FINAL TECHNICAL REPORT
April 1, 2007, through August 31, 2008

Project Title: **COAL GASIFICATION/REFORMING USING
LOW-TEMPERATURE PLASMA PHASE II**

ICCI Project Number: 06-1/5.1B-1
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ABSTRACT

After completion of a Phase I proof-of-feasibility study, the project team performed a Phase II development and experimental study of the Plasma-Assisted Reforming (PAR) technology for solid fuels. The goal of the effort was to evaluate in detail and characterize the PAR-based gasification/reforming of coal for prospective markets, such as hydrogen, fuel gas, syngas, GTL and SNG production. Accomplishments included: Experimental study of coal micronization for the PAR process; Development, design and construction of an entrained flow dielectric barrier discharge (DBD) gasifier/reformer; Experimental study of the PAR in a DBD gasifier/reformer; and Development of Steam Turbine Cycle Retrofit for hydrogen and electricity coproduction with CO_2 capture.

A DBD plasma gasification/reforming test unit was designed, built and installed at GTI. The unit includes coal, steam and oxygen supply and measurement, process heating and control, high voltage power supply and control for DBD, product gas, solids and condensable liquids sampling and measurement. The unit is also equipped with process instrumentation, controls and data acquisition systems.

DBD gasification/reforming experimental studies were focused on process evaluation and optimization, output parameters, operating conditions, stability, and economic and environmental estimate. Tests were performed with pulverized coal at different process variables such as temperature, residence time, coal to steam, and coal to oxygen ratios, coal flowrate and presence of DBD plasma. It was determined that coal conversion increases with local temperature and oxygen flow and that residence time and steam/coal ratio have little or no effect on coal conversion in the range tested. DBD plasma has a positive effect on coal conversion.

Based on experimental and modeling results, a scheme of Steam Turbine Cycle Retrofit for Hydrogen and Electricity Co-production with CO_2 Capture was developed and modeled using ASPEN software. Results have shown that by using this technology about 50 % (HHV) thermal efficiency could be achieved by partial gasification of Illinois # 6 coal prior to combustion in a conventional utility boiler.

Page(s) 2, 6-21, and 27 contain proprietary information.

EXECUTIVE SUMMARY

As an advancement in Gasification Technology, a GTI led team is developing a novel technology, low-temperature <u>P</u>lasma <u>A</u>ssisted <u>R</u>eforming (PAR), for production of hydrogen, syngas for Fisher-Tropsch synthesis, and fuel-gas for gas turbines from coal. In the PAR process, micronized coal is converted to product gas at temperatures of 600°C to 800°C.

The overall project objectives included: Task 1, Evaluation and development study of PAR for production of different gaseous fuels from Illinois and PRB coals, Task 2, Experimental study and data processing. In Task 1, Evaluation and development study of PAR for production of different gaseous fuels from Illinois and PRB coals, as a near-term goal, an application of the PAR technology for retrofit of an existing coal-fired utility boiler is suggested. A technological scheme of steam turbine cycle retrofit for hydrogen and electricity co-production with CO_2 capture was developed and modeled using an ASPEN-Plus program. First, coal is partially gasified using PAR technology and product hydrogen extracted from the gasifier using a H_2 selective membrane. The remaining fuel goes to an existing utility boiler that uses a mixture of oxygen and recirculated flue gases as oxidant. In this case, heat transfer conditions in the furnace remain approximately the same as in the case of conventional air-blown coal combustion and significant changes of furnace geometry can be avoided. Total efficiency of the retrofitted unit was calculated and is about 50 % (HHV basis).

In Task 2, Experimental study and data processing, the goals were to develop, design and build a pilot-scale PAR test unit and perform tests of the PAR process at different conditions. A Dielectric Barrier Discharge (DBD) entrained flow gasification/reforming test unit was designed, built and installed at GTI. The unit includes coal, steam and oxygen supply and measurement, process heating and control, high voltage power supply and control for DBD, product gas, solids and condensable liquids sampling and measurement. The unit is also equipped with process instrumentation, controls and data acquisition systems.

In the DBD gasification/reforming unit, pulverized coal is fed to a micronizer by a screw feeder through an airlock. Micronization is accomplished in a steam jet micronizer with steam at 1.38 MPag and 427 °C supplied from a steam generator. Micronized coal/steam mixture with added steam (optional) is preheated in an electric heater and sent to the reactor. Reactor temperature is set and maintained by electric heaters installed both outside and inside of each reactor section. The reactor is equipped with 12 rows of high-voltage (HV) electrodes to generate DBD plasma. In the DBD reactor, there are four ports for raw product gas sampling at the center of each section, a distribution system for oxygen injection, and iso-kinetic system for solids and condensable liquids sampling at the reactor outlet. Product gas after the reactor is pre-cleaned and dried in a cyclone and wet scrubber. A fabric filter with pore size 1 µm is used for fine cleaning of the product gas. The volume of product gas is measured by a gas totalizer. The cleaned and dried product gas is analyzed by a portable gas chromatograph and real-time gas analyzers.

The testing campaign consisted of four stages: (1) testing of micronization module; (2) thermal testing of the reactor; (3) electrical and thermal testing of the unit with/without steam/coal flowing through it; including HV power supply and DBD plasma testing in air and steam; (4) testing of the PAR process at different process conditions.

During testing of the micronization module, the coal feed and micronizer system were checked and prepared for operation. Steam flow rate through the micronizer was measured by steam condensation at the micronizer outlet. PRB and Illinois coal samples were collected at the micronizer outlet. Steam pressure was at 14.8 bar; steam temperature was 440 °C.

Thermal testing of the reactor was focused on developing an approach for installing high voltage (HV) quartz electrodes into the reactor while avoiding electrodes cracking due to thermal expansion. A suitable approach was developed and tested with reactor temperature up to 760 °C.

HV electrical and thermal testing of the unit included checking for the presence of DBD in the reactor at elevated temperature with/without steam/coal flowing through it. Conclusions about presence/absence of DBD were made on the basis of voltage/current patterns recorded by oscilloscope.

Testing of the PAR process was conducted at the range of variables listed in Table ES.

Table ES. Operating Parameters Ranges.

Parameter	Units	Min	Max
Coal feedrate	kg/hr	0.70	2.98
Steam flowrate	kg/hr	3.42	9.71
Inlet steam temperature	°C	425	456
Average reactor temperature	°C	687	838
Reactor residence time	s	30	96
Stoichiometric ratio (O_2)	-	0.00	0.32

The major components of product gas were hydrogen (42 – 59 vol. %), carbon dioxide (16 – 36 vol. %) and carbon monoxide (2.5 – 10.5 vol. %). Coal conversion rate varied from 22 % at 687 °C without oxygen added to 72 % at 836 °C with oxygen stoichiometry 0.2. Increased coal conversion by applying DBD plasma was 10.7 % at 719°C and 4.3 % at 770 °C on an absolute basis.

Analyses of char samples collected at the reactor outlet have shown that some volatile matter (10 – 15 % of initial amount) still remains in the char after reaction. This fact, and the small diameter of particles (and, hence, small surface of the particle), as well as laminar flow conditions in the reactor, allow speculation that a shield of volatile matter around a reacting coal particle prevents free delivery of reactant (steam) to the reaction zone (coal surface) and reduces the reforming/conversion rate. Potential approaches to overcome the issue and achieve conversions above 90 % are discussed.

The cost analysis of the PAR technology made previously [1] has shown that use of this technology decreases production costs of syngas and hydrogen by $1.0 – 1.5/MBtu compared to a conventional gasification system. Costs of hydrogen produced *via* conventional gasification would be about $19/MBtu, while a PAR-based process would yield $14.5/MBtu that is competitive with the cost of hydrogen produced *via* natural gas reforming. The estimated decrease of electricity production costs was estimated at 8 to 10% compared to an IGCC system. The main factor for the production cost decrease is the lower process temperature that is beneficial for capital equipment and operational costs as well.

Near-term application of the technology suggested in this report is less costly due to the utilization of the existing fuel supply and flue gas cleanup systems. The main capital costs are associated with the gasification island, and, because of low process temperature, are lower than that of an IGCC plant. Based on the capital costs of an IGCC system, one can estimate that the capital costs of the suggested retrofit are about $100-150/kW for a 300 MWe power unit. [3]

OBJECTIVES

The overall project objectives include: Task 1, Evaluation and development study of Plasma – Assisted Reforming (PAR) for production of different gaseous fuels from Illinois and PRB coals, and commercial applications; Task 2, Experimental study and data processing; Task 3 SIUC support of experimental study and coal analysis. Evaluation and development study of PAR was conducted by development and modeling of Steam Turbine Cycle Retrofit for Hydrogen and Electricity Co-production with CO_2 Capture. As a near-term goal, application of the PAR process for retrofit of existing coal-fired utility boilers is suggested. Experimental study of the PAR process was conducted using an experimental unit designed, built and installed at GTI. Task 3, SIUC support of experimental study and coal analysis was cancelled with ICCI approval due to late timing of project results.

INTRODUCTION AND BACKGROUND

GTI is developing a PAR process, which is a low-temperature plasma-assisted gasification technology for solid fuels. Technical background and feasibility studies of the process were presented in the Phase I final report [1]. In this project, the results of Phase 1 studies are used as a basis for development of a technology for retrofit of coal – fired steam cycle to co-produce electricity and hydrogen and capture carbon dioxide formed during coal combustion. To support technology development, PAR process is studied experimentally on pilot – scale laboratory unit.

EXPERIMENTAL PROCEDURES

TASK 1: EVALUATION AND DEVELOPMENT STUDY OF PAR FOR PRODUCTION OF DIFFERENT GASEOUS FUELS FROM ILLINOIS AND PRB COALS, AND COMMERCIAL APPLICATIONS

In this study, the potential application of the Plasma Assisted Reforming (PAR) process for retrofit of existing coal-fired utility boilers for CO_2 capture with simultaneous production of hydrogen as a by-product is considered. Efficient capture of CO_2 usually requires using oxygen instead of air to decrease the nitrogen content in the flue gases and significantly increase the CO_2 concentration. It's well known that oxygen cannot be used directly on existing furnaces because the flame temperature and heat transfer conditions will be changed drastically. The usual solution for this problem is utilization of flue gas recirculation for oxygen dilution to the level similar in air combustion. In this case, the required recirculation rate is about 80% to reach a flame temperature comparable with air-blown coal combustion. So the large recirculation rate requires large ducts, blowers etc. and rarely can fit the existing power island. To significantly decrease the required recirculation rate, the project team suggests a system where partial gasification/reforming of coal before the boiler is applied using PAR process with extraction of hydrogen produced through selective membranes. In this case, the heating value of fuel fed to the retrofitted burner will be significantly decreased and much less recirculation gases are required. The general schematic of the proposed technology is shown in Figure 1.
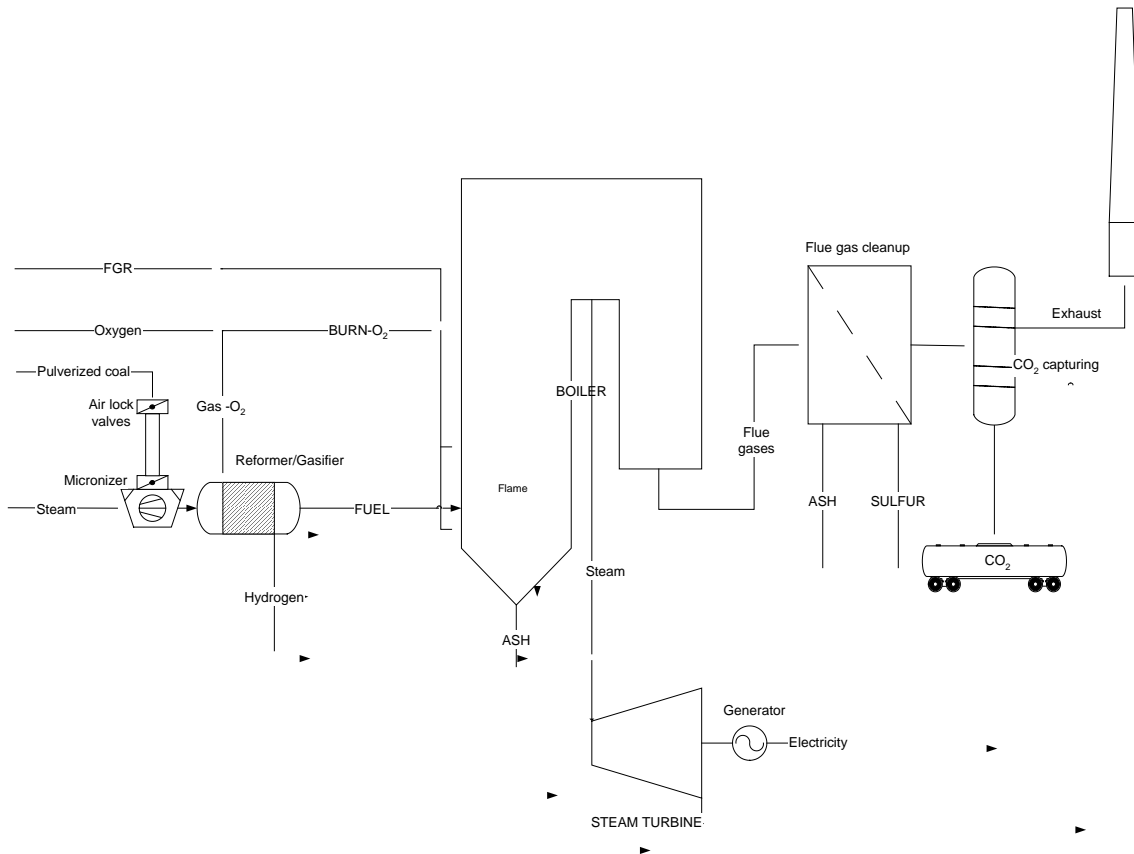
Figure 1. Steam Turbine Cycle Retrofit for Hydrogen and Electricity Co-production with CO$_2$ Capturing.

The process shown in Figure 1 was modeled using an ASPEN-Plus program. The model was based on data experimentally obtained from Task 2 of the current project. The following blocks were modeled: 1) steam jet micronizer; 2) reformer/gasifier; 3) hydrogen separation; 4) furnace; 5) boiler, 6) CO$_2$ separation.

According to the Illinois Basin Coal Sample Program [2], typical composition of Illinois # 6 coal is shown in Table 1.

Steam jet micronizer not only grinds the coal but also dries it. Steam parameters: temperature 593 °C, pressure 13.8 barg. Steam/coal ratio was 1.0/1.1.

Reformer/gasifier was modeled as a Gibbs reactor converting 70% of incoming coal into product gas at temperature 815 °C. The balance of coal (30 %) goes through the reactor. Reforming/gasification reactions consume roughly 25% of total oxygen supply to the unit (ca. 20 % of oxygen for stoichiometric coal combustion).

Hydrogen separation takes place in a separate block for modeling convenience. In a real unit it would be integrated with the reformer/gasifier into one unit and promote reaction completeness. Efficiency of separation was set at 60%.

The furnace was modeled as a Gibbs reactor with full oxidation. Combustion stoichiometry was assumed to be 1.0. Flue gas recirculation was modeled by adding a mixture of 13 wt% H_2O and 87 wt% CO_2. The quantity of recirculated flue gas was set at the level required to get adiabatic temperature equal to that of air-blown coal combustion (ca. 2040°C).

Table 1. Typical Illinois # 6 Coal Composition.

Higher heating value [*]	Moisture [*]	Volatile matter [†]	Fixed carbon [†]	Ash [†]	Carbon [†]	Hydrogen [†]	Nitrogen [†]	Oxygen [†]	Sulfur [†]			Chlorine [†]
									Sulfate	Pyrite	Organic	
HHV	W	V	C_{fix}	A	C	H	N	O	S_{sulf}	S_{pyr}	S_{org}	Cl
Btu/lb	%	%	%	%	%	%	%	%	%	%	%	%
13035	4.8	35.9	53.2	10.9	72.8	5.0	1.6	6.9	0.0	1.2	1.6	0.2

* As-received basis   † Dry basis

Heat available after cooling of combustion products down to 100 °C represents gross heat produced in the boiler. Heat to produce micronizer steam is subtracted from this value and heat from product hydrogen cooled to 65 °C is added to it to get a net heat output from the boiler. This net heat is then converted to electricity with an efficiency of 38 %. The system was sized to 300 MW$_e$ power output.

TASK 2: EXPERIMENTAL STUDY AND DATA PROCESSING

Experimental study of the Plasma-Assisted Reforming of micronized solid fuels was conducted using a specially designed unit. A general schematic of the unit is shown in Figure 2. Pulverized coal is fed to a micronizer by a screw feeder (pos. 4) through an airlock (pos. 3). Micronization is performed by a steam jet micronizer (pos. 2) using steam at 1.38 MPag and 427 °C supplied from steam manifold (pos. 1). Micronized coal/steam mixture with optionally added steam is preheated in an electric heater (pos. 5) and forwarded to the reactor (pos. 6). Additional (bypass) steam is fed through capillary tubing, which is used for flowrate measurement. Reactor temperature is set and maintained by electric heaters installed both outside and inside of each reactor section. The reactor is equipped with an array of high-voltage (HV) and ground electrodes to generate DBD plasma. There are also 4 ports for mixture sampling at the center of each section, and a distribution system for oxygen or other gas injection into the sections of the reactor. At the reactor outlet, an iso-kinetic system for solids and liquid vapor sampling is installed. Product gas after the reactor is cleaned in a cyclone (pos. 10) and wet scrubber (pos. 11). A fabric filter with pore size 1 µm (pos. 12) is used for fine cleaning of product gas. Volume of gas produced for the given time is measured by a gas totalizer (pos.13).
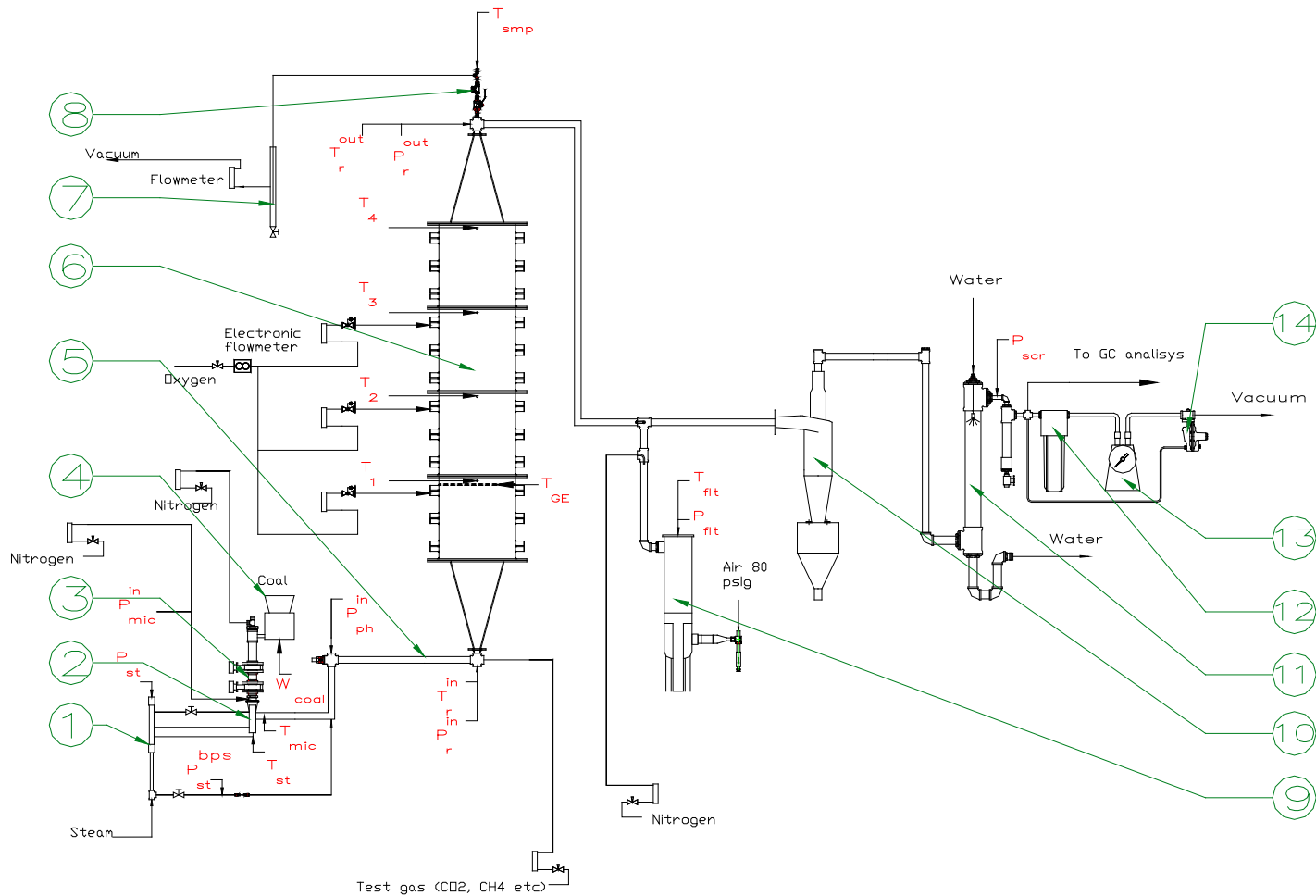
Figure 2. Experimental Unit for Plasma-Assisted Reforming of Solid Fuels Research. 1 – steam manifold; 2 – steam jet micronizer (Jet-O-Mizer); 3 – airlock wilth 2 butterfly valves (Posi-Flate); 4 – Coal feeder (AccuRate); 5 – mixture preheater; 6 – reactor; 7 – condenser; 8 – sintered metal filter; 9, 12 – fine fabric filters; 10 – cyclone; 11 – scrubber; 12 – filter, 13 – gas totalizer; 14 – back-pressure valve with remote pressure registration.

Scrubber pressure is maintained at 0.5 kPag by a backpressure regulator with remote registration (pos. 14) installed at the totalizer outlet before vacuum source. So, a change of pressure drop in the system including increased pressure drop of the filter 12 (while collecting the fines) has no effect on reactor and scrubber pressures.

In Figure 2, the locations of the major unit components as well as measured and recorded parameters, and abbreviations for values (red symbols) are shown. The explanations of the abbreviations for the measured experimental parameters are given in Table 2.

Table 2. Instruments Index for PAR Experimental Unit

Line #	Designation	Service	Instrument type	Instrument location	Mfg	Mod #	Range	Signal type
1.	P_{st}	Steam manifold pressure	Transducer	Steam manifold inlet	WIKA	ECO-1	0-750 psig	4-20 mA
2.	T_{st}	Steam inlet temperature	K-TYPE T/C	Micronizer nozzle inlet	N/A	N/A	50-2000 °F	0-45 mV
3.	W_{coal}	Coal feeder weight	Digital scale	Coal feeder	NCI	3800	0-100 lbs	N/A
4.	P_{mic}^{in}	Micronizer inlet pressure	Gauge	Micronizer inlet	WIKA	N/A	-30" Hg – 15 psig	N/A
5.	P_{st}^{bps}	Bypass steam pressure	Transducer	Capillary tubing inlet	Honeywell	SPTMA	0-500 psig	4-20 mA
6.	T_{mic}	Micronizer outlet temperature	K-TYPE T/C	Micronizer outlet	N/A	N/A	50-2000 °F	0-45 mV
7.	P_{ph}^{in}	Preheater inlet pressure	Gauge	Preheater inlet	N/A	N/A	0-5 psig	N/A
8.	P_{r}^{in}	Reactor inlet pressure	Transducer	Reactor inlet	Honeywell	SPTMA	0-5 psig	4-20 mA
9.	T_{r}^{in}	Reactor inlet temperature	K-TYPE T/C	Reactor inlet	N/A	N/A	50-2000 °F	0-45 mV
10.	T_{GE}	Temperature probe	K-TYPE T/C	Section 1 ground electrode	N/A	N/A	50-2000 °F	0-45 mV
11.	T_1	Section 1 temperature	K-TYPE T/C	Section 1 upper port	N/A	N/A	50-2000 °F	0-45 mV
12.	T_2	Section 2 temperature	K-TYPE T/C	Section 2 upper port	N/A	N/A	50-2000 °F	0-45 mV
13.	T_3	Section 3 temperature	K-TYPE T/C	Section 3 upper port	N/A	N/A	50-2000 °F	0-45 mV
14.	T_4	Section 4 temperature	K-TYPE T/C	Section 4 upper port	N/A	N/A	50-2000 °F	0-45 mV
15.	O_2^{tot}	Total oxygen flowrate	Electronic flowmeter	Oxygen line	OMEGA	FMA-5609ST	0-5 slpm	0-5 V
16.	P_{r}^{out}	Reactor outlet pressure	Transducer	Reactor outlet	Honeywell	SPTMA	0-5 psig	4-20 mA
17.	T_{r}^{out}	Reactor outlet temperature	K-TYPE T/C	Reactor outlet	N/A	N/A	50-2000 °F	0-45 mV
18.	T_{smp}	Sampling line temperature	K-TYPE T/C	Solids sampling line	N/A	N/A	50-2000 °F	0-45 mV
19.	T_{flt}	Filter inlet temperature	K-TYPE T/C	Filter inlet	N/A	N/A	50-2000 °F	0-45 mV

Line #	Designation	Service	Instrument type	Instrument location	Mfg	Mod #	Range	Signal type
20.	P_{flt}	Filter inlet pressure	Gauge	Filter inlet	Dwyer	SGX	-30" - +50 "WC	N/A
21.	P_{scr}	Scrubber pressure	Gauge	Scrubber outlet	N/A	N/A	0–10 "WC	N/A
22.	N	Heating power	Power meter	Power cabinet	Simpson	GIMA-G100	0-41.57 kW	4-20 mA
23.	H_2^{out}	Hydrogen concentration	Analyzer	Scrubber outlet	NOVA	335WP	0-70 %$_v$	4-20 mA
24.	CO_2^{out}	Carbon dioxide concentration	Analyzer	Scrubber outlet	Rosemount Analytical	880A	0-100 %$_{vol}$	0-5 V

MICRONIZATION MODULE

A vertical steam-jet grinding mill Jet-O-Mizer model 0101 by Fluid Energy (see Figure 3) was chosen as a grinding device.
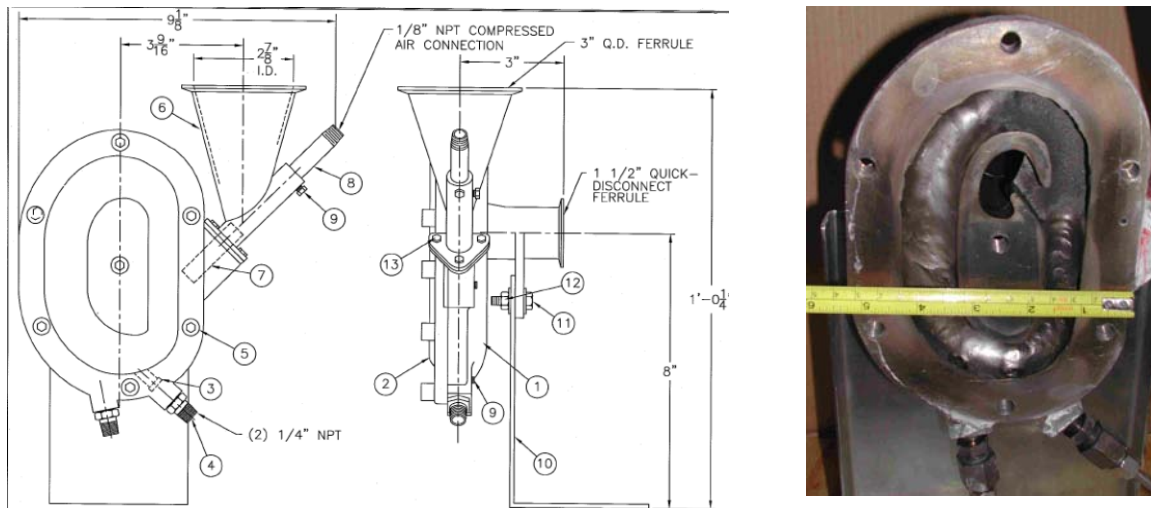

Figure 3. Jet-O-Mizer 0101 Drawing and Photo

Pulverized coal is fed to the Jet-O-Mizer by Schenck AccuRate model 106 screw feeder. Steam is introduced into the Jet-O-Mizer through specially designed nozzles to create a sonic or supersonic grinding stream. Solid particles of raw feed are injected into this violent, turbulent stream by pusher nozzle that creates suction at the Jet-O-Mizer inlet. The high-velocity collisions that result provide thorough and effective pulverization of the feed into smaller particles. The particle stream leaving the reduction chamber flows to the classification zone. As the stream enters the classifier, the direction of flow is reversed. Properly sized product is entrapped by the viscous drag of the exiting flow and conveyed as a micronized coal-steam mixture to the reactor. Larger particles are recycled to the reduction chamber for further grinding.

An additional separate module was designed and fabricated to provide coal feed and grinding without infiltration of ambient air into the micronizer (see Figure 4). To isolate the micronizer inlet from outside air, two 2" Series 486 Posi-Flate air-actuated inflatable-seated butterfly valves were used and an airlock module was formed. Coal dropped first into a receiving chamber where nitrogen pressure at 0.25 kPa was maintained to prevent parasitic air (oxygen) flow through an airlock. A timing controller set at the cycle time 0.5 s provided cycling of butterfly valves. The estimated nitrogen inlet flow was 25 – 50 l/hr. An additional 50 – 60 l/hr of nitrogen was supplied to the micronizer inlet to decrease condensation on the lower valve's disc.
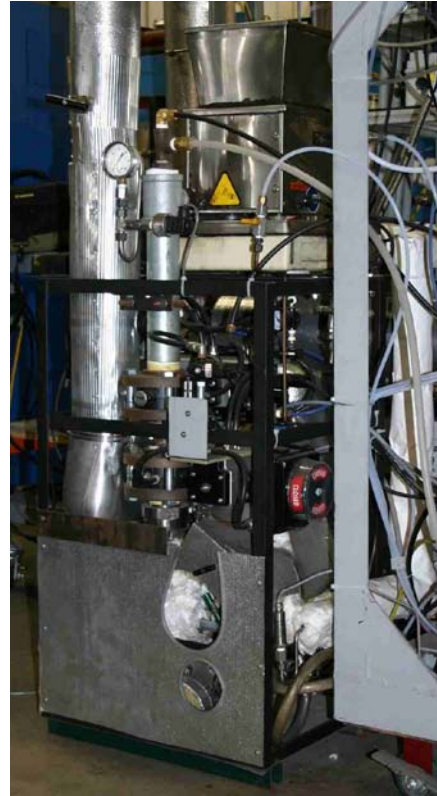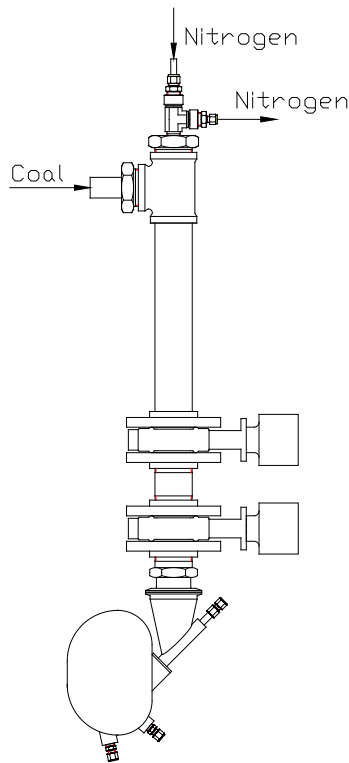

Figure 4. Micronization Module Schematic and Photo

The micronizer and airlock module were assembled on a dedicated frame. The same frame was used to mount steam manifold to distribute steam among Jet-O-Mizer inlets and bypass line. The manifold, micronizer, steam lines and micronizer outlet line were covered with thermal insulation.

After assembly the micronization module was tested to get characteristics of steam flow rates through the micronizer and bypass line on steam manifold pressure (P_{st}) and bypass steam pressure (P_{st}^{bps}). Rates were calculated by condensing and collecting water at the micronizer outlet. Test results are presented in Table 3 and Table 4. Upon completion of tests, correction factors were calculated and theoretical characteristics were updated and used in the following calculations of steam flow rates through the micronizer and bypass lines (see Figure 5 and Figure 6).

Table 3. Micronizer Steam Flow Measurements as a Function of Steam Manifold Pressure

Regime #			I			II			III	
Test #	--	1	2	3	4	5	6	7	8	9
Steam manifold pressure	psig	193	193	193	208	209	210	154	154	155
Steam temperature	°F	819	820	820	831	831	832	802	806	806
Water collected	g	687.2	689	689.4	612.72	614.14	615.5	581.88	557.92	556.27
Test duration	min	12.005	12	12.00	10.02	10.01	10.03	12.74	12.17	12.167
Steam flowrate	lbs/hr	7.57	7.59	7.60	8.09	8.12	8.12	6.04	6.06	6.05
Steam flowrate, calculated	lbs/hr	8.72	8.72	8.72	8.90	8.90	8.91	8.15	8.14	8.15
Correction factor	-	0.87	0.87	0.87	0.91	0.91	0.91	0.74	0.75	0.74

Table 4. Bypass Steam Flow Measurements as a Function of Bypass Steam Pressure

| Test #	--	1	2	3	4	5	6	7	8	9	10	11	12	13
Test duration	s	830	819.3	830	582	647	693	609	610	613	605	607	655	546
Steam pressure	psig	18.9	18.3	17.7	35.6	35.2	34.4	53.9	53.3	52.7	86.8	91.3	99.2	98.3
Steam temperature	°F	791	795	797	801	803	803	805	806	806	810	811	812	813
Water collected	g	229.5	221.8	223.0	234. 5	259.5	272.3	329.7	329.9	329.6	479.7	503.3	581.7	482.4
Steam flowrate	lbs/hr	2.19	2.15	2.13	3.20	3.18	3.12	4.30	4.29	4.27	6.29	6.58	7.05	7.01
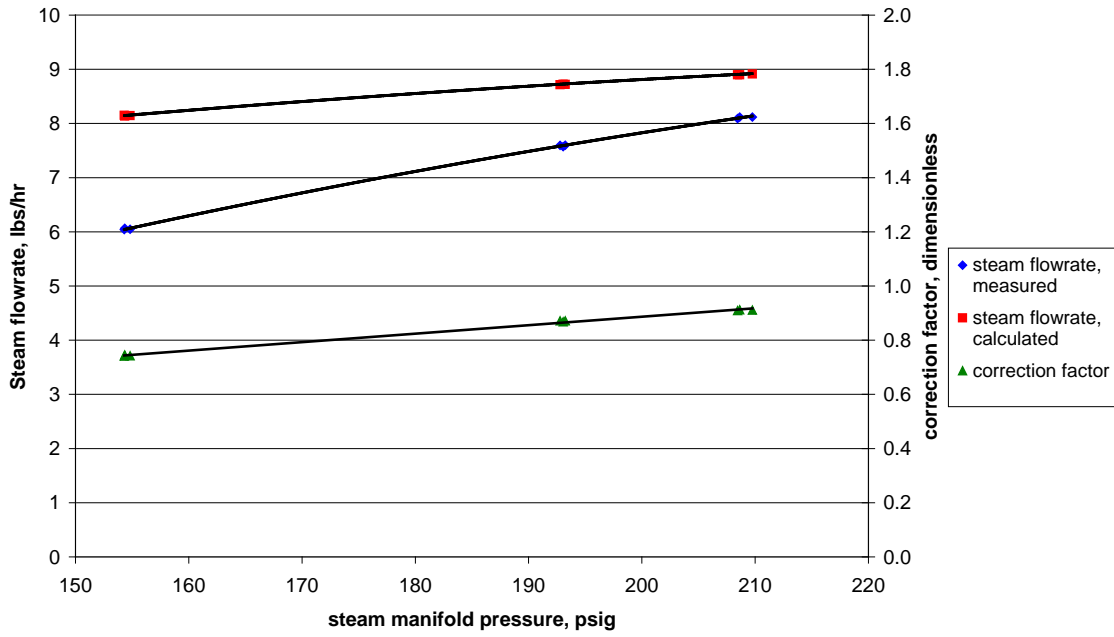
Figure 5. Calculated and Measured Micronizer Steam Flowrate
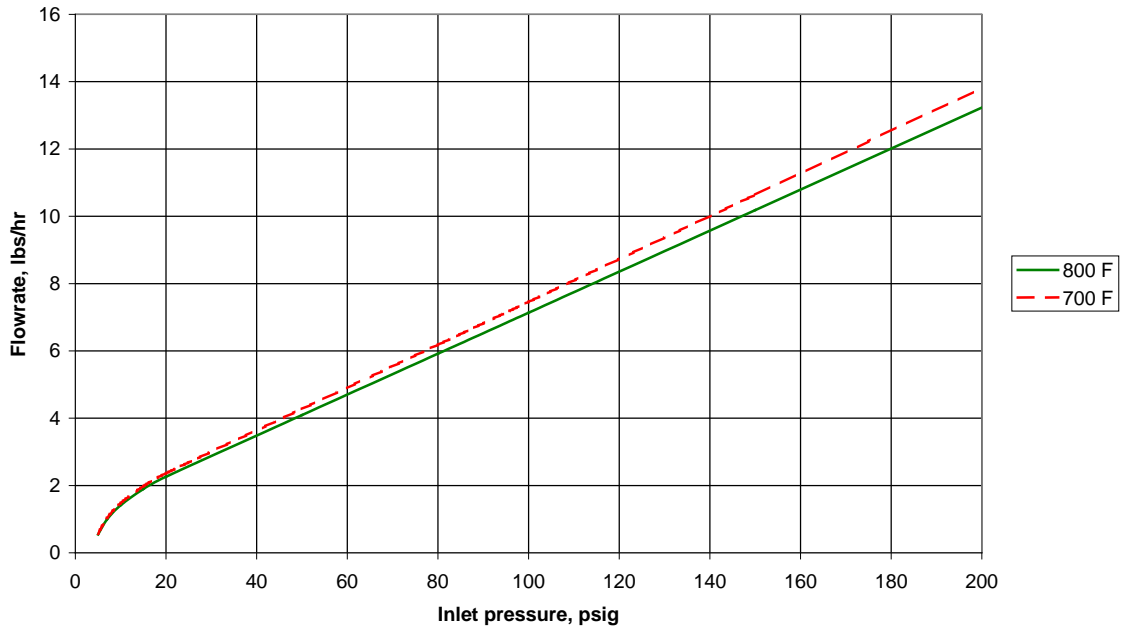

Figure 6. Steam Flowrate Through Bypass Line with 1.4 mm ID Capillary, Corrected per Measurements

PREHEATER

The temperature of the coal/steam mixture after the micronizer is usually in the range 230 – 290°C. A specially designed electric heater was made to increase this temperature and to experimentally determine the possibility of heating micronized coal (MC)/steam mixture. The heater design is shown in Figure 7.

The preheater consists of the electric cartridge heating element inserted into SS 1-1/2" sch. 80 pipe. To enhance heat transfer, the heating element was inserted into a special header with longitudinal ribs and coated with heat transfer cement.

Preheater tests have shown the unit is capable to preheat MC/steam mixture up to 725 °C without plugging or erosion of the passage. A pressure gauge was installed at the preheater inlet to ensure the permeability of the passage.

The temperature at the preheater outlet was maintained by a temperature controller (CN 616 by Omega Engineering, Inc.) with PID function activated.
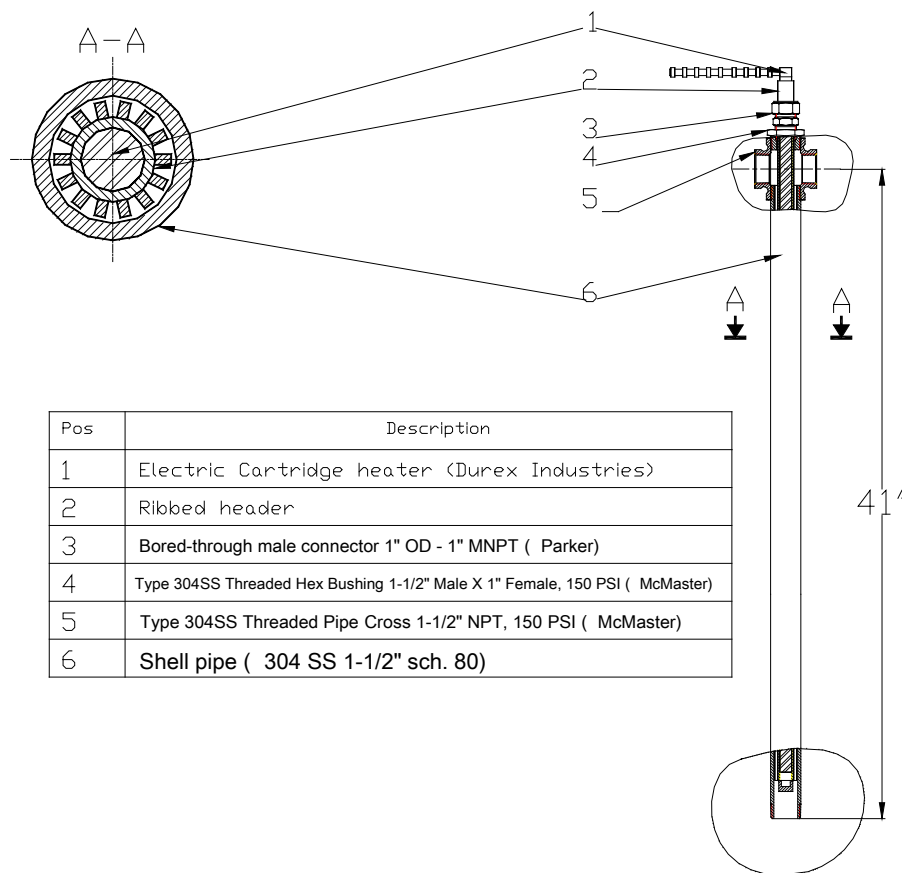

Pos	Description
1	Electric Cartridge heater (Durex Industries)
2	Ribbed header
3	Bored-through male connector 1" OD - 1" MNPT (Parker)
4	Type 304SS Threaded Hex Bushing 1-1/2" Male X 1" Female, 150 PSI (McMaster)
5	Type 304SS Threaded Pipe Cross 1-1/2" NPT, 150 PSI (McMaster)
6	Shell pipe (304 SS 1-1/2" sch. 80)

Figure 7. MC/Steam Mixture Preheater Assembly

REACTOR

The reactor was designed to provide the following performance:

- Uniform reaction temperature up to 800 °C.
- Residence time up to 90 s.
- Application of DBD plasma through 168 HV quartz electrodes.
- Addition of oxygen at different levels with distribution through reactor cross-section.
- Sampling of product gas mixture along the reactor.
- Temperature measurements along the reactor.
- Sampling of solids and condensable material at the reactor outlet.
- Pressure measurements at the reactor inlet and outlet.

To satisfy these requirements the following reactor design was used:

- Reactor consists of 4 reaction sections and 2 transitional sections (inlet and outlet).
- Transitional sections provide connection of reaction sections to piping and additional mixture heating to decrease heat losses from reaction sections.
- Transitional sections were covered by heating jackets. Electric tubular heaters were installed inside these sections.
- Each reaction section is a piece of rectangular duct (W x D x H = 559 x 483 x 610 mm) with inlet and outlet flanges.
- 42 couplings are welded to each sidewall to insert HV quartz electrodes.
- Front wall is used to install inner (process) electric heater and to make ports for mixture sampling and temperature measurements. Back wall is solid.
- Special structure to support ground electrodes is inserted into the section.
- To decrease heat losses, inner surfaces are covered by 75 mm thick thermal insulation; and electrical heating jackets are attached to the outer surface.
- Each of the reaction sections and the transitional sections were connected by flanges with graphite gaskets.

HIGH VOLTAGE ELECTRODES FOR DBD PLASMA GENERATION

Plasma inside the reactor is created by DBD between the HV quartz electrodes and SS ground electrodes. A HV electrode is shown in Figure 8. The electrode itself is SS foil inserted into 5/8" OD quartz tube. High voltage is provided through SS wire with a loop on the inner end that secures electric contact between the wire and foil. The inside tube volume is filled by silica sand (F-95 by U. S. Silica Company) or thermal insulation to displace air from the quartz tube interior and prevent discharge inside the quartz tube.
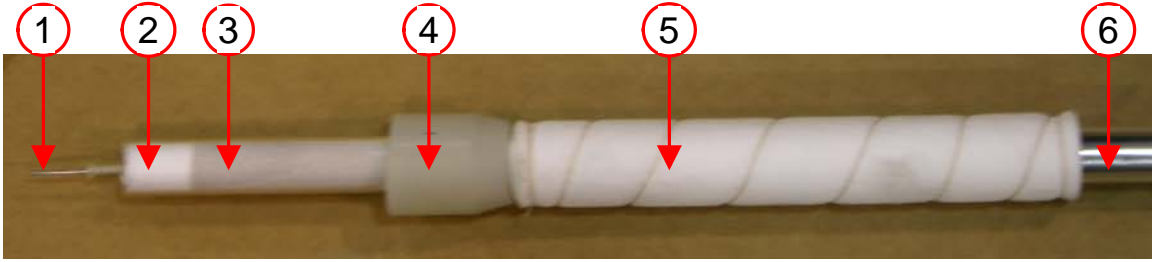
Figure 8. HV Electrode Filled with Quartz Sand. 1-high voltage wire; 2-Kaowool plug; 3-quartz sand; 4-silicone plug; 5-ceramic paper wrap; 6–high voltage electrode inside quartz tube.

Ceramic paper wrap was used to fill the gap between the quartz tube and the thermal insulation plate.

This design of the HV electrode was first tested on the bench-scale test unit built by GTI for an R&D project with DBD applications at conditions similar to the reactor. Voltage and current patterns obtained in air at two temperatures, 700 °C and 584 °C, are shown in Figure 9.
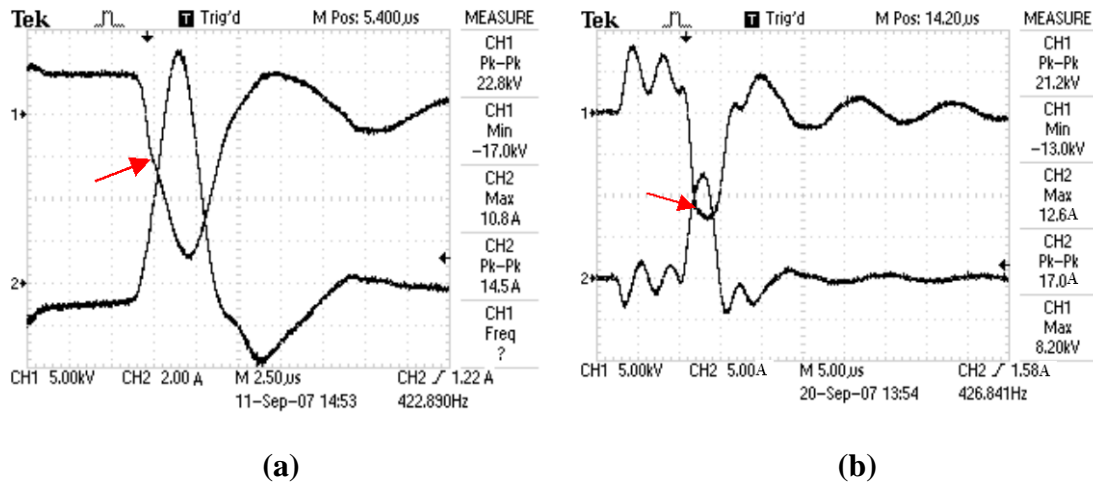

(a)   (b)

Figure 9. Oscillograms of DBD in Air at Atmospheric Pressure with the New Design of HV Electrodes (Channel 1–Voltage, Channel 2–Current). (a) t=700 °C, (b) t=584 °C. Driving pulse width 7 µs.

The bend in the voltage curve indicated by red arrows at≈ 6 kV corresponds to the point where DBD starts at 700 °C. At temperatures of 584 °C, DBD has started at the voltage≈ 11 kV. So, breakdown voltage behaves as expected – the higher the temperature, the lower the breakdown voltage.

HV electrodes were inserted into couplings on the sidewalls of the reactor and sealed and centered by silicone plugs. HV electrodes installed into a reactor section are shown in Figure 10.

Figure 10. HV Electrodes Installed into the Reactor

After installation, HV electrodes were electrically and thermally tested with steam flowing through the reactor at an average reactor temperature of 580 °C. Voltage and current patterns were recorded for each electrode channel of the reactor (2 adjacent rows connected to one power supply). Figure 11 shows patterns recorded for channel #12 located in the top section of the reactor.
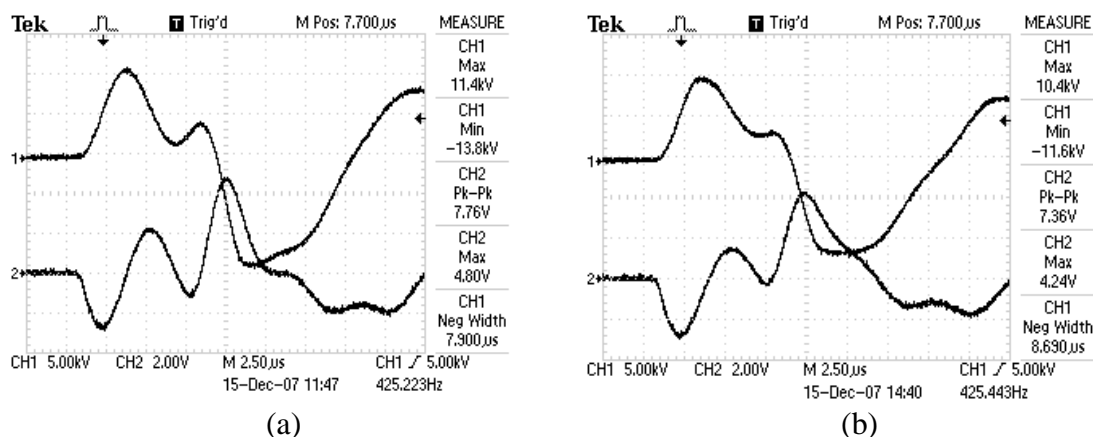

(a)	(b)

Figure 11. Oscillograms Of DBD in Steam at Atmospheric Pressure with the New Design of HV Electrodes (Channel 1–Voltage, Channel 2–Current). (a) t=440 °C, (b) t=600 °C. Driving pulse width 6 μs.

GROUND (NEUTRAL) ELECTRODES AND REACTION SECTIONS

The design of the supporting insert for ground electrodes is shown in Figure 12. Electrodes were installed between two vertical SS plates in such a way that 4 ground electrodes surrounded each HV electrode. HV electrodes are placed in a chessboard order to get the entire cross-section of reactor under plasma treatment.
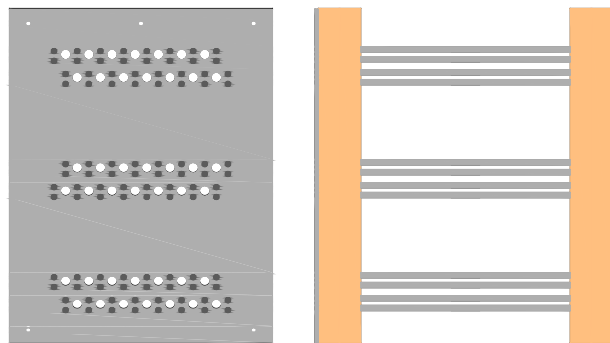
Figure 12. Supporting Structure for Ground Electrodes

Ground electrodes were screwed into one plate, then side thermal insulation boards (holes were drilled for ground and HV electrodes in the boards) were put on ground electrodes and the opposite ends of ground electrodes were inserted into opposite SS plate holes. These opposite ends can slide freely within the holes to compensate for thermal expansion. There is a gap between the supporting plate and section's sidewall for ground electrodes lengthened due to thermal expansion. A schematic of an assembled reaction section is shown in Figure 13.
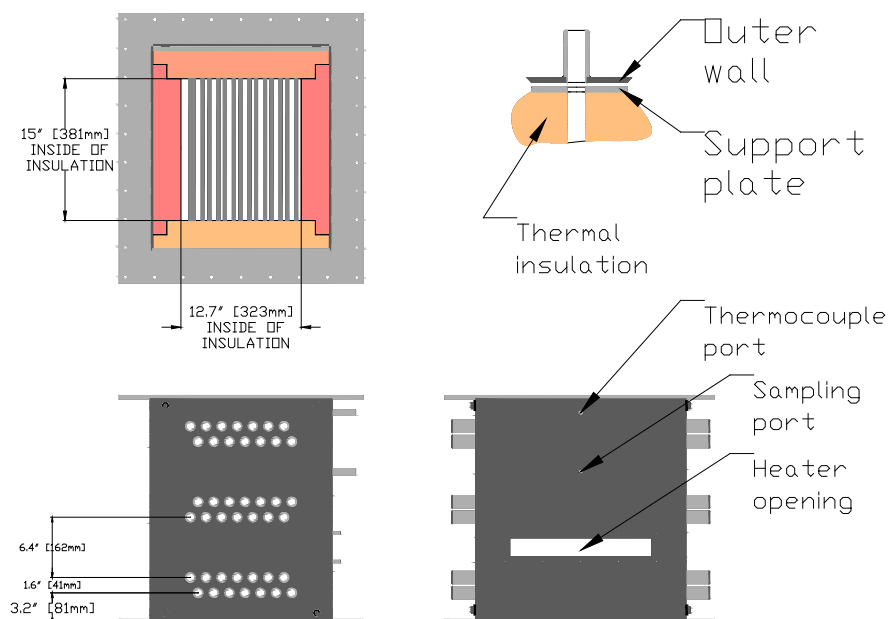

Figure 13. Reactor Section with Ground Electrodes and Thermal Insulation Installed

ELECTRIC HEATERS

Electrical tubular heaters are installed inside of each section to provide the necessary reactor temperature. The heater design is shown in Figure 14.

Inside and outside heaters are controlled by multi-loop temperature controllers (CN616 by Omega Engineering, Inc.). Controllers maintained the temperature of the heater surface at the preset level with hysteresis 3 °F. Supply voltage to the heaters is set by solid-state voltage controllers (18-D3-20 by Payne Engineering Company).
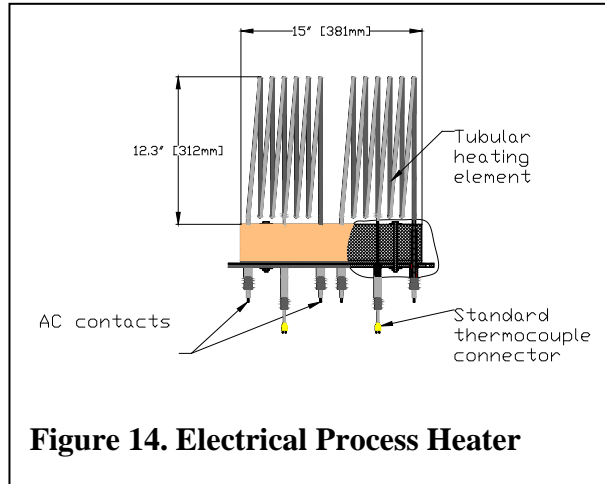

Figure 14. Electrical Process Heater

Usually during testing, the reactor unit was preheated overnight before the start of the test to secure sufficient test duration for the daytime. Safety measures included: setting the heaters' voltage at 100 VAC (nominal 277 VAC) and activation of controllers' high alarm option. When the temperature of the heaters or the reactor surface became higher than a preset value, the alarm circuit closed activating the shunt trip of the main circuit breaker (SQUARE D model FAL341001021).

Heating power controllers were installed in the electrical cabinet with forced draft cooling (Figure 15).

Figure 15. Heaters Power Control Cabinet

Power consumed by the heaters is measured by an electric power meter (Simpson GIMA G100) with analog output module connected to data acquisition system according to Figure 16.
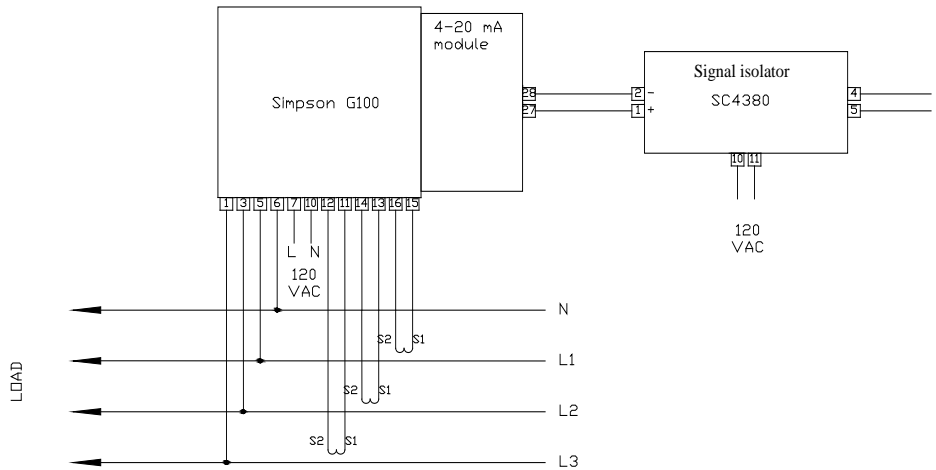
Figure 16. Connection of Simpson GIMA G-100 Power Meter to Data Acquisition System

After installation, the power meter was commissioned during overnight heating up of the unit. Recorded sections' temperatures and heating power are shown in Figure 17.
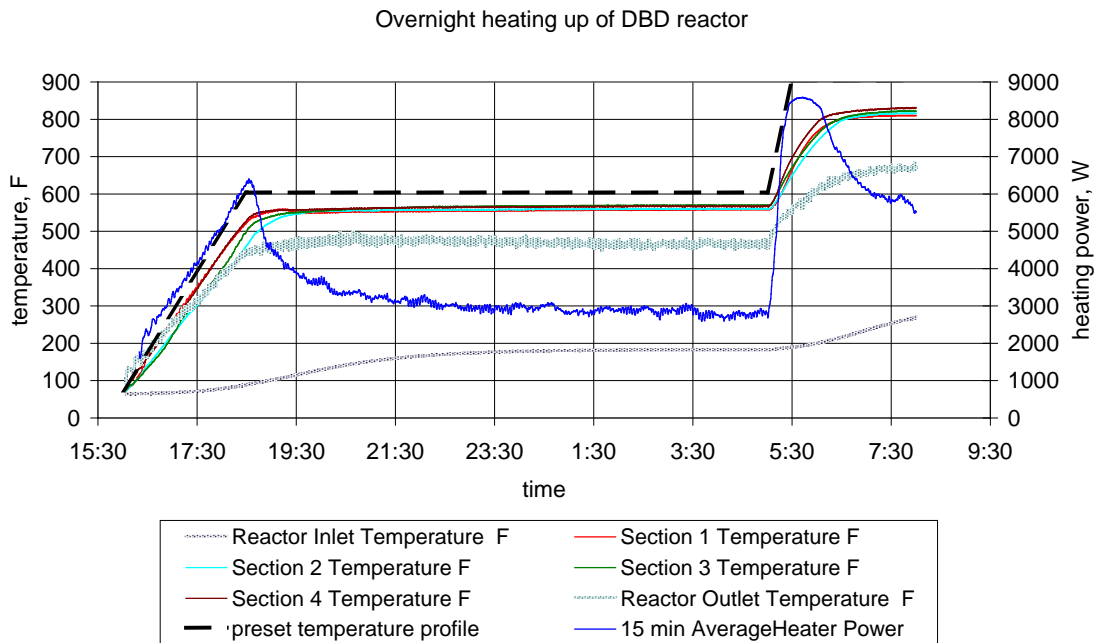

Figure 17. Inner Reactor Temperatures and Heating Power Recorded During Overnight Heating Up of DBD Reactor

TRANSITIONAL SECTIONS

Transitional sections perform the connection of the reactor to inlet and outlet piping, and provide additional mixture heating. They are pyramidal shape with tubular electric heaters installed inside (see Figure 18). The outer surfaces are covered by electrically heated blankets.

Figure 18. Transitional Sections

SOLIDS AND CONDENSABLES SAMPLING AT THE REACTOR OUTLET

To analyze solid char and condensable tars and oils at the reactor outlet a sampling system was designed and installed at the reactor outlet (see Figure 19).
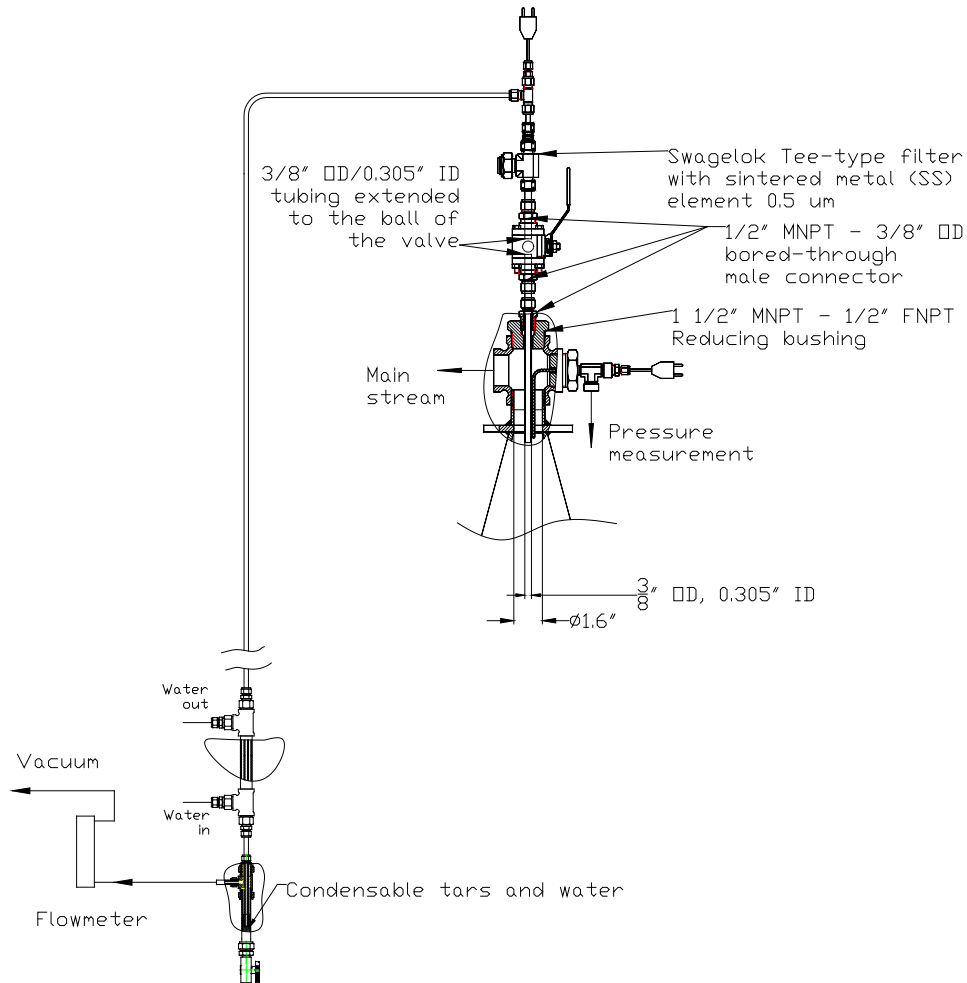
Figure 19. Sampling of Solids and Condensables at the Reactor Outlet

 A sample of solids and product gas mixture is iso-kinetically taken at the reactor outlet, then solids are removed by the heated (to prevent condensation) sintered metal filter (pore size = 0.5 µm), and product gas passes through a condenser where water, tars and oils are separated. Flowrate of dry clean gas is measured by a rotameter. Solid sample is then analyzed to determine C, H and N content as well as moisture and ash content. Liquid sample was weighed and analyzed to determine total oils and tars content in the product gas.

PRODUCT GAS TREATMENT, MEASUREMENT AND ANALYSIS

Syngas produced in the reactor is cleaned from solids, condensable tars and oils as well as excessive water vapors. Coarse cleaning is done by a cyclone and wet scrubber. A fabric filter with pore size 1 µm is used for fine cleaning. A portable gas chromatograph Varian CP-4900 (micro-GC) was used to measure concentrations of H_2, O_2, N_2, CH_4, CO,

CO_2, C_2H_4, C_2H_6, C_3H_8, i-C_4H_{10}, n–C_4H_{10} and C_2H_2. Continuous real–time gas analyzers were used to measure concentrations of H_2 and CO_2. The total volume of clean product gas was measured by gas totalizer DTM – 200A (American Meter Company) and recorded vs. test time every 5 minutes. Sampling gas flow was added to get a total gas flow during test data processing.

Product gas is sucked in by an air-driven jet vacuum pump installed at the system outlet. A backpressure regulator (Fisher Y696AM) was installed at the dry gas totalizer outlet with pressure registration at the scrubber outlet. Regulator maintained gas pressure at the scrubber outlet at the level of 0.5 kPa. Reactor tightness was checked before each test by supplying nitrogen with known flowrate to the reactor inlet and measuring the flowrate at the reactor outlet.

HIGH VOLTAGE POWER MODULES FOR DBD PLASMA GENERATION

The design of HV electrodes was described previously. High voltage to the electrodes is supplied by specially designed power modules. General electrical scheme of HV generation is given on Figure 20. Supply of low voltage (120 V) AC from the inlet is rectified and used for charging the set of capacitors (not shown).

High-power transistors connect capacitors to the primary winding of HV transformer according to the signals generated by driver. Secondary winding of the transformer generates high voltage to form DBD inside the reactor. Drivers and capacitors are installed into separate modules with provisions for controlling the discharge

Figure 20. HV Generation for DBD Powering

parameters (Figure 22). Every two rows of HV electrodes are connected to one HV block (containing HV transformer) installed on the special shelving unit as close as possible to the electrodes (Figure 21).
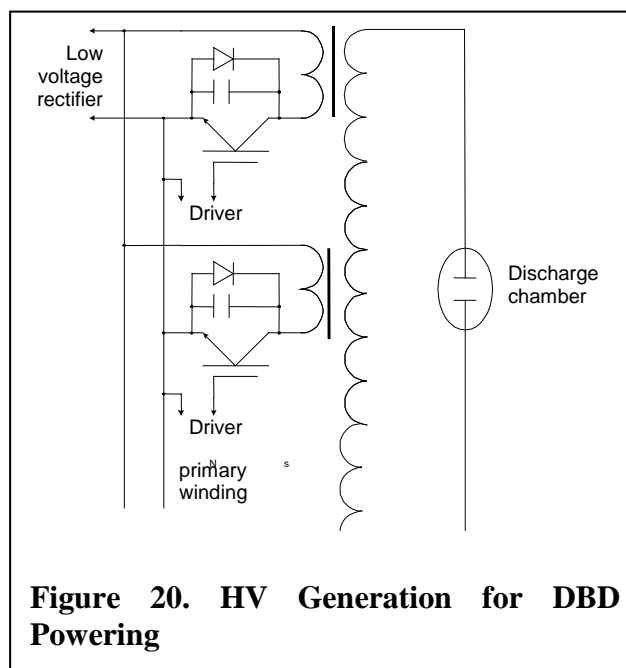
Figure 21. Power Modules Installation and Connection

The DBD assembly has 12 double rows of electrodes and 12 HV power modules. In addition, there were 2 converter modules and 1 capacitors module. Power switches for converter and capacitors modules are installed remotely in the NEMA 4X enclosure (Figure 23). HV modules are powered from converters.

Figure 22. Capacitors (Lower) and Converter (Two Upper) Modules.
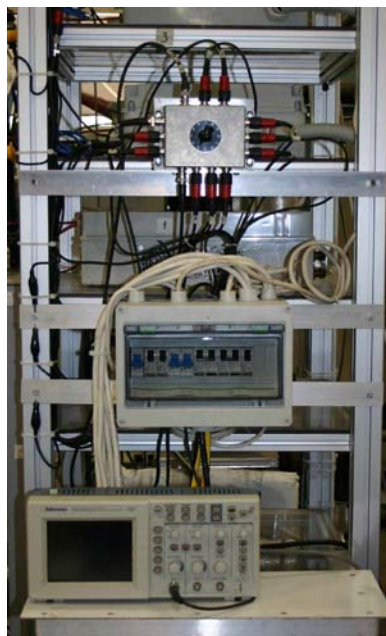
Figure 23. DBD Power Controls

Voltage supplied to each double row of electrodes is measured separately by twelve HV oscilloscope probes (11 Testec TT-HVP15HF and 1 North Star PVM-1). One current probe (Pearson 2877) is installed permanently on the 12th channel (from the bottom) and another current probe (Tektronix A622) is used to conduct current measurement among other 11channels. HV probes are connected to a digital storage oscilloscope (Tektronix TDS 1012) through selector switch.

RESULTS AND DISCUSSION

TASK 1: EVALUATION AND DEVELOPMENT STUDY OF PAR FOR PRODUCTION OF DIFFERENT GASEOUS FUELS FROM ILLINOIS AND PRB COALS, AND COMMERCIAL APPLICATIONS

A proposed technology of Steam Turbine Cycle Retrofit for Hydrogen and Electricity Co-production with CO_2 Capture was modeled to determine overall system efficiency and estimation of prospects to implement it on existing power plants. Modeling results are shown in Table 5.

The plant consumes 276,511 lbs/hr of Illinois # 6 coal and produces 300 MWe of electricity and 14,488 lbs/hr of hydrogen. So, overall thermal efficiency is about 53%. Total flow of combustion products at the furnace outlet is $2.24 \cdot 10^6$ lbs/hr including $1.19 \cdot 10^6$ lbs/hr (53 %) of recirculation gases. Flowrate of exhaust gas going to cleanup is $1.05 \cdot 10^6$ lbs/hr consisting of primarily carbon dioxide (66 wt %) and water vapor (29 %). Total amount of water vapor exhausted is $3.05 \cdot 10^5$ lbs/hr.

A reference steam cycle air-blown plant would consume 206,830 lbs/hr of coal producing 300 MWe of electricity with net efficiency 38 %. Total amount of flue gases produced is $2.56 \cdot 10^6$ lbs/hr ($3.29 \cdot 10^7$ scf/hr) including $1.12 \cdot 10^5$ lbs/hr of water vapor.

The modeling results show that PAR process could be effectively used for partial reforming/gasification of coal prior to the boiler and co-produce power and hydrogen. The required level of recirculated flue gases is below 50 % of total flue gas flow. Taking into account that flue gases volumetric flowrate in the PAR technology shown in Figure 1 is roughly 1.4 times less than that of flue gases produced by air-blown combustion (per unit of heat generated in the boiler), the volumetric flowrate of recirculated flue gases is about 35 % of flue gases produced in the furnace before suggested retrofit.

Table 5. Modeling Steam Cycle Retrofit for Hydrogen and Electricity Co-production with CO2 Capturing

Stream label	PULVERIZED COAL	STEAM	GASIFIER OXYGEN	FUEL	HYDROGEN	BURNER OXYGEN	FGR	FLAME	FLUE GAS
Temperature F		1100	200	1500	150	200	215	3486.034	215
Pressure psi	14.69595	214.6959	14.69595	14.69595	14.696	14.69595	14.69595	14.69595	14.69595
Substream: MIXED									
Mass Flow lb/hr									
H2O	0	304162.1	0	180752.4	0	0	154569.64	459782.47	459782.5
O2	0	0	126642.03	7.26E-13	0	361399.9	0	236.34796	236.348
N2	0	0	0	2946.319	0	0	0	4196.7704	4196.77
NO	0	0	0	9.72E-09	0	0	0	32.226581	32.22658
SO2	0	0	0	1.14E-02	0	0	0	14672.782	14672.78
H2	0	0	0	24147.07	14488.2	0	0	0	0
HCL	0	0	0	379.0114	0	0	0	541.44501	541.445
CO	0	0	0	167555	0	0	0	0	0
CO2	0	0	0	226854.2	0	0	1034427.6	1735068.3	1735068
CH4	0	0	0	62.36324	0	0	0	0	0
H2S	0	0	0	5339.029	0	0	0	0	0
COS	0	0	0	220.7113	0	0	0	0	0
HCN	0	0	0	1.30E-02	0	0	0	0	0
NH3	0	0	0	2.36E+00	0	0	0	0	0
Mass Fractions									
H2O		1	0	0.297164	0	0	0.13	0.2076206	0.207621
O2		0	1	1.19E-18	0	1	0	1.07E-04	1.07E-04
N2		0	0	4.84E-03	0	0	0	1.90E-03	1.90E-03

Stream label	PULVERIZED COAL	STEAM	GASIFIER OXYGEN	FUEL	HYDROGEN	BURNER OXYGEN	FGR	FLAME	FLUE GAS
NO		0	0	1.60E-14	0	0	0	1.46E-05	1.46E-05
SO2		0	0	1.88E-08	0	0	0	6.63E-03	6.63E-03
H2		0	0	0.039699	1	0	0	0	0
HCL		0	0	6.23E-04	0	0	0	2.44E-04	2.44E-04
CO		0	0	0.275467	0	0	0	0	0
CO2		0	0	0.372957	0	0	0.87	0.7834925	0.783493
CH4		0	0	1.03E-04	0	0	0	0	0
H2S		0	0	8.78E-03	0	0	0	0	0
COS		0	0	3.63E-04	0	0	0	0	0
HCN		0	0	2.14E-08	0	0	0	0	0
NH3		0	0	3.89E-06	0	0	0	0	0
Total Flow lbmol/hr	0	16883.56	3957.7128	33428.13	7187.05	11294.17	32084.399	65348.56	65348.56
Total Flow lb/hr	0	304162.1	126642.03	608258.4	14488.2	361399.9	1188997.2	2214530.9	2214531
Total Flow cuft/hr	0	1305008	1906054.1	4.78E+07	3200725	5439328	15744450	1.88E+08	3.20E+07
Vapor Frac		1	1	1	1	1	1	1	1
Liquid Frac		0	0	0	0	0	0	0	0
Solid Frac		0	0	0	0	0	0	0	0
Enthalpy Btu/lbmol		-95219.98	865.2775	-53890.9	503.768	865.2775	-1.51E+05	-1.02E+05	-1.42E+05
Enthalpy Btu/lb		-5285.512	27.04094	-2961.69	249.9	27.04094	-4061.541	-3016.165	-4187.99
Enthalpy Btu/hr		-1.61E+09	3424519.4	-1.80E+09	3620610	9772590	-4.83E+09	-6.68E+09	-9.27E+09
Entropy Btu/lbmol-R		-6.874041	1.452181	14.18768	0.87938	1.452181	0.8630535	19.93171	-0.30377
Entropy Btu/lb-R		-0.381567	0.0453823	0.779715	0.43623	0.045382	0.023289	0.5881645	-8.96E-03
Density lbmol/cuft		0.012938	2.08E-03	6.99E-04	2.25E-03	2.08E-03	2.04E-03	3.47E-04	2.04E-03
Density lb/cuft		0.233073	0.0664419	0.012714	4.53E-03	0.066442	0.0755185	0.0117599	0.069105

Stream label	PULVERIZED COAL	STEAM	GASIFIER OXYGEN	FUEL	HYDROGEN	BURNER OXYGEN	FGR	FLAME	FLUE GAS
Average Molecular Weight		18.01528	31.9988	18.196	2.01588	31.9988	37.05842	33.88799	33.88799
Substream: $TOTAL									
Total Flow lb/hr	276510.9869	304162.1	126642.03	707315.1	14488.2	361399.9	1188997.2	2243223.9	2243224
Enthalpy Btu/hr	-1.62E+08	-1.61E+09	3424519.4	-1.77E+09	3620610	9772590	-4.83E+09	-6.66E+09	-9.28E+09
ALL PHASES ***									
Mass Flow lb/hr									
H2O	0	304162.1	0	180752.4	0	0	154569.64	459782.47	459782.5
O2	0	0	126642.03	7.26E-13	0	361399.9	0	236.34796	236.348
N2	0	0	0	2946.319	0	0	0	4196.7704	4196.77
NO	0	0	0	9.72E-09	0	0	0	32.226581	32.22658
SO2	0	0	0	1.14E-02	0	0	0	14672.782	14672.78
H2	0	0	0	24147.07	14488.2	0	0	0	0
HCL	0	0	0	379.0114	0	0	0	541.44501	541.445
CO	0	0	0	167555	0	0	0	0	0
CO2	0	0	0	226854.2	0	0	1034427.6	1735068.3	1735068
CH4	0	0	0	62.36324	0	0	0	0	0
H2S	0	0	0	5339.029	0	0	0	0	0
COS	0	0	0	220.7113	0	0	0	0	0
HCN	0	0	0	1.30E-02	0	0	0	0	0
NH3	0	0	0	2.36E+00	0	0	0	0	0
COAL	276510.9869	0	0	78971.54	0	0	0	0	0
ASH	0	0	0	20085.09	0	0	0	28692.992	28692.99
Total Flow cuft/hr	3188.052779	1305008	1906054.1	4.78E+07	3200725	5439328	15744450	1.88E+08	3.20E+07

Stream label	PULVERIZED COAL	STEAM	GASIFIER OXYGEN	FUEL	HYDROGEN	BURNER OXYGEN	FGR	FLAME	FLUE GAS
Mass fraction of gases	0	1	1	0.859954	1	1	1	0.987209	0.987209
Mass fraction of solids	1	0	0	0.140046	0	0	0	0.0127909	0.012791
Density lb/cuft	86.7335	0.233073	0.0664419	0.014784	4.53E-03	0.066442	0.0755185	0.0119123	0.07
Substream: NCPSD									
Mass Flow lb/hr									
COAL	276510.9869	0	0	78971.54	0	0	0	0	0
ASH	0	0	0	20085.09	0	0	0	28692.992	28692.99
Mass Frac									
COAL	1	0	0	0.797236	0	0	0	0	0
ASH	0	0	0	0.202764	0	0	0	1	1
Total Flow lb/hr	276510.9869	0	0	99056.63	0	0	0	28692.992	28692.99
Enthalpy Btu/lb	-586.7068			350.1355				732.0044	-319.4375
Enthalpy Btu/hr	-1.62E+08			3.47E+07				21003396	-9165618
Density lb/cuft	86.7335			98.78229				217.6791	217.6791
Average Molecular Weight	1	1	1	1	1	1	1	1	1

TASK 2: EXPERIMENTAL STUDY AND DATA PROCESSING

43 tests with PRB coal were done on experimental unit at conditions shown in Table 6.

Table 6. Operating Parameters Ranges

Parameter	Units	Min	Max
Coal feedrate	kg/hr	0.70	2.98
Steam flowrate	kg/hr	3.42	9.71
Inlet steam temperature	°C	425	456
Average reactor temperature	°C	687	838
Reactor residence time	s	30	96
Stoichiometric ratio (O_2)	-	0.00	0.32

A summary of the results is shown in Table 7.

The major components of product gas were hydrogen (42 – 59 vol. %), carbon dioxide (16 – 36 vol. %) and carbon monoxide (2.5 – 10.5 vol. %). Coal conversion rate varied from 22 % at 687 °C without oxygen added to 72 % at 836 °C with oxygen stoichiometry 0.2. Increasing of coal conversion by applying of DBD plasma was 10.7 % at 719 °C and 4.3 % at 770 °C.

Table 7. Summary of Test Results with PRB Coal

test #	date	Average reactor temperature	Residence time	coal feedrate	Steam/coal ratio	average gas flowrate	carbon conversion	O_2 flowrate	SR (O_2)	DBD power
--	mm/dd/yy	F	s	pph	lb/lb	scfh	%	scfh	--	kW
1	10/24/07	1269	92	4.48	1.68	51.4	22.5%	0.0	0.00	0.00
2	11/6/07	1298	91	2.46	3.11	33.7	27.4%	0.0	0.00	0.00
5	12/18/07	1282	93	1.88	4.08	30.9	33.4%	0.0	0.00	0.00
6	12/18/07	1275	93	1.88	4.08	30.6	33.3%	0.0	0.00	0.00
8	12/21/07	1322	90	1.87	4.06	38.1	43.8%	0.0	0.00	0.00
9	12/21/07	1329	88	1.87	4.06	47.9	54.5%	0.0	0.00	0.89
10	12/21/07	1324	88	1.87	4.07	49.0	56.5%	0.0	0.00	0.00
11	12/21/07	1331	88	1.87	4.08	49.7	56.6%	0.0	0.00	0.89
13	3/26/08	1361	85	1.92	4.02	49.8	58.9%	3.8	0.10	0.00
14	3/26/08	1364	84	1.92	4.03	54.4	69.0%	7.7	0.19	0.00
15	4/1/08	1354	87	1.91	3.98	46.4	56.1%	3.9	0.10	0.00
16	4/1/08	1363	46	1.87	7.94	43.1	53.8%	3.9	0.10	0.00

test #	date	Average reactor temperature	Residence time	coal feedrate	Steam/coal ratio	average gas flowrate	carbon conversion	O$_2$ flowrate	SR (O$_2$)	DBD power
--	mm/dd/yy	F	s	pph	lb/lb	scfh	%	scfh	--	kW
17	4/15/08	1319	90	1.90	4.00	42.9	51.3%	3.8	0.10	0.00
18	4/15/08	1334	88	2.00	3.81	47.8	58.3%	6.0	0.14	0.00
19	4/15/08	1352	86	2.00	3.82	47.2	61.3%	9.2	0.22	0.00
20	4/22/08	1419	82	1.54	4.96	46.9	78.9%	8.8	0.27	0.00
21	4/22/08	1430	81	1.57	4.87	48.4	82.5%	10.6	0.32	0.00
22	4/25/08	1416	82	1.93	3.98	46.4	64.1%	9.4	0.23	0.00
23	4/25/08	1420	81	1.93	4.00	50.3	68.4%	9.0	0.22	1.78
24	4/29/08	1430	80	1.88	4.12	49.6	67.0%	9.6	0.24	1.78
25	4/29/08	1426	81	1.89	4.08	48.6	65.3%	9.5	0.24	0.00
26	4/29/08	1425	80	1.90	4.07	50.5	67.1%	9.6	0.24	0.00
27	4/29/08	1428	80	1.91	4.06	51.9	69.0%	9.5	0.24	1.78
28	4/29/08	1429	80	1.92	4.03	50.8	67.4%	9.6	0.24	1.78
29	4/29/08	1426	80	1.93	4.01	50.3	66.3%	9.4	0.23	0.00
30	5/7/08	1401	39	6.56	2.38	169.7	55.9%	0.0	0.00	0.00
31	5/7/08	1434	34	3.41	5.41	86.0	63.4%	13.8	0.19	0.00
32	5/7/08	1438	31	3.28	6.21	80.2	61.9%	13.0	0.19	1.78
33	5/7/08	1408	31	3.16	6.77	79.3	53.0%	0.1	0.00	1.78
34	5/7/08	1398	33	3.11	6.34	82.7	57.1%	0.0	0.00	0.00
35	5/13/08	1530	32	3.50	5.28	96.2	71.3%	15.8	0.22	0.00
36	5/13/08	1520	31	3.69	5.11	103.0	70.3%	13.4	0.17	0.00
37	5/20/08	1535	31	3.36	5.58	100.1	70.4%	15.9	0.23	0.00
38	5/20/08	1534	32	3.44	5.26	102.1	71.2%	16.0	0.22	0.00
39	5/20/08	1530	32	3.78	4.79	112.3	69.5%	15.7	0.20	0.00
40	5/23/08	1528	33	3.63	4.89	98.5	68.6%	15.8	0.21	0.00
41	5/23/08	1540	32	3.63	5.07	99.1	69.5%	15.8	0.21	1.78
42	5/23/08	1533	32	3.73	4.94	103.4	69.6%	15.7	0.20	0.00
43	5/23/08	1538	31	3.77	5.04	106.6	71.7%	15.7	0.20	1.78

In tests 14 to 17 and 19 to 22, carbon conversion calculated from gas measurements was compared to coal conversion obtained from analyses of char at the reactor outlet. The discrepancy obtained was not more than 10 % (relative), confirming the validity of the measurements. The temperature dependence of carbon conversion to gas phase is shown in Figure 24. Results are grouped by stoichiometric ratio of oxygen and presence/absence of DBD plasma.
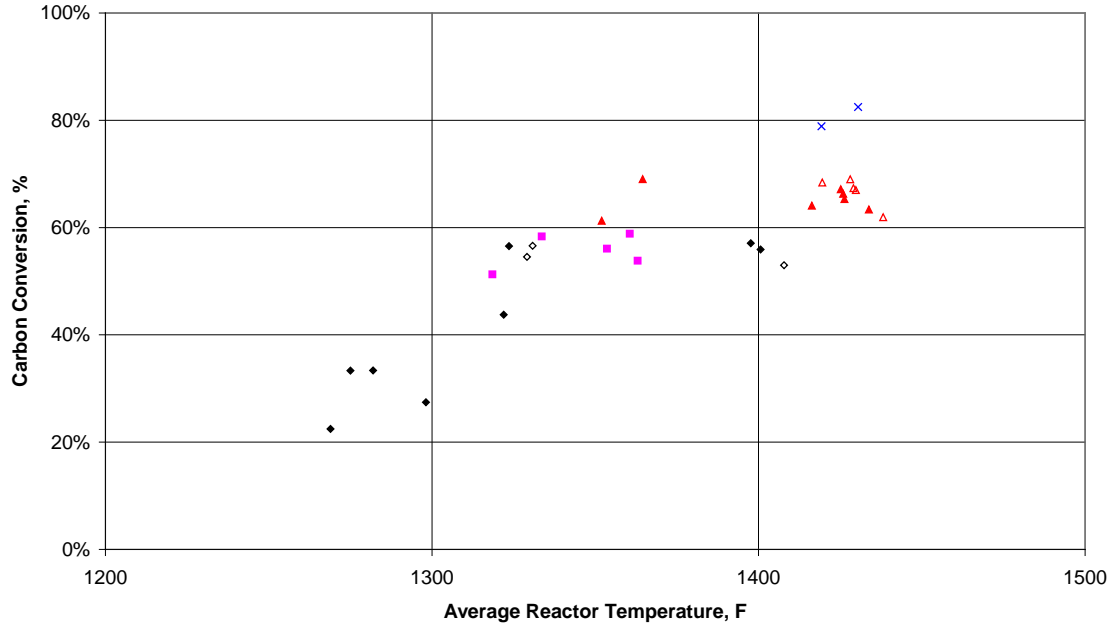
Figure 24. Conversion of Total Coal Carbon to Gas Phase *vs.* **Average Reactor Temperature.** ♦ SR (O$_2$) = 0, DBD off; ■ SR (O$_2$) = 0.1, DBD off; ▲ SR (O$_2$) = 0.2, DBD off; **x** SR (O$_2$) = 0.3, DBD off; ◊ SR (O$_2$) = 0, DBD on; △ SR (O$_2$) = 0.2, DBD on
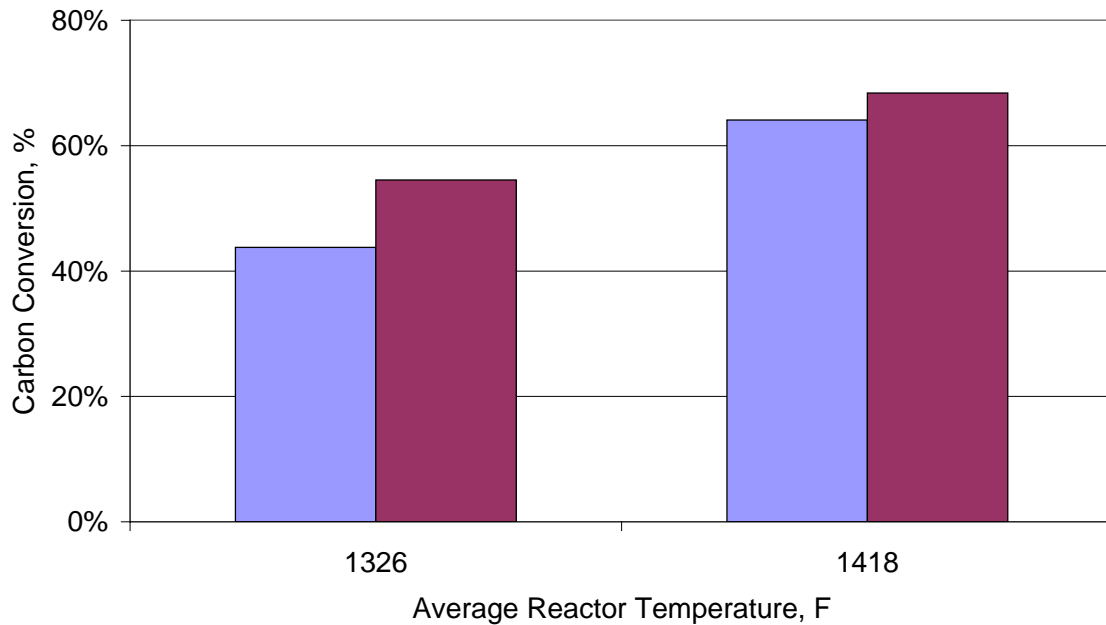

Figure 25. Carbon Conversion with/without Presence of DBD Plasma. ■ **DBD on;** ■ **DBD off.**

Influence of DBD plasma on the reaction is shown in Figure 25.

Analyses of char samples collected at the reactor outlet have shown that some volatile matter (10 – 15 % of initial amount) is still remaining after the reactor (see Figure 26). This fact, and the small diameter of the particles (and, hence, small surface of the particle), as well as laminar flow conditions in the reactor, indicate that a cloud of volatile matter around a reacting coal particle prevents free delivery of reactant (steam) to the reaction zone (coal surface).
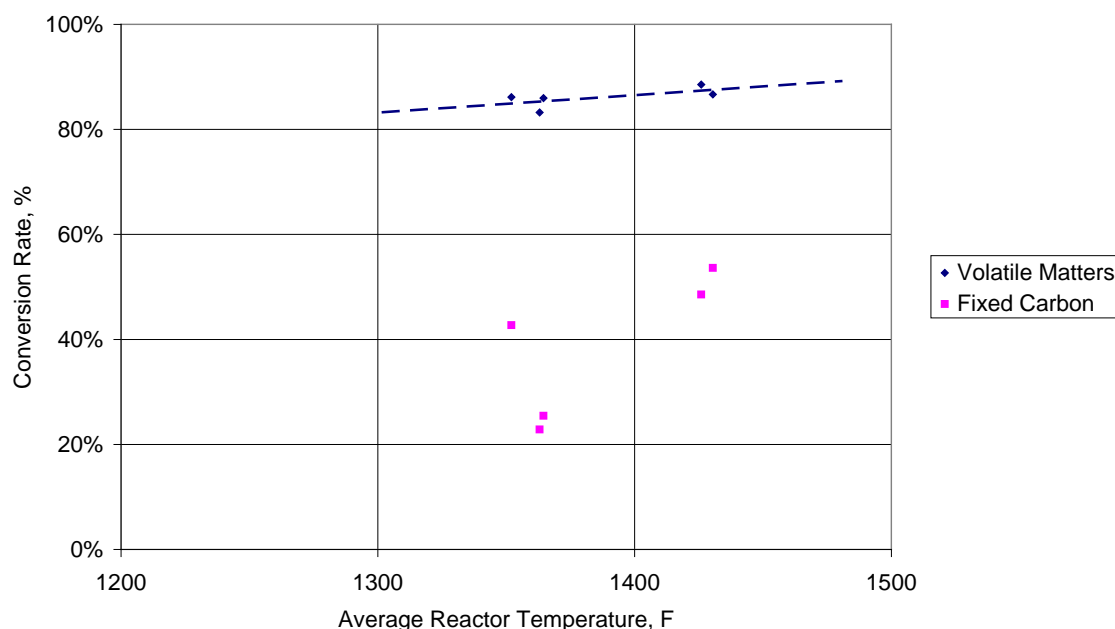
Figure 26. Volatile Matter and Fixed Carbon Conversion.

CONCLUSIONS AND RECOMMENDATIONS

A prospective near-term application of PAR technology was developed during the project. The application developed is recommended as a retrofit to existing coal-fired utility boilers. Benefits of this technology are: better conditions for CO_2 sequestration with simultaneous increase of thermal efficiency, and the co-production of hydrogen. The retrofit suggested includes utilization of a relatively small amount of flue gas recirculation, the PAR reactor and an oxygen plant.

Sulfur and ash removal can be done on existing equipment even more efficiently due to decreased volume (roughly 3 times) of gases to be cleaned. The extra space available due to decreasing the size of cleanup equipment can be used to site the CO_2–capture plant and oxygen plant. The technology suggested requires additional development efforts aimed at optimization of reactor design and technology suitability for real power plants.

An experimental study of the PAR process has shown that a satisfactory coal conversion (>70%) can be obtained at temperatures below 800 °C. Use of DBD plasma can add

roughly 10 % (absolute basis) to coal conversion compared to the non-use of plasma. It was concluded that to achieve a higher carbon conversion requires complete devolatilization of coal during the PAR process to promote reagent delivery to the surface of the coal particle for carbon conversion.

Further experimental efforts should be focused to decrease reactor residence time necessary to get satisfactory carbon conversion. These efforts could be two-fold: 1) promoting devolatilization of coal particles; and 2) promoting turbulent flow conditions in the reactor to get better availability of reactant (steam) in the reaction zone. Excluding the quartz barrier can also be beneficial for industrial applications of the PAR technology.

The cost analysis of the PAR technology made previously [1] has shown that use of this technology decreases production costs of syngas and hydrogen by $1.0 – 1.5/MBtu compared to a conventional gasification system. Costs of hydrogen produced *via* conventional gasification would be about $19/MBtu, while a PAR-based process would yield $14.5/MBtu that is competitive with the cost of hydrogen produced *via* natural gas reforming. The estimated decrease of electricity production costs was estimated at 8 to 10% compared to an IGCC system. The main factor for the production cost decrease is the lower process temperature that is beneficial for capital equipment and operational costs as well.

Near-term application of the technology suggested in this report is less costly due to the utilization of the existing fuel supply and flue gas cleanup systems. The main capital costs are associated with the gasification island, and, because of low process temperature, are lower than that of an IGCC plant. Based on the capital costs of an IGCC system, one can estimate that the capital costs of the suggested retrofit are about $100-150/kW for a 300 MWe power unit. [3]

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