# ADVANCED HIGH-TEMPERATURE, HIGH-PRESSURE TRANSPORT REACTOR GASIFICATION

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# ADVANCED HIGH-TEMPERATURE, HIGH-PRESSURE TRANSPORT REACTOR GASIFICATION


## ABSTRACT

The U.S. Department of Energy (DOE) National Energy Technology Laboratory Office of Coal and Environmental Systems has as its mission to develop advanced gasification-based technologies for affordable, efficient, zero-emission power generation. These advanced power systems, which are expected to produce near-zero pollutants, are an integral part of DOE's Vision 21 Program. DOE has also been developing advanced gasification systems that lower the capital and operating costs of producing syngas for chemical production. A transport reactor has shown potential to be a low-cost syngas producer compared to other gasification systems since its high-throughput-per-unit cross-sectional area reduces capital costs. This work directly supports the Power Systems Development Facility utilizing the KBR transport reactor located at the Southern Company Services Wilsonville, Alabama, site.

Over 2800 hours of operation on 11 different coals ranging from bituminous to lignite along with a petroleum coke has been completed to date in the pilot-scale transport reactor development unit (TRDU) at the Energy & Environmental Research Center (EERC). The EERC has established an extensive database on the operation of these various fuels in both air-blown and oxygen-blown modes utilizing a pilot-scale transport reactor gasifier. This database has been useful in determining the effectiveness of design changes on an advanced transport reactor gasifier and for determining the performance of various feedstocks in a transport reactor.

The effects of different fuel types on both gasifier performance and the operation of the hot-gas filter system have been determined. It has been demonstrated that corrected fuel gas heating values ranging from 90 to 130 Btu/scf have been achieved in air-blown mode, while heating values up to 230 Btu/scf on a dry basis have been achieved in oxygen-blown mode. Carbon conversions up to 95% have also been obtained and are highly dependent on the oxygen–coal ratio. Higher-reactivity (low-rank) coals appear to perform better in a transport reactor than the less reactive bituminous coals. Factors that affect TRDU product gas quality appear to be coal type, temperature, and air/coal ratios.

Testing with a higher-ash, high-moisture, low-rank coal from the Red Hills Mine of the Mississippi Lignite Mining Company has recently been completed. Testing with the lignite coal generated a fuel gas with acceptable heating value and a high carbon conversion, although some drying of the high-moisture lignite was required before coal-feeding problems were resolved. No ash deposition or bed material agglomeration issues were encountered with this fuel.

In order to better understand the coal devolatilization and cracking chemistry occurring in the riser of the transport reactor, gas and solid sampling directly from the riser and the filter outlet has been accomplished. This was done using a baseline Powder River Basin subbituminous coal from the Peabody Energy North Antelope Rochelle Mine near Gillette, Wyoming.

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

# ADVANCED HIGH-TEMPERATURE, HIGH-PRESSURE TRANSPORT REACTOR GASIFICATION

## EXECUTIVE SUMMARY

A transport reactor has shown potential to be a low-cost syngas producer compared to other gasification systems since its high-throughput-per-unit cross-sectional area reduces capital costs. The goal of the advanced high-temperature, high-pressure transport gasification program at the Energy & Environmental Research Center is to demonstrate acceptable hydrodynamic and gasification performance of the transport reactor development unit (TRDU) under a variety of operating conditions and using a wide range of fuels.

Current objectives are focused on understanding and improving the operation of the transport reactor gasifier itself under both air-blown and oxygen-blown conditions. Also, in order to better understand the coal devolatilization and cracking chemistry occurring in the riser of a transport gasifier, gas and solid sampling directly from the riser and the filter outlet has been accomplished. A secondary objective of the program is to demonstrate acceptable performance of hot-gas filter elements on the hot, dust-laden fuel gas stream coming from the pilot-scale system prior to long-term demonstration tests. In order to extend the database of fuels tested, two types of coal were obtained and tested: a lignite from the Red Hills Mine near Ackerman, Mississippi, and a baseline Powder River Basin (PRB) subbituminous coal from the Peabody Energy North Antelope Rochelle Mine near Gillette, Wyoming.

Testing with the higher-ash, high-moisture, low-rank Mississippi lignite coal resulted in a fuel gas with a heating value ranging from 83–130 Btu/scf in air-blown mode, which would be considered more than acceptable to operate a gas turbine. A corrected heating value of up to 230 Btu/scf was achieved in oxygen-blown mode. Carbon conversions were high, ranging from 88%–98%. Operation of the hot-gas filter vessel presented no issues for the integrated system even with the high ash loading to the filter system, and no bed material agglomeration or ash deposition problems were encountered.

Proximate–ultimate analysis of the solid char samples shows that the amount of volatile matter in the mixing zone char was relatively low, with a significantly higher amount of volatile matter still remaining in the char in the lower riser and midriser; however, the amount of volatile matter had dropped considerably by the top of the riser and especially in the filter ash. The gas analysis from the riser during the oxygen-blown testing shows that at the lower riser and midriser locations the amount of hydrogen, carbon monoxide, and methane in the fuel was less than half of the final gas composition shown at the filter outlet gas composition. The amount of organics recovered from the water sample collected from the top of the riser during air-blown testing was more consistent with the lower amount of organics recovered from the mixing zone. Benzene concentrations were mostly measured in the range from 2000 to 5000 ppmv, while total aromatics were estimated to range from 20,000 to 25,000 ppmv. Gas and solid sampling from the riser during the Mississippi lignite tests indicated that little coal devolatilization and tar cracking were observed in the transport reactor mixing zone and lower riser and that most of the syngas was formed by tar cracking in the upper riser and cyclones.

Since the primary objective of the PRB testing was to better understand coal devolatilization and cracking chemistry occurring in the riser of the TRDU, the number of test conditions was kept to a minimum, with all tests performed in air-blown mode. There were three test conditions, transport air with a mix zone temperature of 900°C, transport air with a mix zone temperature of 925°C, and transport nitrogen with a mix zone temperature of 900°C. The coal resulted in a syngas with corrected heating values that were above 125 Btu/scf and carbon conversions greater than 93% for all conditions tested.

Proximate–ultimate analysis of the solid char samples shows that volatiles are fairly low (~10%) for the entire length of the riser but double in the filter vessel. In the mixing zone, lower riser, and midriser samples, volatiles were fairly consistent for all three test conditions.

Condensates show a general trend of very low total organic carbon (OC) in the mix zone (~100 mg/$m^3$), a significant increase in the lower riser (~400–700 mg/$m^3$), a steady decrease with increased riser height, and total OC in the filter vessel similar to that in the mixing zone.

Aliphatics and aromatics were determined with a Fourier transform infrared (FT–IR) cell. FT–IR analysis shows that aliphatics were 5000–30,000 ppm in the mix zone, 30,000–110,000 ppm in the lower and midriser, 35,000–40,000 ppm in the top riser, and approximately 40,000 ppm in the filter. Aromatics ranged from 2000 to 17,000 ppm in the mix zone, 7000 to 18,000 ppm in the lower riser, 5000 to 9000 ppm in the midriser, 8000 to 35,000 ppm in the top riser, and 12,000 to 20,000 ppm in the filter vessel.

Gas chromatography analysis of gas samples shows that hydrogen varied from 2% to 5% in the mix zone, 6% to 8% in the lower riser, 9% to 12% in the mid- and top risers, and 8% to 10% in the filter vessel. Carbon monoxide ranged from 2% to 5% in the mix zone, 3% to 6% in the lower and midriser, 6% to 7% in the top riser and 7% to 9% in the filter vessel. Methane was about 1% in the mix zone, 2.5%–3% in the lower riser, 2.5%–4% in the midriser, 2%–3.5% in the top riser, and 1.5%–2% in the filter vessel.

Overall, gas and solid sampling from the riser and filter during PRB testing revealed that the volatile matter, OC, aliphatics, and methane seemed to reach peaks in the mid- to upper riser and start to fall off by the time they get to the filter outlet, while the hydrogen and carbon monoxide are continually increasing through the TRDU riser and filter outlet.

# ADVANCED HIGH-TEMPERATURE, HIGH-PRESSURE TRANSPORT REACTOR GASIFICATION

## INTRODUCTION

The objective of the advanced high-temperature, high-pressure transport reactor gasification program at the Energy & Environmental Research Center (EERC) is to demonstrate the successful operation of a transport reactor on a wide variety of fuels. In order to extend the database of fuels tested, two types of coal were obtained and tested: a lignite from the Red Hills Mine near Ackerman, Mississippi, and a baseline Powder River Basin (PRB) subbituminous coal from the Peabody Energy North Antelope Rochelle Mine near Gillette, Wyoming. The lignite coal was tested in a cooperative effort between the EERC, the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), and the North American Coal Corporation. The PRB subbituminous coal was tested in cooperation with DOE NETL and Siemens Power Inc.

The goal of the advanced high-temperature, high-pressure transport gasification program at the EERC is to demonstrate acceptable hydrodynamic and gasification performance of the transport reactor development unit (TRDU) under a variety of operating conditions and using a wide range of fuels. Current objectives are focused on understanding and improving the operation of the transport reactor gasifier itself under both air-blown and oxygen-blown conditions. Recently, in order to better understand the coal devolatilization and cracking chemistry occurring in the riser of a transport, gas and solid sampling directly from the riser and the filter outlet has been accomplished. A secondary objective of the program is to demonstrate acceptable performance of hot-gas filter elements on the hot, dust-laden fuel gas stream coming from the pilot-scale system prior to long-term demonstration tests.

## PROJECT DESCRIPTION

The pilot-scale TRDU has an exit gas temperature of up to 980°C (1800°F), a gas flow rate of 325 scfm (0.153 $m^3/s$), and an operating pressure of 120 psig (9.3 bar). 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, and a primary cyclone and standpipe. The standpipe is connected to the mixing section of the riser by an L-valve transfer line. All of the components in the system are refractory-lined and designed mechanically for 150 psig (11.4 bar) and an internal temperature of 1090°C (2000°F). Detailed design criteria and a comparison to actual operating conditions on the design coal are given in Table 1.

The premixed coal and limestone feed to the transport reactor can be admitted through three 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 only one nozzle at a time.

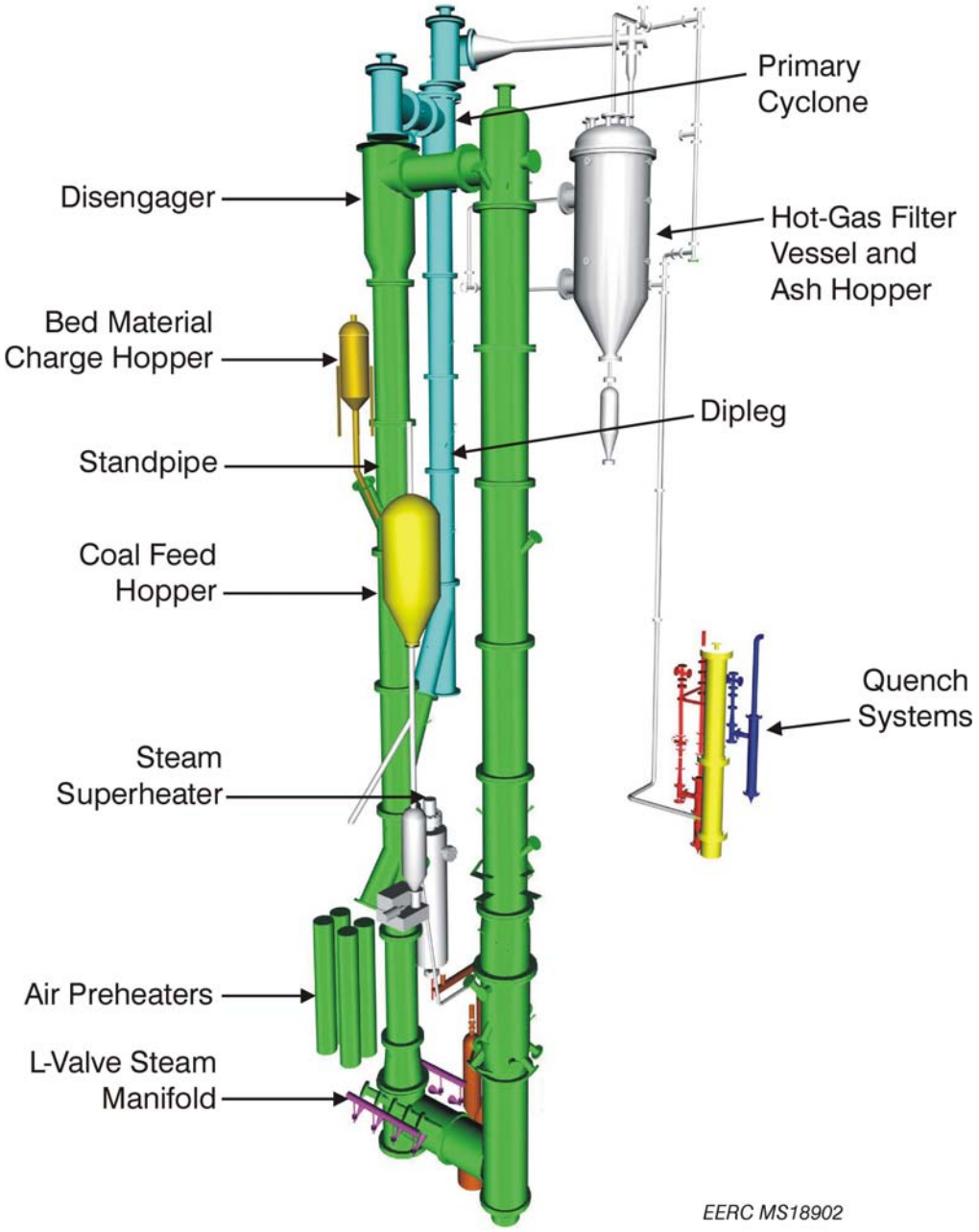


Figure 1. TRDU and hot-gas filter vessel (HGFV) in EERC gasification tower.

**Table 1. Summary of TRDU Design and Operation on the Design Coal**

| Parameter | Design[1] | Actual |
|---|---|---|
| Coal | Illinois No. 6 | Illinois No. 6 |
| Moisture Content, % | 5 | 8.5 |
| Pressure, psig | 150 (11.3 bar) | 120 (9.3 bar) |
| Steam/Coal Ratio | 0.34 | 0.34 |
| Air/Coal Ratio | 4 | 2.3 |
| Ca/S Ratio, moles | 1.5 | 2 |
| Air Inlet Temperature, °C | 427 | 180 |
| Steam Preheat, °C | 537 | 350 |
| Coal Feed Rate, lb/hr | 198 (89.9 kg/hr) | 220 (99.9 kg/hr) |
| Gasifier Temperature, maximum °C | 1010 | 950 |
| ΔT, maximum °C | 17 | 60 to 100 |
| Carbon Conversion,[2] % | > 80 | 76.5 |
| HHV[3] of Fuel Gas, Btu/scf (cor.[4]) | 100 | 110 |
| Heat Loss as Coal Feed, % | 19.5 | 13[5] |
| Heat Loss, Btu/hr | 252,000 | 450,000[5] |

[1] Kellogg, Brown, and Root (KBR) design specifications.
[2] Carbon conversion = (wt carbon feed − wt carbon removed)/wt carbon feed × 100.
[3] Higher heating value.
[4] Corrected.
[5] Higher coal feed rate and lower air and steam preheat resulted in lower percent heat loss but higher net heat loss.

The coal feed is measured by a revolutions-per-minute (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 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 fluffing gas in the standpipe, L-valve aeration flows, and 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, and cyclones. The data acquisition and control system scans the data points every 0.5 s and saves the process data every 30 s. 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. Solids from the primary cyclone were collected in a lock hopper for earlier tests. In later tests, the dip leg solids were recirculated back to the standpipe through the dip leg crossover. Gas exiting this cyclone enters a

series of jacketed-pipe heat exchangers before entering the HGFV. The cleaned gases leaving the HGFV are depressurized and combusted in a thermal oxidizer. Heat and material balance data from around the thermal oxidizer provide an additional measure of carbon conversion and sulfur removal. Even with the large amount of nitrogen purges and relatively high heat losses, the fuel gas from the TRDU is of generally sufficient quality to sustain combustion in the thermal oxidizer without the requirement of supplemental fuel.

**HGFV**

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. i.d. (121.9 cm) and 185 in. (470 cm) long and is designed to handle gas flows of approximately 325 scfm at temperatures up to 815°C (1500°F) and pressures of 120 psig (8.3 bar). The refractory has a 28-in. (71.1-cm) i.d. with a shroud diameter of approximately 22 in. (55.9 cm). The vessel is sized such that it could handle candle filters up to 2.0 m long; however, 1.5-m iron aluminide metal candle filters were utilized in these reported gasification tests. Candle filters are 2.375 in. (6 cm) o.d. with a 4-in. (10.2-cm) center line-to-center line spacing. The filter design criteria are summarized in Table 2. A schematic of the filter system is shown in Figure 2.

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 2.0 ft/min to be tested using 1.5-m candles. Higher face velocities are achieved by using fewer candles. The majority of testing has been performed at a face velocity of approximately 4.0 to 4.5 ft/min. These recent tests have utilized the Pall iron aluminide metal candle filters exclusively.

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

**Table 2. Design Criteria and Actual Operating Conditions for the Pilot-Scale HGFV**

| Operating Conditions | Design | Actual |
|---|---|---|
| Inlet Gas Temperature | 540°C | 450°–580°C |
| Operating Pressure | 150 psig (10.3 bar) | 120 psig (8.3 bar) |
| Volumetric Gas Flow | 325 scfm (0.153 $m^3$/s) | 350 scfm (0.165 $m^3$/s) |
| Number of Candles | 19 (1 or 1.5 m) | 13 (1 m) |
| Candle Spacing | 4 in. ℄ to ℄ (10.2 cm) | 4 in. ℄ to ℄ (10.2 cm) |
| Filter Face Velocity | 2.5–10 ft/min, (1.3 to 2.3 cm/s) | 4.5 ft/min, (2.3 cm/s) |
| Particulate Loading | <10,000 ppmw | <38,000 ppmw |
| Temperature Drop Across HGFV | <30°C | 25°C |
| Nitrogen Backpulse System Pressure | up to 600 psig (42 bar) | 250 to 350 psig (17 to 24 bar) |
| Backpulse Valve Open Duration | up to 1 s | ¼ s |

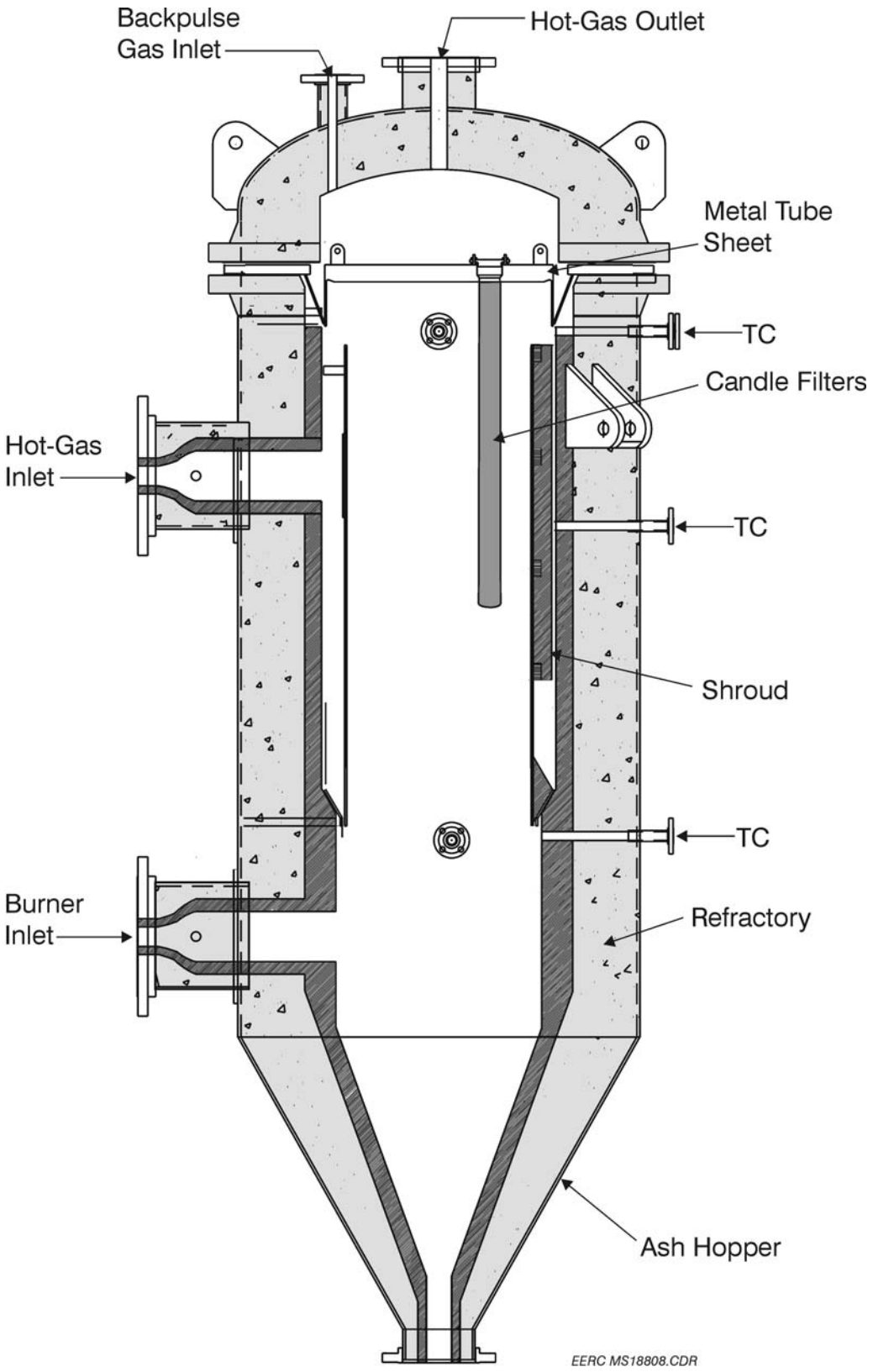


Figure 2. Schematic of filter vessel design with internal refractory, tube sheet, and shroud.

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 are controlled by regulating the pressure (up to 600 psig [42 bar]) of the nitrogen reservoir and controlling the solenoid valve pulse duration. Figure 1 also shows the filter vessel location and process piping in the EERC gasifier tower. Lower operating filter temperatures around 260°C (500°F) were tested utilizing recent modifications that added extra heat exchange surface in order to operate the filter vessel at these lower temperatures. The desire to filter the syngas at lower temperatures is being driven by the desire to remove trace metals such as Hg, As, Se, and Cd at elevated temperatures to leave the syngas moisutre in the gas stream; however, no sorbent system has been successfully demonstrated above 205° to 300°C (400° to 600°F). Most of the previous filter tests were completed in the 425°–650°C (800°–1200°F) range. Ports for obtaining hot, high-pressure particulate and trace metal samples both upstream and downstream of the filter vessel are part of the filter system piping.

## ACCOMPLISHMENTS

### TRDU Fuel Analysis

Three samples of Mississippi lignite from the Red Hills Mine of the Mississippi Lignite Mining Company were analyzed. These were as-received after drying to less than 35% moisture and after drying in the Great River Energy (GRE) low-temperature coal-drying facility to approximately 24% moisture. The Mississippi lignite was tested both with and without limestone that was supplied from the Red Hills continuous fluidized-bed (CFB) Power Plant in Ackerman, Mississippi. The PRB subbituminous coal, which is similar to other PRB coals frequently tested in the TRDU, was sized to −10 mesh (2000 μm) and mixed with 3 wt% Plum Run dolomite. Table 3 shows the proximate, ultimate, HHV, and x-ray fluorescence (XRF) analyses of the coals tested. Table 4 shows the XRF analyses of the Red Hills limestone and the Plum Run dolomite. The calcium-based sorbents were mixed with the respective coals to provide a Ca/S ratio of approximately 1.5 on a sorbent-only basis for the fuels being gasified (~4 wt% for the Mississippi lignites).

### TRDU Operation

A total of 27 successful test campaigns have been completed to date, with approximately 2850 hours of operation in gasification on several different fuels (1, 2). These fuels have ranged from less reactive bituminous coals and petcoke to the more reactive subbituminous and lignite coals. Operating temperatures have been varied from 815° to 1050°C (1500° to 1900°F), depending on the fuel reactivity and the fuel ashes' propensity to agglomerate. As shown in Table 5, the Mississippi lignite is considered a lignitic B coal under the ASTM International coal classification scheme. The TRDU has been operated in both air- and oxygen-blown mode on these low-rank coals.

**Table 3. Proximate, Ultimate, HHV, and XRF Analysis Results for Coals Tested**

| | Mississippi Lignite Coal[1] | −10-mesh Partially Dried MS Lignite Coal | −10-mesh GRE-Dried Lignite Coal | As-Received PRB Coal |
|---|---|---|---|---|
| Proximate Analysis, as run, wt% | | | | |
| Moisture | 42.6 | 34.7 | 23.7 | 23.40 |
| Volatile Matter | 23.0 | 23.9 | 30.0 | 33.82 |
| Fixed Carbon | 21.4 | 24.4 | 23.6 | 37.28 |
| Ash | 17.1 | 17.0 | 22.7 | 5.49 |
| Ultimate Analysis, MF,[2] wt% | | | | |
| Carbon | 49.35 | 52.54 | 49.42 | 51.71 |
| Hydrogen | 3.91 | 4.15 | 3.94 | 6.18 |
| Nitrogen | 1.21 | 1.26 | 1.18 | 0.90 |
| Sulfur | 0.79 | 0.88 | 0.96 | 0.24 |
| Oxygen | 14.98 | 15.09 | 14.69 | 35.47 |
| Ash | 29.76 | 26.08 | 29.81 | 5.49 |
| Ash Composition, % as oxides | | | | |
| Calcium, CaO | 11.1 | 14.2 | 15.7 | 29.7 |
| Magnesium, MgO | 3.2 | 3.3 | 3.2 | 10.10 |
| Sodium, $Na_2O$ | 0.3 | 0.3 | 0.4 | 1.43 |
| Silica, $SiO_2$ | 50.1 | 47.2 | 47.3 | 22.50 |
| Aluminum, $Al_2O_3$ | 20.0 | 19.2 | 17.9 | 13.80 |
| Ferric, $Fe_2O_3$ | 5.4 | 5.6 | 4.8 | 8.41 |
| Titanium, $TiO_2$ | 1.2 | 1.2 | 1.2 | 1.24 |
| Phosphorus, $P_2O_5$ | 0.1 | 0.1 | 0.1 | 0.96 |
| Potassium, $K_2O$ | 1.1 | 0.9 | 1.0 | 0.41 |
| Sulfur, $SO_3$ | 7.6 | 8.0 | 8.4 | 11.40 |
| High Heating Value | | | | |
| MF, Btu/lb | 8089 | 8609 | 8140 | N/A |
| As-Received, Btu/lb | 4646 | 5620 | 6207 | 8770 |

[1] As-received.
[2] Moisture-free.

**Table 4. XRF Analyses of Red Hills Limestone and Plum Run Dolomite**

| | −35-mesh Red Hills Limestone | −35-mesh Plum Run Dolomite |
|---|---|---|
| Sorbent Composition, % as oxides | | |
| Calcium, CaO | 59.0 | 66.6 |
| Magnesium, MgO | 1.2 | 27.5 |
| Sodium, $Na_2O$ | 0.6 | 0.3 |
| Silicon, $SiO_2$ | 23.7 | 2.7 |
| Aluminum, $Al_2O_3$ | 10.8 | 1.0 |
| Ferric, $Fe_2O_3$ | 3.1 | 1.3 |
| Titanium, $TiO_2$ | 0.4 | 0.0 |
| Phosphorus, $P_2O_5$ | 0.2 | 0.0 |
| Potassium, $K_2O$ | 1.0 | 0.3 |
| Sulfur, $SO_3$ | 0.0 | 0.4 |
| Loss on Ignition, as run | 34.8 | 43.1 |

**Table 5. ASTM International Coal Classification Criteria**

| Class | Group | Fixed Carbon[1] | Volatile Matter[1] | Heating Value[2] |
|---|---|---|---|---|
| Anthracitic | Metaanthracite | >98 | <2 | |
| | Anthracite | 92–98 | 2–8 | |
| | Semianthracite | 86–92 | 8–14 | |
| Bituminous | Low-volatile | 78–86 | 14–22 | |
| | Medium-volatile | 69–86 | 22–31 | |
| | High-volatile A | <69 | >31 | >14,000 |
| | High-volatile B | | | 13,000–14,000 |
| | High-volatile C | | | 10,500–13,000 |
| Subbituminous | Subbituminous A | | | 10,500–11,500 |
| | Subbituminous B | | | 9500–10,5000 |
| | Subbituminous C | | | 8300–9500 |
| Lignitic | Lignite A | | | 6300–8300 |
| | Lignite B | | | <6300 |

Note: This classification system is based on ASTM Standard D 388–66, which is published annually by ASTM International in its compilation of standards.

[1] The fixed carbon and volatile matter, reported as percentages, are determined on a dry, mineral-matter-free basis. The mineral matter is calculated from the ash content by the Parr formula: mineral matter = 1.08(percent ash + 0.55[percent sulfur]).

[2] Calculated on mineral-matter-free coal with bed moisture content.

Since the primary purpose of TRDU testing with the PRB coal was to perform gas and particulate sampling in the riser and filter vessel, the number of different test conditions was kept to a minimum. All tests were performed in air-blown mode. Essentially, three different sets of conditions were used for the entire run. Initial testing was performed using nitrogen as the transport gas to convey the fuel feed from the auger to the mixing zone. The second test condition utilized air as the transport gas; finally, the mixing zone temperature was increased while still using air as the fuel transport gas. In addition, since there was an interest in trying to observe the devolatilization of the coal during the transition from combustion mode to gasification, the TRDU was brought into combustion mode three times, and sampling from the mixing zone was conducted while the TRDU was transitioned back into gasification mode. The average operating conditions for each of these steady-state test conditions are shown in Table 6. Table 7 summarizes the range of operating conditions and results achieved for the Mississippi lignite coal.

In general, operation on the more reactive low-rank western coals has displayed higher carbon conversions and product gas heating values even when operating at lower reactor temperatures than comparable bituminous coal tests. Figure 3 summarizes previous testing on the effect of the oxygen to moisture- and ash-free (maf) coal ratio on carbon conversion and the corrected dry product gas heating value obtained under oxygen-blown conditions for the various ranks of coals. As can be seen, the more reactive lower-rank fuels had higher carbon conversions at similar corrected dry product gas heating values than the higher-rank bituminous coals. The

**Table 6. TRDU Operating Data/Gas Compositions and Corrected Compositions for PRB Testing**

| Test | 1 | 2 | 3 |
|---|---|---|---|
| Transport Gas | $N_2$ | Air | Air |
| Gasifier Temperature, °C | 901 | 898 | 925 |
| Coal/Sorbent Feed Rate | 338 | 355 | 375 |
| Air Flow, lb/hr | 1160 | 1035 | 1115 |
| Steam Flow, lb/hr | 120 | 120 | 120 |
| Steam:maf Coal, lb/lb | 0.49 | 0.46 | 0.44 |
| $O_2$:maf Coal, lb/lb | 0.99 | 0.84 | 0.86 |
| Carbon Conversion (solids) | 93.3 | 93.4 | 93.7 |
| TRDU Product Gas Composition, vol% | | | |
| $H_2$ | 6 | 8.2 | 7.6 |
| CO | 6.1 | 8.5 | 7.9 |
| $CH_4$ | 2.2 | 1.6 | 1.6 |
| $CO_2$ | 11.2 | 12.9 | 12.9 |
| $N_2$ | 75.1 | 68.9 | 68.2 |
| Total | 100.6 | 100.1 | 98.2 |
| Heating Value, Btu/scf | 61 | 70 | 66 |
| $N_2$-Free Heating Value, Btu/scf | 92 | 98 | 90 |
| Dry Gas, No Theoretical Heat Losses, vol% | | | |
| $H_2$ | 13.7 | 16.2 | 14.3 |
| CO | 13.9 | 16.8 | 14.9 |
| $CH_4$ | 5.0 | 3.2 | 3.0 |
| $CO_2$ | 16.1 | 17.2 | 17.1 |
| $N_2$ | 51.2 | 46.6 | 50.7 |
| Total | 100.0 | 100.0 | 100.0 |
| Heating Value, Btu/scf | 140 | 139 | 125 |

bituminous coals were operated at higher oxygen/maf coal ratios than the lower-rank coals since they typically were operated at higher reactor temperatures in an effort to achieve the same level of steam gasification. For all fuels, carbon conversion increased, and corrected dry product gas heating value decreased with an increasing oxygen/maf coal ratio.

Oxygen-blown operation requires the addition of considerable excess steam to maintain the reactor temperatures below the temperature where ash deposition and agglomeration of the circulating ash material become a problem. Figure 4 is a plot of both the corrected dry and wet product gas heating values and carbon conversion for the lignite coals tested under both air and oxygen-blown conditions. Carbon conversion seems to be primarily dependent on the ratio of the weight of oxygen fed to the weight of the maf coal fed regardless of what form the oxygen was fed (air versus oxygen). The higher $O_2$/maf coal ratio for Mississippi lignite as compared to the previously tested North Dakota lignite was primarily due to the higher operating temperature on the TRDU since potential ash agglomeration problems did not limit the temperature of operation.

**Table 7. Operating Conditions for Mississippi Lignite Testing**

| Coal Name: | Mississippi |
|---|---|
| Coal Type: | Lignite |
| Moisture Content, % | 25.2–40 |
| Pressure, psig | 120 |
| Steam:maf Coal Ratio | 0.47–0.67 |
| $O_2$:maf Coal Ratio | 0.85–1.36 |
| Ca:S Ratio, mole (sorbent only) | 1.5 |
| Coal and Sorbent Feed Rate, lb/hr | 417–509 |
| Av. Mixing Zone Temp., °C | 787–858 |
| HHV of Fuel Gas, act., Btu/scf | 35–50 |
| HHV of Fuel Gas, cor., Btu/scf | 83–130 |
| Conversion, % | 87.8–97.7 |
| Carbon in Bed, %, standpipe | 0.3–2.0 |
| Total Operating Hours | 202 |

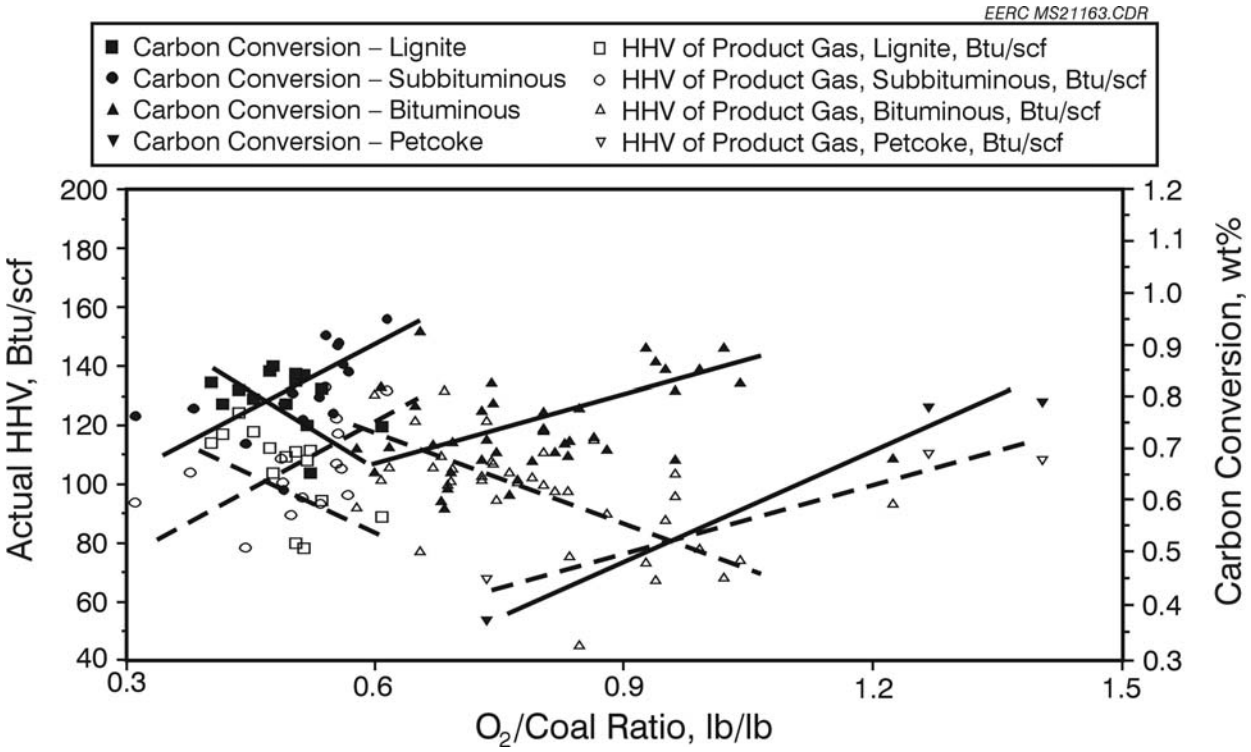


Figure 3. Comparison of carbon conversion and fuel gas heating values as a function of $O_2$/coal ratio for various coal types under air-blown operating conditions.

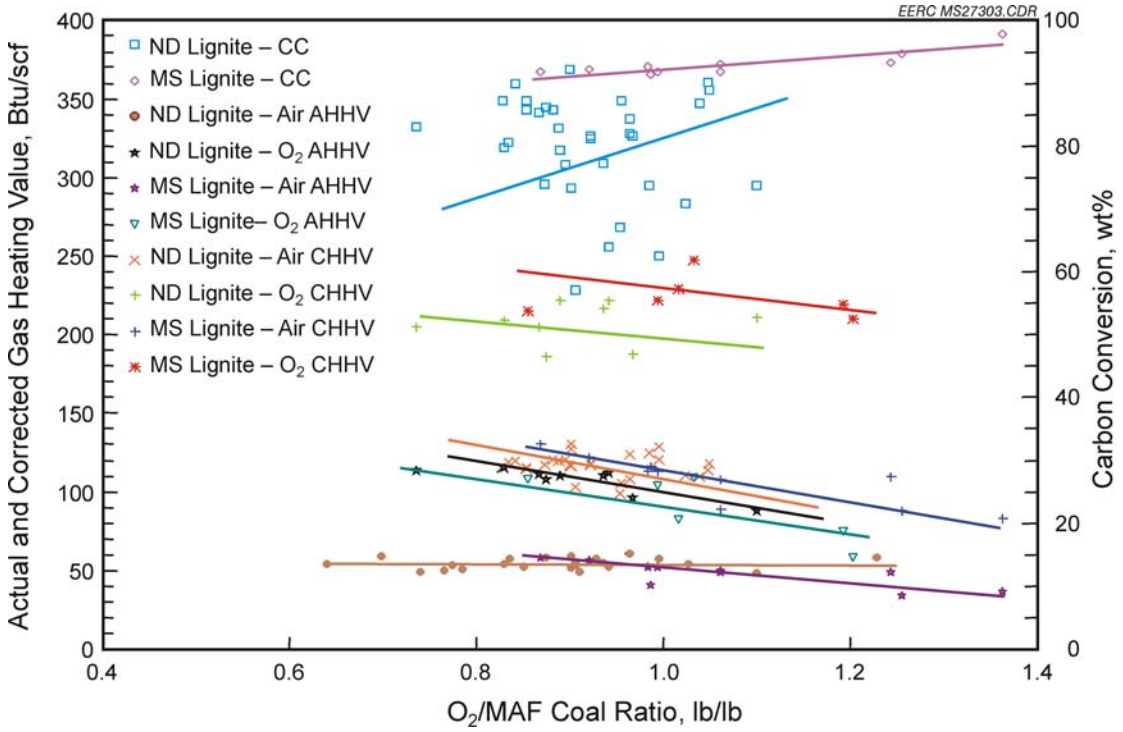


Figure 4. Effect of $O_2$/coal ratio on North American lignite carbon conversion and syngas heating value (CC – carbon conversion; AHHV – actual higher heating value; CHHV – corrected higher heating value).

Slightly higher oxygen/maf coal ratios were also required for the higher-ash Mississippi lignite because of the extra heat needed to bring all of the higher levels of coal ash up to bed temperature. The higher operating temperatures allowed very high carbon conversions (>92%) that approached 98% as compared to carbon conversions that were around 90% for the North Dakota lignites. The corrected dry product gas heating value for the oxygen-blown test has a significantly HHV than air-blown operation (210–230 Btu/scf as compared to 83–130 Btu/scf). A comparison of the fuel gas heating values shows that the Mississippi lignite coal had corrected heating values that were mostly higher than 115 Btu/scf, which is considered by GE to be the heating value of syngas in which successful operation of a gas turbine can be guaranteed. Hydrogen sulfide emissions averaged about 900 to 1000 ppm (40% sulfur retention) in air-blown operation on the partially dried coal and increased to approximately 1500 ppm on the GRE-dried coal. These emissions increased to approximately 1800 to 2000 ppm in $O_2$-blown operation on partially dried lignite and increased up to approximately 3000 ppm on the GRE-dried lignite.

Sampling with Dräger tubes indicated that ammonia was approximately 2000 to 2500 ppm in air-blown testing and about 3800 ppm during $O_2$-blown operation.

Tables 8 and 9 summarize the identified steady-state periods that had the best performance for the Mississippi lignite testing. Typically, the best performance is a balance of fuel gas heating value and carbon conversion.

**Table 8. Operating Conditions for Best-Case Gasification Performance for Mississippi Lignite Testing**

| Test | PD[1] MS Lignite | GRE-Dried MS Lignite | PD MS Lignite | GRE-Dried MS Lignite |
|---|---|---|---|---|
| Oxidant | Air | Air | Oxygen | Oxygen |
| Gasifier Temp., °C | 822 | 830 | 818 | 847 |
| Coal/Sorbent Feed Rate, lb/hr | 501 | 489 | 509 | 489 |
| Airflow, lb/hr | 1056 | 968 | 269 | 246 |
| $O_2$ Flow, lb/hr | 0 | 0 | 195 | 172 |
| Steam Flow, lb/hr | 126 | 123 | 272 | 195 |
| Steam:Coal Ratio, lb/lb | 0.51 | 0.47 | 1.08 | 1.07 |
| $O_2$/maf Coal Ratio, lb/lb | 0.984 | 0.869 | 1.017 | 0.994 |
| Carbon Conversion | 92.7 | 91.7 | 92.4 | 95.2 |

[1] Partially dried.

**Table 9. Actual and Corrected TRDU Product Gas Compositions for Best-Case Steady-State Tests for Mississippi Lignite Testing**

| Test | PD MS Lignite | GRE-Dried MS Lignite | PD MS Lignite | GRE-Dried MS Lignite |
|---|---|---|---|---|
| Oxidant | Air | Air | Oxygen | Oxygen |
| Product Gas Composition, vol% | | | | |
| $H_2$ | 6.6 | 6.9 | 11.6 | 15.6 |
| CO | 4.3 | 5.1 | 5.3 | 7.6 |
| $CH_4$ | 1.5 | 1.7 | 2.4 | 2.6 |
| $CO_2$ | 14.4 | 15.9 | 23.9 | 27.6 |
| $N_2$ | 73.4 | 71.0 | 60.0 | 48.7 |
| Total | 100.2 | 100.6 | 103.3 | 102.2 |
| Heating Value, Btu/scf | 50 | 56 | 78 | 102 |
| $N_2$-Free Heating Value, Btu/scf | 64 | 69 | 128 | 137 |
| Product Gas, vol% | Adjusted for 450,000 Btu/hr Heat Loss | | | |
| $H_2$ | 14.9 | 16.2 | 33.8 | 34.1 |
| CO | 9.7 | 11.9 | 15.4 | 16.6 |
| $CH_4$ | 3.3 | 3.9 | 6.9 | 5.7 |
| $CO_2$ | 18.1 | 20.3 | 43.8 | 38.6 |
| $N_2$ | 53.9 | 47.7 | 0.0 | 5.1 |
| Total | 100 | 100 | 100 | 100 |
| Heating Value, Btu/scf | 113 | 130 | 230 | 222 |

**HGFV Operation**

Operation of the HGFV during the gasification tests reported here utilized ten 1.5-m Pall Advanced Separation iron aluminide candle filters exclusively. The HGFV was operated between 190° and 309°C (375° and 588°F) at a face velocity of approximately 2.2–3.2 ft/min for the Mississippi lignites and 3.6-4.2 ft/min for the PRB. Backpulse operating parameters were approximately 360 psig backpulse reservoir pressure for the Mississippi lignites and 300 psig for the PRB, both with a 0.5-second opening time. The average particulate loading going into the HGFV ranged from approximately 4500 up to 38,000 ppm, with a $d_{50}$ between 9 and 20 µm. The top size for the Mississippi lignites was 90% less than 50 µm (see Figure 5), while it was 90% less than 40 µm for the PRB (see Figure 6).

According to the data from the Mississippi lignite testing, it appears that the filter particle size was increasing with increasing time. Figure 5 also shows the particle-size distribution for these same samples for both the circulating bed material (standpipe) and filter ash along with the particle-size distribution of the feed coal. This figure shows that the coal had an average feed size of approximately 400–500 µm, with less than 12 wt% being less than 75 µm. The circulating bed material was approximately 200 µm in size as compared to the 160-µm average size of the silica sand. Outlet dust loadings were maintained at 1 ppmw or below, indicating good performance from the iron aluminide candle filters.

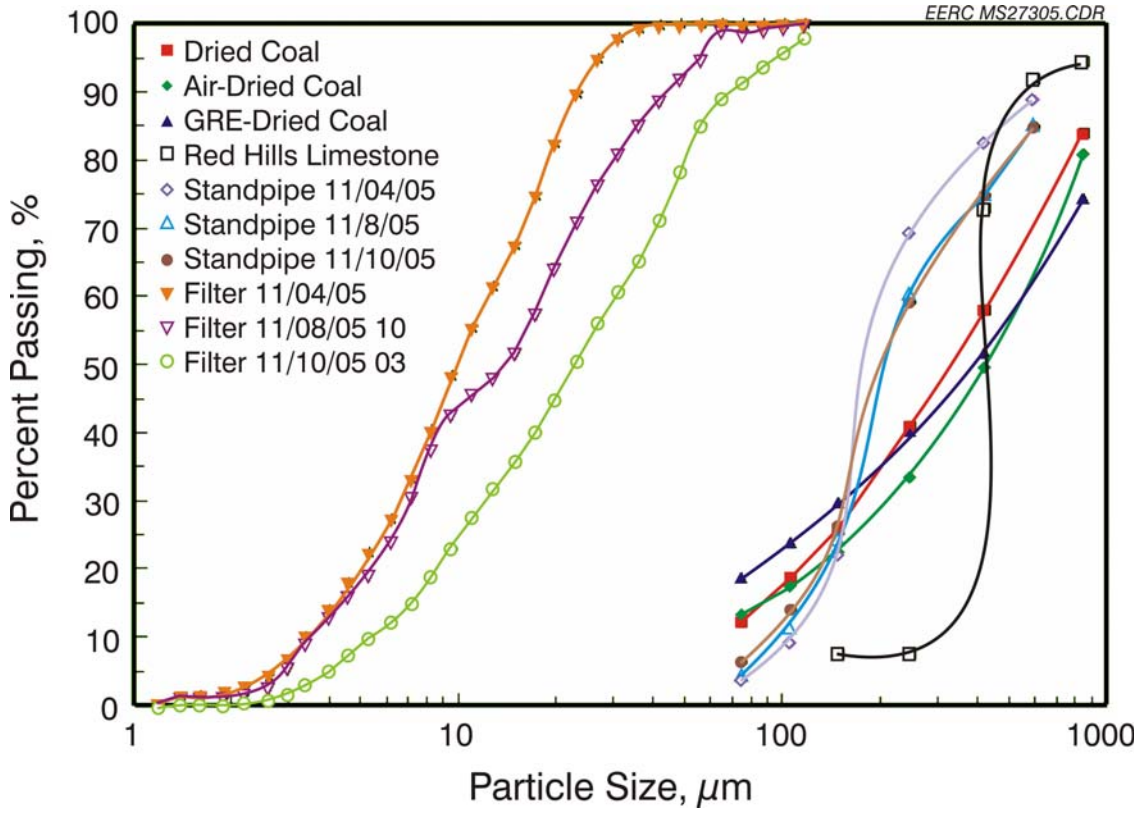


Figure 5. Particle-size distributions for Mississippi lignite samples collected under air- and $O_2$-blown operation.

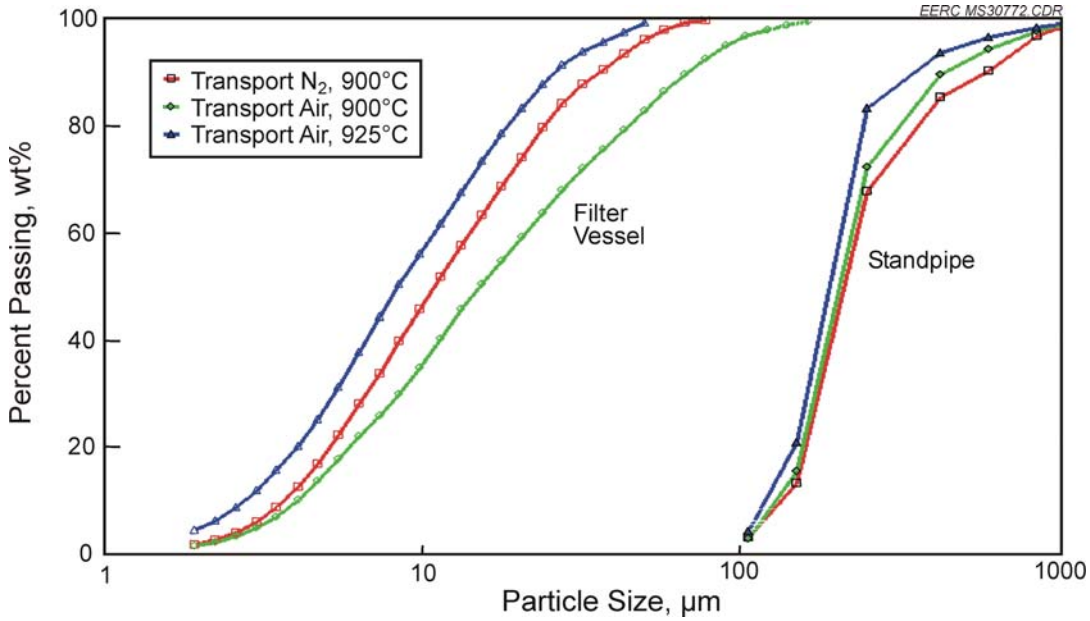


Figure 6. Particle-size distributions for the Rochelle PRB samples collected under air-blown operation.

During PRB testing, the differences in size distribution for the filter vessel samples corresponds to the level of carbon in each sample, with the lowest carbon (40%) having the smallest $d_{50}$, while the highest carbon content (53%) had the highest $d_{50}$. Figure 6 also shows the particle-size distribution for these same samples for the circulating bed material (standpipe) ash. This figure shows that the circulating bed material was fairly consistent in size, with a $d_{50}$ of about 200 µm and a total range of about 100 to 600 µm.

No substantial increase in the "cleaned" filter baseline was observed in these tests. Filter baseline pressure drop was nominally 40–50 in. of water, with candles being backpulsed when an 80-in. pressure drop was reached. The Mississippi lignite filter ash typically averaged 15 wt% carbon, with a range of 10–28 wt% carbon, while the PRB filter ash typically averaged 41 wt% carbon, with a range of 28–57 wt% carbon. The filter ash had a relatively low bulk density of approximately 20–25 lb/ft$^3$ because of its small size and carbon content. 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 will be reentrained back onto the filters after they are backpulsed. In gasification mode, the pulse frequency for these tests was similar to the typically short backpulses seen with other coals, with pulses occurring every 7 to 11 minutes. This rapid pulsing is thought to be due to the higher-carbon, low-density filter cake being able to minimize its porosity on the surface of the candle, thereby resulting in a rapid rise in pressure drop across the filters.

Tables 10 and 11 show ash analyses from samples taken at the end of each operating condition (air versus oxygen) for the Mississippi lignite testing. These analyses show that the circulating standpipe material was still enriched in silica from the start-up sand. However, the filter ash seems to be very representative of the coal ash plus the small amount of dolomite being

**Table 10. XRF Analysis of TRDU Samples Generated from the Partially Dried Mississippi Lignite, %**

| | PD MS Lignite | PD MS Lignite – Air | | PD MS Lignite – Oxygen | |
|---|---|---|---|---|---|
| | Coal Ash | Standpipe | Filter | Standpipe | Filter |
| Si | 41.5 | 76.8 | 48.0 | 57.0 | 42.8 |
| Al | 19.1 | 13.4 | 21.3 | 14.9 | 18.5 |
| Fe | 7.4 | 2.3 | 6.9 | 3.3 | 6.7 |
| Ti | 1.3 | 0.6 | 1.4 | 0.8 | 1.3 |
| P | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Ca | 19.1 | 3.2 | 15.9 | 19.8 | 25.1 |
| Mg | 3.8 | 1.6 | 3.7 | 1.7 | 3.4 |
| Na | 0.4 | 0.3 | 0.5 | 0.4 | 0.4 |
| K | 1.5 | 1.3 | 1.6 | 1.8 | 1.6 |
| S | 6.0 | 0.3 | 0.7 | 0.2 | 0.4 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

**Table 11. XRF Analysis of TRDU Samples Generated from the GRE-Dried Mississippi Lignite, %**

| | GRE-Dried MS Lignite | GRE-Dried MS Lignite – Air | |
|---|---|---|---|
| | Coal Ash | Standpipe | Filter |
| Si | 41.4 | 63.1 | 45.8 |
| Al | 17.8 | 15.3 | 18.1 |
| Fe | 6.3 | 4.6 | 6.4 |
| Ti | 1.3 | 0.9 | 1.4 |
| P | 0.1 | 0.1 | 0.1 |
| Ca | 21.0 | 11.1 | 20.0 |
| Mg | 3.6 | 1.7 | 3.2 |
| Na | 0.6 | 0.8 | 0.7 |
| K | 1.6 | 2.0 | 1.9 |
| S | 6.3 | 0.5 | 1.6 |
| Total | 100.0 | 100.0 | 100.0 |

fed into the TRDU. This is very consistent with previous testing in which the filter ash chemistry was shown to be very representative of the coal/dolomite ash chemistry from within a few hours of starting up the gasifier. It typically takes a hundred hours or more to flush most of the silica sand from the circulating bed material. Figure 7 shows a comparative histogram showing these ash chemistry data. Analysis of some filter ash samples showed that the reactive sulfide concentration in the ash was approximately 60 ppm, which is well below the 500 ppm limit that would necessitate combustion in a sulfator or disposal as a hazardous waste stream.

Table 12 shows ash analyses from samples taken at the end of each operating condition for the PRB testing. Typically, the sand will diminish over time, and the standpipe material composition will more closely resemble that of the coal ash; however, the silica remained high during the entire week of testing. This is because each riser sample removed up to 45 pounds of

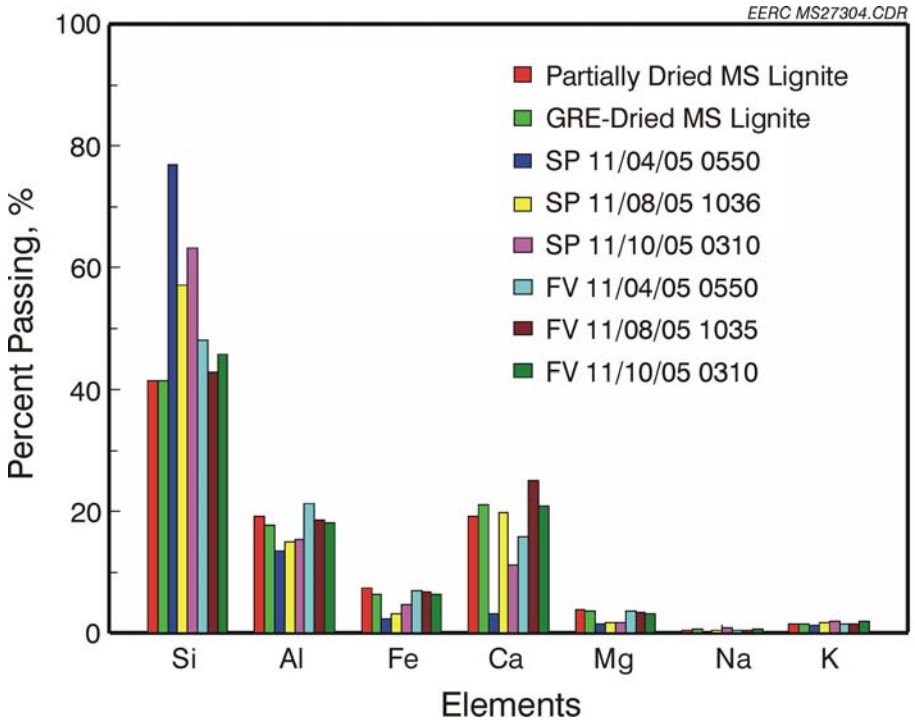


Figure 7. Histogram plot of the major species in the Mississippi lignite ash samples.

**Table 12. XRF Analysis of TRDU Rochelle PRB Samples**

| | Wyodak Coal Ash | Transport Nitrogen, 900°C | | Transport Air, 900°C | | Transport Air, 925°C | |
|---|---|---|---|---|---|---|---|
| | | Standpipe | Filter | Standpipe | Filter | Standpipe | Filter |
| Si | 18.1 | 89.4 | 27 | 85.2 | 26.0 | 87.8 | 24.4 |
| Al | 12.5 | 2.3 | 11.0 | 3.0 | 10.0 | 3.0 | 87 |
| Fe | 10.1 | 1.0 | 6.6 | 1.1 | 6.4 | 1.2 | 5.6 |
| Ti | 1.3 | 0.1 | 1.1 | 0.1 | 1.2 | 0.1 | 1.0 |
| P | 0.7 | 0.3 | 0.6 | 0.3 | 0.7 | 0.3 | 0.5 |
| Ca | 36.5 | 3.7 | 36.8 | 5.4 | 40.3 | 3.8 | 41.6 |
| Mg | 10.5 | 2.1 | 13.1 | 3.5 | 13.3 | 2.4 | 16.5 |
| Na | 1.8 | 0.4 | 1.5 | 0.7 | 1.2 | 0.7 | 1.0 |
| K | 0.6 | 0.6 | 0.6 | 0.7 | 0.4 | 0.7 | 0.4 |
| S | 7.8 | 0.0 | 1.1 | 0.0 | 0.5 | 0.0 | 0.4 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

solids from the system and fresh sand was added to maintain an adequate solids inventory in the system. The filter ash seems to be very representative of the coal ash plus the small amount of dolomite being fed into the TRDU. Figure 8 shows a comparative histogram showing these ash chemistry data.

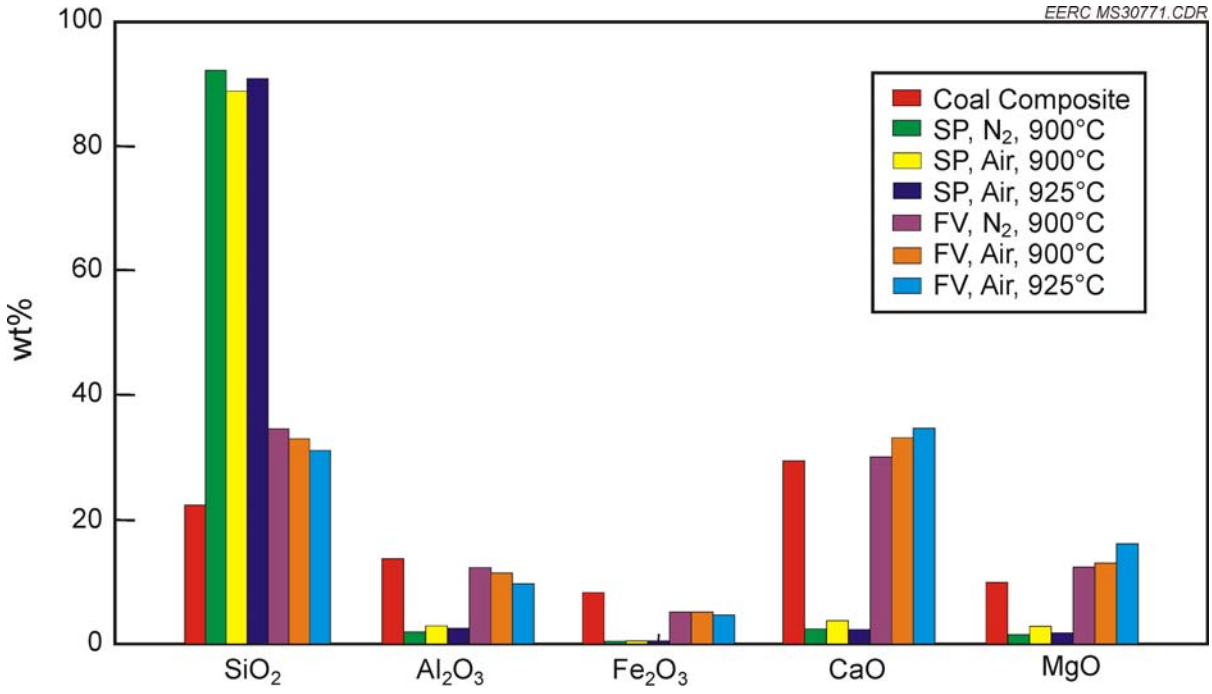


Figure 8. Histogram plot of the major species in the Rochelle PRB ash samples.

### Riser Gas and Particulate Sampling

Gas and particulate sampling was completed from various positions in the riser in order to determine the coal devolatilization and cracking chemistry occurring in the riser of the transport reactor. Gas and solid sampling directly from the riser and the filter outlet has been accomplished. This was done using a baseline PRB subbituminous coal from the Peabody Energy North Antelope Rochelle Mine near Gillette, Wyoming.

## CONCLUSIONS

The transport reactor gasifier, a fast-circulating fluid-bed gasifier, has demonstrated excellent performance on low-rank coals, especially the Mississippi lignite. Carbon conversions well in excess of 90% have been demonstrated for both subbituminous coals and lignites in general, and carbon conversions for the Mississippi lignite ranged from 88% up to nearly 98% over the conditions tested. Typically, lower carbon conversions are achieved with the less reactive bituminous coals. Fuel gas heating values from 83 up to 130 Btu/scf were achieved with air-blown operation, which would be considered to be more than acceptable to operate a gas turbine. Lower fuel moisture content did result in improved fuel gas heating value. Oxygen-enriched air operation generated acceptable corrected fuel gas heating values that ranged up to 230 Btu/scf in oxygen-blown mode. Operation of the hot-gas filter system presented no issues for the integrated system even with the high ash loading to the filter system. Gas and solid sampling from the riser indicated that little coal devolatilization and tar cracking were observed

in the transport reactor mixing zone and lower riser and that most of the syngas was formed by tar cracking in the upper riser and cyclones.

A PRB subbituminous coal from the Peabody Energy North Antelope Rochelle Mine near Gillette, Wyoming, was successfully tested in the TRDU for approximately 175 hours. The coal was gasified under air-blown conditions at temperatures between 900° and 925°C at velocities of approximately 42 ft/sec. The coal had corrected syngas heating values that were above 125 Btu/scf and had carbon conversions greater than 93% for all conditions tested. Riser gas and particulate sampling indicated that the volatile matter, OC, aliphatics, and methane seemed to reach peaks in the mid- to upper riser and started to fall off by the time they got to the filter outlet, while the hydrogen and carbon monoxide were continually increasing through the TRDU riser and filter outlet.

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