compared on a dry basis. However, when compared on a wet basis, the air-blown and oxygen-blown operation both provided a fuel gas of comparable heating value considering the significantly higher steam flows which must be injected to keep the process temperatures below ash melting temperatures. For strictly power production, air-blown operation makes more economic sense since the high capital and operating costs associated with an air separation unit (ASU) is not needed. If the plant also

wants to consider chemicals and fuels production, oxygen-blown operation is required in order to reduce the size of the subsequent unit operations. No problems with sodium-based bed material agglomeration and deposition were detected with these fuels even though some lignites were considered to be high-sodium fuels. Hot-gas filter operation and performance was excellent with no operating problems encountered with these fuels.

6.0 RECOMMENDATIONS

Before the construction of a commercial transport reactor should begin, a longer-duration proof-of-concept test on the selected lignite feedstock should be conducted on the larger-scale Power Systems Development Facility (PSDF) located at the Southern Company Services (SCS) facility in Wilsonville, Alabama. The economics of a transport reactor need to be determined especially in light of a potential requirement to install a selective catalytic reduction (SCR) unit in the heat recovery steam generator of the combined cycle for NO_x BACT (best available control technology) control.

7.0 REFERENCE

- 1 EERC. *Task 3.13 Hot-Gas Filter Testing, Final Report*; EERC: Grand Forks, ND, 98-EERC-10-12, Oct 1998; 93pp.

APPENDIX A
STATISTICAL DATA

UND.EERC AIR TRANSPORT

ESTIMATED PERFORMANCE. PG6101(FA) 60 Hz. (PRELIMINARY -FOR STUDY PURPOSES ONLY)

Load Condition

Ambient Temp. Deg f. 13. 42. 67.
Ambient Relative Humid. % 80.0 70.0 67.0
Output kW 79,990. 78,460. 73,790.
Heat Rate (LHV) Btu/kWh 9,550. 9,470. 9,560.
Heat Cons. (LHV) X 106 Btu/h 763.8 742.6 705.5
Exhaust Flow X 103 Ib/h 1794. 1753. 1666.
Exhaust Temp. Deg f. 1065. 1072. 1088.

EMISSIONS

THERMAL

NOx ppmvd @ 15% O2 <25 <25 <25
NOx as NO2 IblMMBtu 0.023 0.023 0.023

CHEMICAL

NOx ppmvd @ 15% O2 330 329 327
NOx as NO2 IblMMBtu 2.057 2.057 2.057

PRIMARY FUEL

Compositions: %Vol
CO 10.83 10.83 10.83
CO2 15.99 15.99 15.99
H2 17.86 17.86 17.86
H2O 9.99 9.99 9.99
N2 41.32 41.32 41.32
CH4 2.84 2.84 2.84
C2H6 0.18 0.18 0.18
C2H4 0.29 0.29 0.29
NH3 0.20 0.20 0.20
AR 0.44 0.44 0.44
H2S 0.06 0.06 0.06
LHV BTUllb 1815.9 1815.9 1815.9
Flow Rate Ib/h 420,610. 408,950. 388,490.
Pressure psia 375.0 375.0 375.0
Temperature of 550 550 550

AIR EXTRACTION

Flow Rate Iblh 210,300. 204,480. 194,250.
Pressure psia 198.8 194.2 184.4
Temperature of 725.1 750.7 780.7

EXHAUST ANALYSIS % VOL.

Argon 0.85 0.85 0.84
Nitrogen 70.94 70.70 70.17
Oxygen 9.99 9.98 9.87
Carbon Dioxide 8.44 8.39 8.36
Water 9.79 10.08 10.76

SITE CONDITIONS

Elevation ft. 1940.0
Site Pressure psia 13.71
Inlet Loss in Water 3.5
Exhaust Loss in Water 15.0
Application 7 A6 Air-Cooled Generator
Combustion System IGCC Combustor

Emission information based on GE recommended measurement methods. NOx emissions are corrected to 15% O2 without heat rate correction and are not corrected to ISO reference condition per 40CFR 60.335(c)(I). NOx levels shown will be controlled by algorithms within the SPEEDTRONIC control system. Note that machine development will be required. Information above is contingent upon successful development of air extraction, fuel, & combustion system.

IPS- versioncode- 2.5.5 OptN 61010898
BERRYJI 0111810212:58 UNDEERC AirTransport.dat

UND.EERC OXYGEN TRANSPORT

ESTIMATED PERFORMANCE. PG6101(FA) 60 Hz. (PRELIMINARY -FOR STUDY PURPOSES ONLY)

Load Condition

Ambient Temp. Degf. !3. 42. 67.
Ambient Relative Humid. % 80.0 70.0 67.0
Output kW 77,340. 73,220. 68,090.
Heat Rate (LHV) Btu/kWh 9,870. 9,920. !0,!20.
Heat Cons. (LHV) X 106 Btu/h 763.2 726.2 688.8
Exhaust Flow X 103 Ib/h !733. !646. !565.
Exhaust Temp. Degf. !067. !087. !!06.

EMISSIONS

THERMAL

NOx ppmvd @ !5% O2 <25 <25 <25
NOx as NO2 !b/MMBtu 0.0!3 0.0!2 0.0!0

CHEMICAL

NOx ppmvd @ !5% O2 477 475 473
NOx as N~ Ib/MMBtu 2.597 2.597 2.597

PRIMARY FUEL

Compositions: %Vol
CO 8.!4 8.!4 8.!4
CO2 23.35 23.35 23.35
H2 23.00 23.00 23.00
H2O 39.90 39.90 39.90
N2 1.06 !.06 !.06
CH4 3.36 3.36 3.36
C2H6 0.36 0.36 0.36
C2H4 0.!2 0.!2 0.!2
NH3 0.28 0.28 0.28
AR 0.03 0.03 0.03
H2S 0.40 0.40 0.40
LHV BTU/lb 23!9.4 23!9.4 23!9.4
Flow Rate Ib/h 329,050. 3!3,!!0. 296,960.
Pressure psia 375.0 375.0 375.0
Temperature of 550 550 550

AIR EXTRACTION

Flow Rate Ib/h 224,740. 2!3,860. 202,820.
Pressure psi a 192.8 !83.0 !73.6
Temperature of 699.8 73!.7 762.7

EXHAUST ANALYSIS % VOL.

Argon 0.84 0.84 0.83
Nitrogen 6!.75 6!.47 60.98
Oxygen !0.30 !0.22 !0.!3
Carbon Dioxide 8.99 8.99 8.94
Water !8.!2 !8.49 !9.!3

SITE CONDITIONS

Elevation ft. !940.0
Site Pressure psi a !3.7!
!n!et Loss in Water 3.5
Exhaust Loss in Water !5.0
Application 7 A6 Air-Cooled Generator
Combustion System !GCC Combustor
Emission information based on GE recommended measurement methods. NOx emissions are corrected to !5% O2 without heat rate correction and are not corrected to !SO reference condition per 40CFR 60.335(c)(I). NOx levels shown will be controlled by algorithms within the SPEEDTRONIC control system.
Note that machine development will be required. Information above is contingent upon successful development of air extraction, fuel, & combustion system.
IPS- version code- 2.5.5 Opt: N 6!0!0898

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