TECHNICAL PROGRESS REPORT NUMBER 40972R11
FOR QUARTER: July 1 – September 30, 2003

Development of Pressurized Circulating Fluidized Bed Partial Gasification Module (PGM)

DOE Contract No: DE-FC26-00NT40972

Issued: October 29, 2003

Foster Wheeler Development Corporation
12 Peach Tree Hill Road
Livingston, NJ 07039

Disclaimer

Abstract

Foster Wheeler Power Group, Inc. is working under US Department of Energy contract No. DE-FC26-00NT40972 to develop a partial gasification module (PGM) that represents a critical element of several potential coal-fired Vision 21 plants. When utilized for electrical power generation, these plants will operate with efficiencies greater than 60% and produce near zero emissions of traditional stack gas pollutants.

The new process partially gasifies coal at elevated pressure producing a coal-derived syngas and a char residue. The syngas can be used to fuel the most advanced power producing equipment such as solid oxide fuel cells or gas turbines, or processed to produce clean liquid fuels or chemicals for industrial users. The char residue is not wasted; it can also be used to generate electricity by fueling boilers that drive the most advanced ultra-supercritical pressure steam turbines.

The amount of syngas and char produced by the PGM can be tailored to fit the production objectives of the overall plant, i.e., power generation, clean liquid fuel production, chemicals production, etc. Hence, PGM is a robust building bock that offers all the advantages of coal gasification but in a more user-friendly form; it is also fuel flexible in that it can use alternative fuels such as biomass, sewerage sludge, etc.

This report describes the work performed during the July 1 – September 30, 2003 time period.

Table of Contents

1.0 Introduction 1
2.0 Executive Summary 3
3.0 Proposed Program 3
4.0 Experimental 5
5.0 Results and Discussion 5
6.0 Conclusions 20
7.0 References 20
8.0 Bibliography 20
9.0 Acronyms and Abbreviations 20

List of Graphical Materials

Figures

1 Vision 21 Modules – Enabling Technologies 3
2 Partial Gasifier Module Experimental Test Unit 4
3 Simplified Schematic of PGM with ACFB Boiler 7
4 Vision 21 Early Implementation PGM Demonstration Plant 8
5 Fuel Carbon Conversion vs. PCFB Gasifier Temperature 13
6 VTR05 Set Point 7 Composition of Overheads 15
7 VTR05 Set Point 7 Overheads Mean Particle Size 15
8 VTR05 Set Point 7 Overheads Size Distribution 16
9 VTR05 Set Point 7 Composition of Overheads by Size Distribution 16
10 VTR05 Set Point 7 Analysis of Overheads 17
11 VTR05 Set Point 9 Solids Composition 18
12 VTR05 Set Point 9 Solids Mean Particle Size 19
13 VTR05 Set Point 9 Char Carbon Conversions 19

Tables

1 Typical Compositions of Fuels Tested 10
2 Vision 21 Test Conditions and Test Results 11, 12

1.0 Introduction

Foster Wheeler Development Corporation is working under DOE contract No. DE-FC26-00NT40972 to develop a partial gasification module (PGM) that represents a critical element of several potential coal-fired Vision 21 plants. When utilized for electrical power generation, these plants will operate with efficiencies greater than 60% while producing near zero emissions of traditional stack gas pollutants.

The new process partially gasifies coal at elevated pressure producing a coal-derived syngas and a char residue. The syngas can be used to fuel the most advanced power producing equipment such as solid oxide fuel cells or gas turbines or processed to produce clean liquid fuels or chemicals for industrial users. The char residue is not wasted; it can also be used to generate electricity by fueling boilers that drive the most advanced ultra-supercritical pressure steam turbines.

The unique aspect of the process is that it utilizes a pressurized circulating fluidized bed partial gasifier and does not attempt to consume the coal in a single step. To convert all the coal to syngas in a single step requires extremely high temperatures (~2500 to 2800F) that melt and vaporize the coal and essentially drive all coal ash contaminants into the syngas. Since these contaminants can be corrosive to power generating equipment, the syngas must be cooled to near room temperature to enable a series of chemical processes to clean the syngas. Foster Wheeler's process operates at much lower temperatures that control/minimize the release of contaminants; this eliminates/ minimizes the need for the expensive, complicated syngas heat exchangers and chemical cleanup systems typical of high temperature gasification. By performing the gasification in a circulating bed, a significant amount of syngas can still be produced despite the reduced temperature and the circulating bed allows easy scale up to large size plants. Rather than air, it can also operate with oxygen to facilitate sequestration of stack gas carbon dioxide gases for a 100% reduction in greenhouse gas emissions.

The amount of syngas and char produced by the PGM can be tailored to fit the production objectives of the overall plant, i.e., power generation, clean liquid fuel production, chemicals production, etc. Hence, PGM is a robust building block that offers all the advantages of coal gasification but in a more user friendly form; it is also fuel flexible in that it can use alternative fuels such as biomass, sewerage sludge, etc.

The PGM consists of a pressurized circulating fluidized bed (PCFB) reactor together with a recycle cyclone and a particulate removing barrier filter. Coal, air, steam, and possibly sand are fed to the bottom of the PCFB reactor and establish a relatively dense bed of coal/char in the bottom section. As these constituents react, a hot syngas is produced which conveys the solids residue vertically up through the reactor and into the recycle cyclone. Solids elutriated from the dense bed and contained in the syngas are collected in the cyclone and drain via a dipleg back to the dense bed at the bottom of the PCFB reactor. This recycle loop of hot solids acts as a thermal flywheel and promotes efficient solid-gas chemical reaction.

Left untreated the syngas will contain tar/oil vapors, alkali vapors, and hydrogen sulfide at levels dependent on PGM operating conditions and fuels. The downstream users of the syngas will dictate a tolerance level for each of these gas constituents. If the users can tolerate both tar vapors and hydrogen sulfide, the syngas can be cooled to a level that condenses the alkali vapors on the particulate being removed by the barrier filter. Although this is a simple solution to an alkali problem, syngas cooling typically lowers the plant efficiency. When efficiency is to be maximized, as in the case of Vision 21 plants, the clean up can be done hot/without syngas cooling. In this case, lime based sorbents can be fed to the PCFB reactor along with the coal to catalytically enhance tar cracking and react with the hydrogen sulfide to capture the sulfur as calcium sulfide. Depending upon sorbent feed rates and gas residence times, the hydrogen sulfide can be reduced to near equilibrium levels which for high sulfur fuels (>3% sulfur) amounts to 95 to 98% sulfur capture. Alkali levels can be brought to gas turbine acceptable levels by injecting finely ground getter material such as emathlite or bauxite into the syngas downstream of the recycle cyclone. The fine particulate that escapes the recycle cyclone together with the injected alkali getter material are carried into the barrier filter by the syngas. As the syngas flows through the porous filter elements, the particulate collects on the outside of the elements and forms a permeable dust cake that ensuing syngas must pass through. The getter absorbs the alkali vapors as the syngas flows to the filter and passes through the filter dust cake. As the dust cake thickness increases, the filter pressure drop increases. Upon reaching a predetermined pressure drop, the dust cake is blown off the element by a back pulse of a clean high-pressure gas such as nitrogen injected into the clean side of the element. The dislodged dust cake falls to the bottom of the filter vessel and drains from the unit. If even higher sulfur capture efficiencies are desired, a second more reactive sorbent can be injected into the syngas for enhanced filter cake sulfur capture. Although the barrier filter is provided to reduce syngas particulate loadings to less than 1 ppm, it can also serve as a reactor in that its filter cake can be used for alkali vapor removal and sulfur capture. The char-sorbent-getter residue generated in the PGM drains continuously from the filter along with an intermittent PCFB reactor bed drain for transfer to the char combustor.

The proposed partial gasifier module (PGM) represents a building block of the Vision 21 program, which can be connected with a variety of additional modules to form complete Vision 21 plants (Figure 1). The PGM represents an “enabling” technology within the Vision 21 framework in that it can serve as a central processing unit for converting the raw fuel (coal, coke, biomass, or other opportunity fuels) into useful by-products (electricity, steam, chemicals, or transportation fuels).

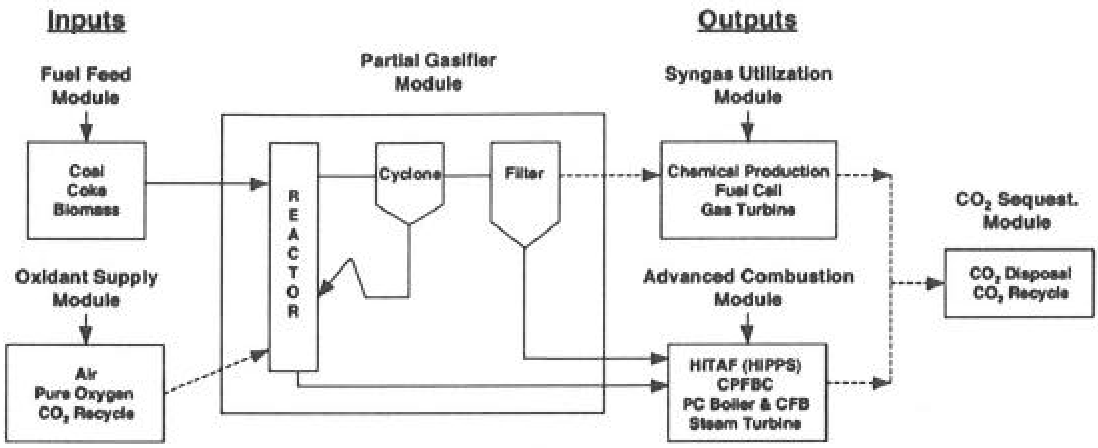

Fig. 1 Vision 21 Modules – Enabling Technologies

2.0 Executive Summary

FW's partial gasification tests in an air blown pressurized circulating fluidized bed gasifier pilot plant have been successfully completed. Under this test program, five different coals, petroleum coke, and sawdust were gasified and the effects of oxygen and CO_2 enrichment of the fluidizing air studied via 22 test points. The testing has shown that the PCFB gasifier:

a. can gasify a wide variety of fuels;
b. can handle highly caking coals without agglomeration problems;
c. can operate in a co-firing biomass-coal mode;
d. can operate with oxygen and carbon dioxide enriched air;
e. can use porous metal filters to filter particulate without tar/oil blinding;
f. char residue can be easily handled.

3.0 Proposed Program

FW possesses a coal-fired PCFB pilot plant at its John Blizard Research Center in Livingston, NJ. The facility can be operated in either a combustion or gasification mode with a gross heat input of up to 12 million Btu/hr. To support the Vision 21 program, the facility will be operated in the gasification mode with the focal point being the PCFB reactor with its recycle cyclone dipleg and loop seal and a barrier filter. These three components form the PGM shown in Fig. 2 and a syngas cooler can be installed to control the filter inlet temperature.

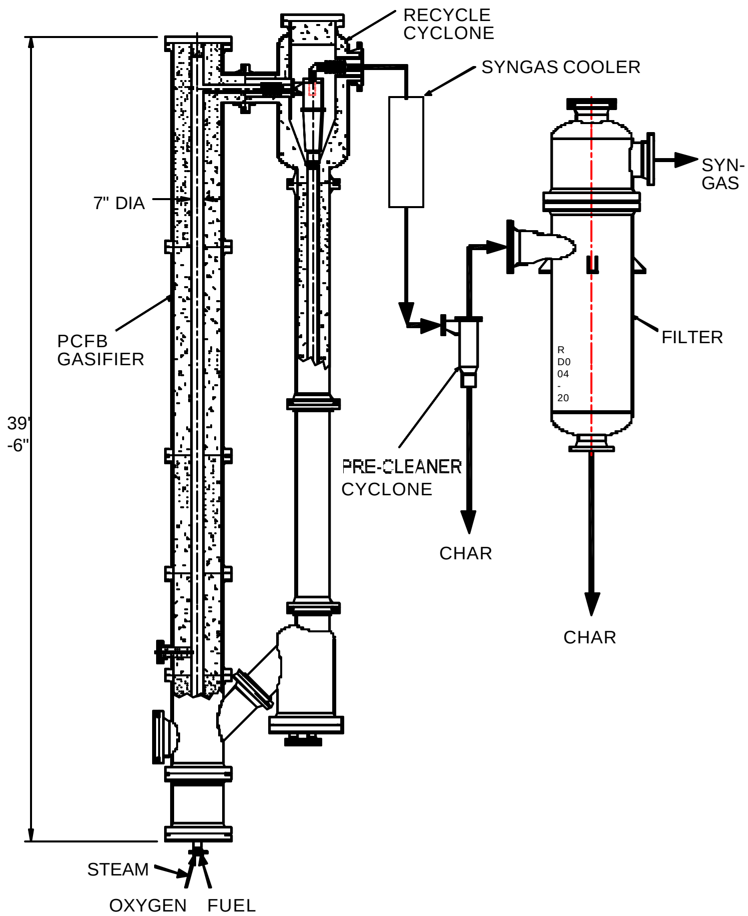

Fig. 2 Partial Gasifier Module Experimental Test Unit

The PCFB reactor is a 30” OD x 39’-6” tall vessel that is refractory lined to a 7” ID. Two lock hopper feed trains operating in parallel bring coal and sorbent to process pressure and feed the materials into a common line that injects the material into the reactor. The coal and sorbent are blown into the unit by air via a vertical 1” Sch 80 pipe located on the centerline and at the base of the unit. A 1½” pipe concentric with the feed pipe admits the balance of the process air together with steam. A relatively dense bed of coal, char, and sorbent form at the base of the unit. Syngas, together with entrained bed particulate matter, flow vertically up the unit at velocities ranging from 12 to 15 ft/sec and exit via a 4” ID radial nozzle 34’-10” above the top of the feed pipe. A recycle cyclone removes larger size particles from the syngas and returns them to the base of the unit via a dipleg and loop seal. The partially cleaned syngas passes through a cooler, a second stage cyclone, and enters a barrier filter vessel for removal of the remaining particulate. The filter can contain up to twenty-two 2 3/8” OD x 60” long candles all hung at one elevation from a metallic horizontal tube sheet. The syngas cooler is designed to yield filter inlet temperatures ranging from 650 to 800EF to allow operation with porous metal iron aluminide candles. The char-sorbent residue generated in the PGM is drained from the bottom of the PCFB reactor via a

2½" wide annulus around the 1½" air supply pipe. The draining material enters a holding section where counter flowing nitrogen cools the material as a packed bed to approximately 500EF. A lock hopper provided under the PCFB reactor and under the filter collects and depressures the material in batches for disposal.

Under the Vision 21 program, the PGM will be operated at varying conditions to determine syngas and char yields, heating values, and compositions when operating with:

1. alternative fuels, e.g., coke and coal-biomass cofiring
2. oxygen-enriched air

The Vision 21 effort is divided into the following five tasks:

Task 1 – Research and Development – Included in this effort are characterization of feedstocks to be tested, material evaluations to determine process induced corrosion rates, computer modeling of the PGM, and updates of possible Vision 21 plant configurations.

Task 2 – Engineering Design – Included in this task is the design of all modifications that must be made to and the procurement of materials that must be incorporated in the existing pilot plant to facilitate the Vision 21 test program.

Task 3 – Construction – This task covers the construction of all Task 2 changes/ modifications.

Task 4 – Testing – Included in this effort are parametric tests and data analyses dealing with alternate feedstocks and oxygen-enriched air plus evaluations of Stamet feed pump and filter performance.

Task 5 – Project Management – Conduct all activities needed to insure that project objectives are met on time and within budget; issue all cost and progress reports and a final report documenting the results of all test activities.

4.0 Experimental

Testing was completed January 2002. See Section 5 for test conditions.

5.0 Results and Discussion

Progress for July-September, 2003, Time Period

Task 1 – Research and Development

Vision 21 commercial plant performance predictions were completed in the 2nd quarter year 2002 reporting period, that showed that a PGM based plant, incorporating a SOFC and a char burning atmospheric pressure CFB boiler in the Figure 3 configuration, would exceed the 60% efficiency goal. As a follow up to that effort, FW is preparing a conceptual design and a budgetary cost estimate for a near term demonstration of that plant. Rather than attempt to maximize plant efficiency, the objective of the demonstration is to operate the plant's key components for the first time as an integrated system. The plant will incorporate components with those technologies/capabilities/sizes expected to be available in 5 to 10 years and, as such, the plant will be a first, lower efficiency step toward the extensive R&D needed to reach the Vision 21 60% efficiency goal.

The proposed demonstration plant incorporates a 20 MWe SOFC operating at 1800F with a nominal 1280F discharge temperature and the below assumed performance

Nominal 1800F SOFC Performance Assumptions:

- hydrogen conversion: 85%
- converted hydrogen energy to electricity: 53%
- converted hydrogen energy to steam cycle: 44%
- converted hydrogen energy lost; 3%

The demonstration plant incorporates a PGM with a SOFC and an atmospheric pressure circulating fluidized bed boiler that burns the char residue along with fresh coal. Figure 4 is a simplified schematic of the plant. After cooling and removal of particulate matter, the syngas produced by the PGM is divided into three streams. One stream conveys PGM char to the CFB boiler, a second fuels the SOFC after undergoing water gas shift and membrane separation of non-hydrogen components, and the third fuels the gas turbine combustor.

The plant has a gross output of 367.4 MWe; it incorporates a General Electric 6 F gas turbine producing 87.4 MWe of power together with a 20 MWe SOFC and a 3600 psig/1050F/1050F/2 in. Hg. supercritical pressure steam turbine producing 260.0 MWe.

In the plant configuration shown in Figure 3 the gas turbine compressor supplies the air required by the PGM, the SOFC, and the gas turbine combustor. Most present day gas turbines can export about 20 to 25% of their compressor discharge air without requiring a development effort. If this approach were to be used in the demonstration plant more than 25% of the compressor air would have to be exported. To eliminate the need for gas turbine development work and to ease integration/ operating complexity in this first of a kind plant, the SOFC has been provided with its own dedicated air compressor. As a result, only about 19% of the gas turbine compressor discharge needs to be exported and the additional air provided by the SOFC compressor increases the plant gross power output by about 5 MWe.

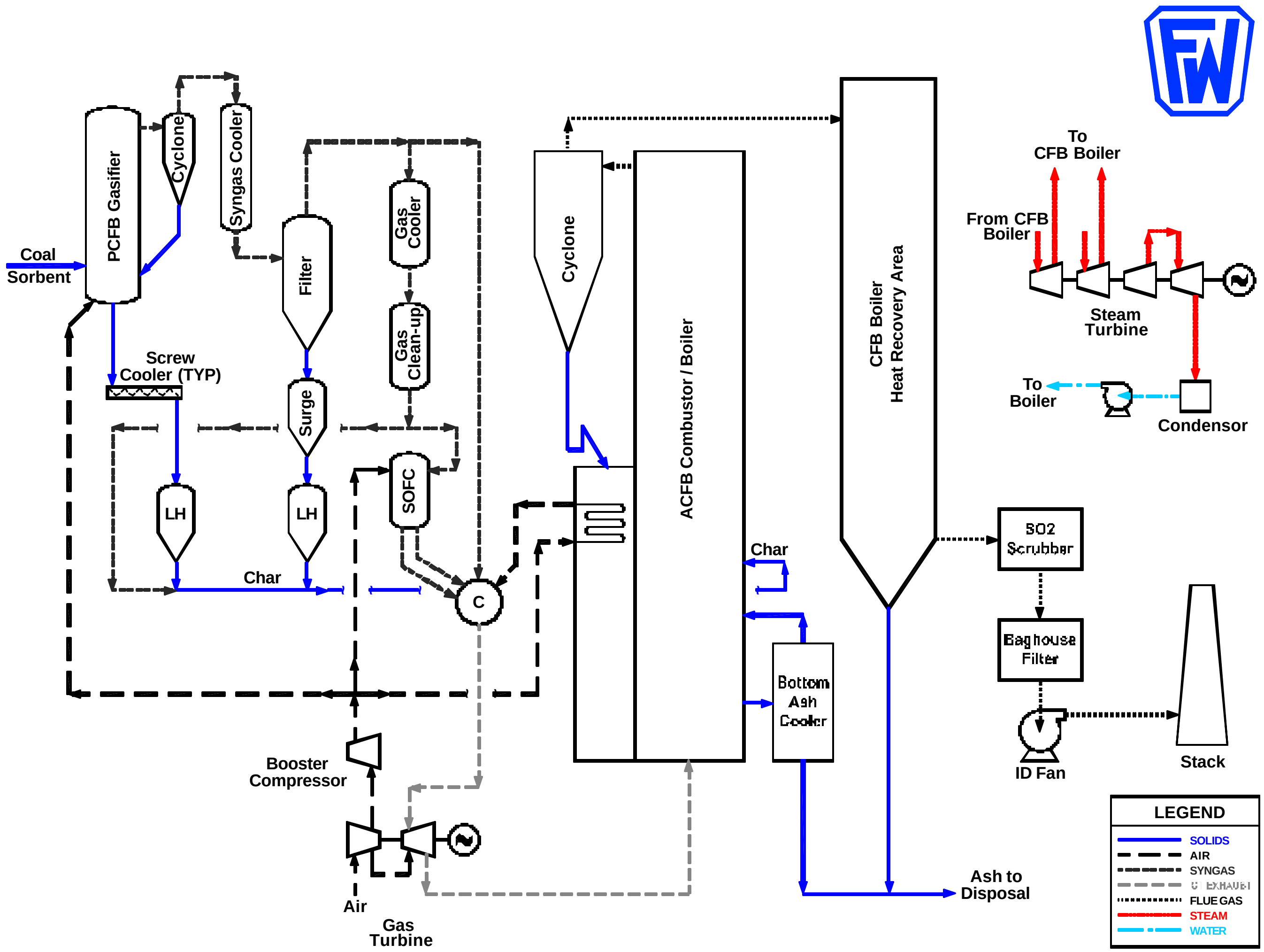

Fig. 3 Simplified Schematic of PGM with ACFB Boiler

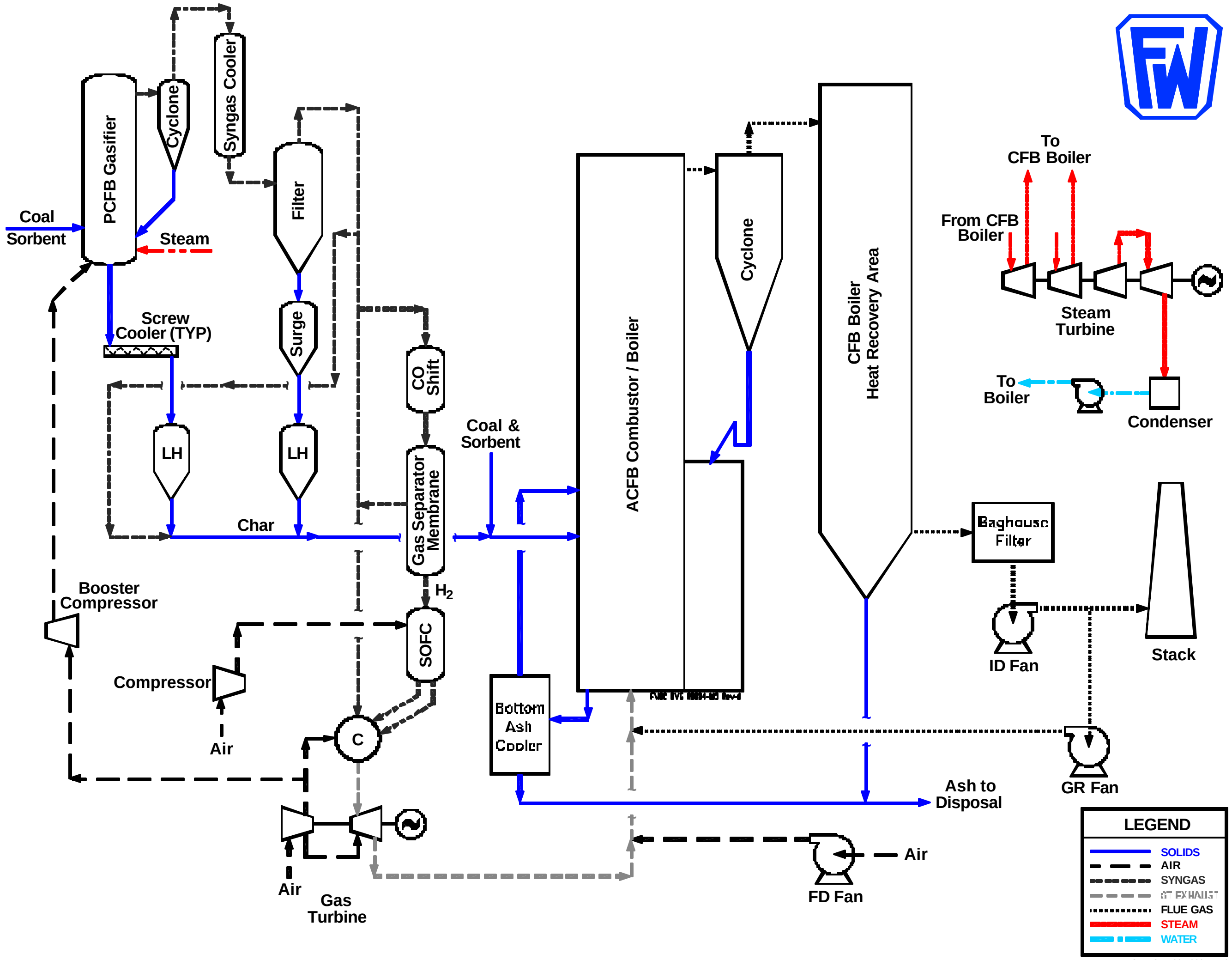

Fig. 4 Vision 21 Early Implementation PGM Demonstration Plant

Even though Figure 4 is a demonstration plant, economics dictate that it have high availability and its complexity should not be daunting to electric utility operators. Providing the SOFC with a separate compressor simplifies control and operation and, should the SOFC portion of the plant be out of service, the gas turbine and CFB boiler can continue to generate electricity at essentially their respective full load values. Similarly the CFB boiler is provided with forced draft and gas recirculation fans that allow it to operate even if the gas turbine and SOFC are both out of service.

A preliminary/first cut heat and material balance was prepared for the Figure 4 demonstration plant in a previous reporting period. The plant operates with bituminous coal from the West Elk Mine in Colorado (see Table 1 for a typical coal analysis). The 1900F syngas produced by the partial gasifier is cooled to 650F and stripped of entrained particulate matter in a porous metal filter. The particulate free syngas divides into three streams. About 1% is used to convey PGM char to the CFB boiler, 72% proceeds to the gas turbine combustor, and the 27% balance undergoes water gas shifting and hydrogen membrane separation. The hydrogen permeate at 450F and 20 psia is compressed to 350 psia, undergoes a final stage of cleanup at 972F (sulfur and chlorides removal via a zinc oxide bed), and is delivered to the SOFC at 972F. Air at 270F is supplied to the SOFC which operates at 1277F. The unused hydrogen exiting the SOFC is quenched by mixing with the membrane retentate whereas the exiting air is cooled to 1123F via heat exchange with the air entering the SOFC. The two exiting streams are then burned with the balance of the PGM syngas in the gas turbine combustor yielding a 2084F firing temperature.

At the 28th International Technical Conference on Coal Utilization & Fuel Systems, Oak Ridge National Laboratory gave a paper on an inorganic hydrogen separating membrane under development that appears suitable for the proposed demonstration plant. A syngas fuel specification was forwarded to Oak Ridge and membrane performance and sizing data was received as the reporting period ended

Task 2 – Engineering Design

This task was completed in a prior reporting period

Task 3 – Construction

This task was completed in a prior reporting period

Task 4 – Testing

PGM pilot plant testing was completed in January 2002 and a total of four coals, petroleum coke, and sawdust were tested; Table 1 presents their typical compositions and it is to be noted that the particular Pennsylvania and Virginia coals shown were specifically chosen because of their high free swelling index; they are highly caking coals and were selected to demonstrate the PCFB gasifier's ability to accommodate agglomerating fuels. One test point was completed with the sawdust cofired with the highly caking Dilworth bituminous coal, 7 points with petroleum coke, 3 points with subbituminous and 11 points with bituminous coals. Of the 7 petroleum coke test points, two used oxygen enriched air and one used carbon dioxide enriched air.

Table 1 Typical Composition of Fuels Tested

Mine Location	Eagle Butte WY	West Elk CO	Jones Fork KY	Dilworth PA	Buchanan VA	---	---
Fuel	**Subbitum.**	**Bitum.**	**Bitum.**	**Bitum.**	**Bitum.**	**Pet Coke**	**Sawdust**
Proximate, Wt % AR							
Moisture	23.57	3.55	6.83	7.50	7.12	1.84	4.28
Volatiles	31.50	37.11	35.74	33.41	19.05	11.14	76.79
Fixed Carbon	39.23	51.53	49.77	51.63	67.93	84.12	16.55
Ash	5.70	7.81	7.66	7.46	5.90	2.90	2.38
Ultimate, Wt % AR							
Carbon	54.09	73.22	70.93	72.96	79.44	88.03	47.64
Hydrogen	3.45	5.16	4.65	4.67	3.85	3.73	5.42
Nitrogen	0.72	1.51	1.44	1.45	1.08	1.28	0.44
Chlorine	0.00	0.05	0.14	0.12	0.17	0.00	0.00
Sulfur	0.29	0.64	1.06	1.41	0.74	2.16	0.03
Ash	5.70	7.81	7.66	7.46	5.90	2.90	2.38
Moisture	23.57	3.55	6.83	7.50	7.13	1.84	4.28
Oxygen	12.18	8.06	7.29	4.43	1.69	0.06	39.81
HHV, Btu/lb	9070	12899	12798	12977	13760	14793	8238
FSI	---	1 1/2	3 1/2	8	8	---	---

Table 2 lists the operating conditions together with start and stop times for each of the 22 test points. Mass and energy balances were prepared for each of the test points, their carbon conversions and syngas heating values determined, and their data added to Table 2.

The carbon conversions calculated for the 22 test points are shown in Figure 5. As expected, carbon conversions increased with increasing temperature and the subbituminous coal, Eagle Butte, being very reactive had the highest carbon conversions; they ranged from 80 to 90 % over the nominal 1750 to 1810F temperature range. The bituminous West Elk, Jones Fork, and Dilworth coals had similar fixed carbon and volatile matter contents and their carbon conversions fell along a line running from about 60 up to 80% over the 1840 to 1960F temperature range. Syngas lower heating values on a dry and purge nitrogen free basis ranged from about 110 to 120 Btu/SCF for the subbituminous to 90 to 125 Btu/SCF for the bituminous coals.

Table 2 Vision 21 Test Conditions and Test Results

Test Run		VTR-01-01	VTR-01-02	VTR-01-03	VTR-02-01	VTR-03-01	VTR-03-02	VTR-04-01	VTR-04-02	VTR-04-03	VTR-04-04	VTR-04-05	VTR-04-06	VTR-04-07
Begin Date		10/02/01	10/03/01	10/03/01	10/23/01	11/13/01	11/13/01	12/04/01	12/05/01	12/05/01	12/06/01	12/06/01	12/07/01	12/07/01
Begin Time		23:00	2:00	12:15	5:00	6:00	18:00	17:00	0:30	10:00	2:30	13:00	2:00	11:00
End Date		10/03/01	10/03/01	10/03/01	10/23/01	11/13/01	11/13/01	12/04/01	12/05/01	12/05/01	12/06/01	12/06/01	12/07/01	12/07/01
End Time		1:00	4:00	14:15	7:00	8:00	20:00	20:00	4:30	13:00	6:30	15:00	5:00	13:00
Operation Condition														
Fuel	-	West Elk	West Elk	West Elk	JF Coal	JF Coal	JF Coal	EB Coal	EB Coal	EB Coal	BU Coal	BU Coal	DW Coal	DW Coal
Carbon content	%	73.6	73.6	73.6	77.8	79.9	79.9	60.1	60.1	59.1	85.0	85.0	80.0	80.0
Pbed (PI-3007)	psig	117	117	123	93	90	117	116	120	103	122	107	117	109
Tbed (TI-3016)	F	1925	1931	1909	1941	1955	1961	1804	1808	1744	1851	1909	1896	1844
Tbed (TI-3012)	F	1936	1940	1915	1946	1959	1963	1816	1818	1756	1855	1903	1891	1838
Carbon conversion	%	72.4	76.8	72.6	80.2	76.2	76.1	88.3	90.6	80.6	46.1	56.2	66.4	61.3
Feed														
Coal Feed Rate	lb/h	325	311	328	218	228	308	362	347	342	362	239	269	276
Limestone Feed Rate	lb/h	3	3	4	14	29	17	1	1	1	1	1	1	1
Sand Feed Rate	lb/h	0	0	0	0	0	0	9	8	11	5	45	0	0
Air Flow Rate	lb/h	1200	1189	1200	1000	999	1209	1200	1200	1050	1200	1050	1154	1050
Steam Feed Rate	lb/h	107	114	159	175	164	216	35	97	31	157	141	134	140
O2 or CO2 Feed Rate	lb/h													
Output														
Filter Char Drain (FD)														
Drain Rate	lb/h	116	56	66	125	68	89	80	82	113	248	158	138	111
Carbon content	%	68	84	71	4	40	70	18	12	27	87	62	57	70
d_{50}	micr	45	31	30	161	145	81	133	134	99	49	65	72	56
Bed Drain (PD)														
Drain Rate	lb/h	0	0	0	0	0	0	0	0	0	15	0	0	0
Carbon content	%	5	5	5	4	27	22	5	0	0	0	0	0	0
d_{50}	micr	249	249	249	225	244	243	249	311	311	318	318	318	318
Process gas														
flow rate*	lb/h	1472	1502	1507	1335	1279	1639	1544	1605	1351	1487	1349	1442	1354
heating value LHV*	Btu/scf	122	121	124	90	99	109	119	111	120	99	82	107	107
composition* (by v)														
Ar	%	0.82	0.85	0.86	0.89	0.91	0.87	0.73	0.74	0.75	0.84	0.85	0.82	0.76
N_2	%	59.7	60.1	58.1	64.56	62.7	59.5	60.2	60.5	59.9	65.26	69.5	63.1	63.5
CO	%	12.3	13.2	11.5	7.35	9.7	10.6	14.7	11.9	14.0	8.59	6.5	10.9	8.9
CO_2	%	13.1	12.0	13.9	15.46	15.5	14.2	11.5	13.3	11.7	12.78	13.6	13.0	13.3
H_2	%	12.5	12.3	13.7	10.17	10.7	12.9	11.5	12.2	11.9	11.35	8.8	11.7	11.8
CH_4	%	1.3	1.1	1.4	1.06	1.0	1.6	1.3	1.3	1.3	0.85	0.5	1.0	1.5
C6+	%	0.35	0.34	0.36	0.31	0.31	0.28	0.30	0.29	0.30	0.34	0.3	0.3	0.3
H2S	ppm	600	600	300	1500	2300	1900	1000	1200	900	900	900	1600	1500
NH3	ppm	600	600	300	1600	1100	1500	1000	1600	1500	700	500	500	600
H2S(Drag)	ppm	161	158	162	1741	1867	1618	559	740	521	648	646	1257	1188
NH3(Drag)	ppm	104	102	105	1202	477	771	981	1461	1321	665	423	442	520

Table 2 Vision 21 Test Conditions and Test Results (continued)

Test Run		VTR-05-01	VTR-05-02	VTF-05-03	VTF-05-04	VTF-05-05	VTF-05-06	VTF-05-07	VTF-05-08	VTR-05-09
Begin Date		01/15/02	01/16/02	01/16/02	01/16/02	01/17/02	01/17/02	01/17/02	01/18/02	01/18/02
Begin Time		22:30	6:00	14:15	23:30	6:00	12:35	20:27	5:33	13:00
End Date		01/16/02	01/16/02	01/16/02	01/17/02	01/17/02	01/17/02	01/17/02	01/18/02	01/18/02
End Time		0:30	8:00	16:15	1:30	8:00	14:35	22:37	8:33	15:00
Operation Condition										
Fuel	-	Coke	Coke	Coke	Coke, CO2	Coke, O2	Coke, O2	Coke	DW	DW/sawdust
Carbon content	%	88.0	88.0	88.23	88.5	88.6	88.6	88.6	82.4	75.1
Pbed (PI-3007)	psig	101	106	103	101	95	83	104	107	110
Tbed (TI-3016)	F	1902	1834	1907	1901	1889	1898	1946	1901	1883
Tbed (TI-3012)	F	1912	1845	1918	1913	1902	1911	1956	1913	1900
Carbon conversion	%	71.8	67.4	70.7	65.0	52.8	48.7	66.8	71.0	71.8
Feed										
Coal Feed Rate	lb/h	219	251	219	238	337	326	227	254	237
Limestone Feed Rate	lb/h	15	14	27	16	15	15	27	15	7
Sand Feed Rate	lb/h	36	32	63	36	35	36	62	35	17
Air Flow Rate	lb/h	1100	1100	1100	1100	831	584	1100	1100	1100
Steam Feed Rate	lb/h	128	152	150	31	142	178	128	129	126
O2 or CO2 Feed Rate	lb/h				CO2=137	O2=65	O2=103			
Output										
Filter Char Drain (FD)										
Drain Rate	lb/h	166	112	101	127	149	146	34	83	90
Carbon content	%	65	77	62	76	81	81	62	66	61
d_{50}	micr	62	47	73	92	89	89	60	46	64
Bed Drain (PD)										
Drain Rate	lb/h	0	0	0	0	0	0	0	0	0
Carbon content	%	NA	NA	NA	NA	NA	NA	NA	0	0
d_{50}	micr	NA	NA	NA	NA	NA	NA	NA	NA	NA
Process gas										
flow rate*	lb/h	1432	1513	1491	1445	1434	1277	1477	1510	1535
heating value LHV*	Btu/scf	83	90	80	82	117	129	89	98	100
composition* (by v)										
Ar	%	0.84	0.79	0.83	0.77	0.63	0.56	0.83	0.78	0.78
N_2	%	66.1	64.16	66.74	62.46	56.29	50.56	67.42	63.94	63.6
CO	%	8.28	9.05	7.83	11.76	15.11	14.57	8.33	8.96	8.76
CO_2	%	14.89	14.09	14.55	18.43	12.95	16.28	13.93	13.71	14.25
H_2	%	9.12	10.88	9.23	5.99	13.88	16.44	8.77	10.66	10.34
CH_4	%	0.44	0.55	0.39	0.27	0.68	0.91	0.35	1.57	1.88
C6+	%	0.29	0.28	0.28	0.28	0.27	0.28	0.29	0.28	0.28
H2S	ppm	1100	1300	1200	1100	1600	1700	1100	1200	1000
NH3	ppm	100	400	300	500	800	2800	1600	100	1700
H2S(Drag)	ppm	1118	1995	1111	1156	985	1631	1057	569	629
NH3(Drag)	ppm	117	797	241	74	71	66	94	155	281

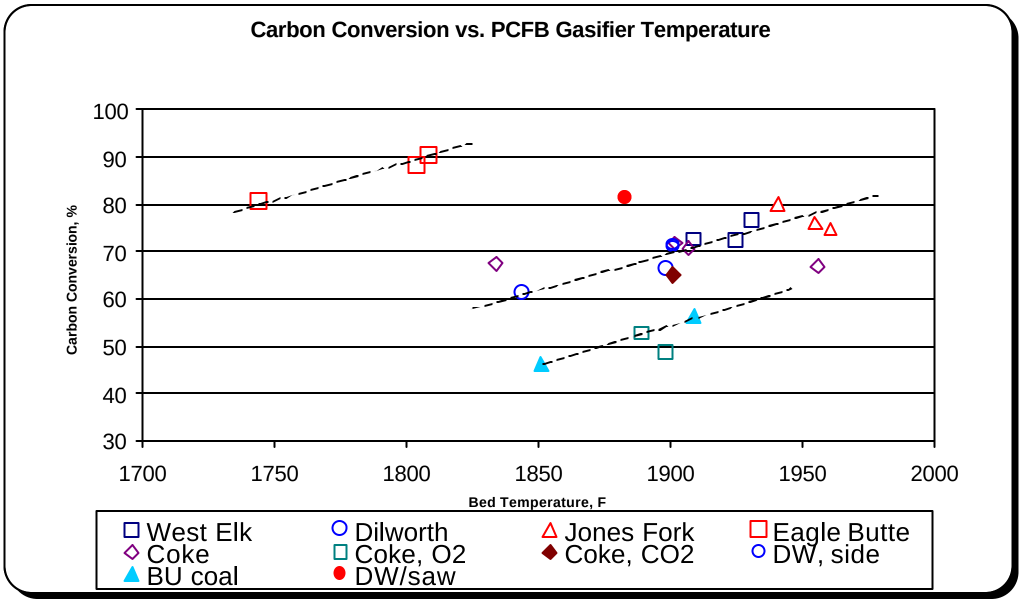

Figure 5 Fuel Carbon Coversion vs. PCFB Gasifier Temperature

The Buchanan coal had a volatile content about half that of the other bituminous coals and its carbon conversions (46 to 56%) and heating values (80 to 100 Btu/SCF) were much lower than the others for the same range in temperatures.

The carbon conversion observed with petroleum coke was less sensitive to temperature ranging from 67 to 72% as the operating temperature was varied between 1834 to 1946. When oxygen enriched air was used, less heat absorbing nitrogen entered the unit and for the same temperature, less oxygen and, hence, less carbon conversion was needed. As a result, the carbon conversions observed with petroleum coke and oxygen enriched air falls below the air only data; enriching the air with carbon dioxide had little effect on carbon conversion. In air blown operation the coke syngas lower heating value ranged from 80 to 90 Btu/SCF whereas increasing oxygen enrichment increased these values to 117 and 129 Btu/SCF.

A review of the Table 2 test summary reveals that 21 of the 22 test points were completed without the need to drain bed material from the PCFB gasifier. Even though coal and a very small amount of limestone were fed continuously to the gasifier, there was no need to drain bed material from the gasifier. The injected coal and limestone continuously circulated through the riser, recycle cyclone, and dipleg return of the gasifier until process reactions and attrition reduced the circulating particles to a density and size that enabled them to escape the recycle cyclone. When the escape rates exceeded the feed rates, sand was added with the coal and limestone to keep the inventory of circulating solids within desired limits.

Test Point VTR04-4 was the only point that required a bed drain. It was conducted with the low volatile/high carbon Buchanan coal at a relatively low temperature. This test point possessed the lowest carbon conversion of all the points (46.1 percent) and, because of this, required a small bed drain to keep the inventory of circulating solids within desired limits. When the test temperature was raised to 1951ºF, carbon conversion increased and there was no further need to drain bed material.

A commercial scale PCFB gasifier is expected to behave similarly; it will not require a continuous drain of material from the bottom of the riser. Instead, a bottom drain will be taken intermittently as part of a bed cleansing procedure, once a shift, to prevent the possible accumulation of over size bed material. As a result, the amount of char contained in the “solids” that escape the recycle cyclone limits/determines the gasifier carbon conversion efficiency and an analysis of the escaping solids, called overheads, was undertaken. Since this material is a mixture of char, limestone, and sand with differing particle size distributions and densities, it is very difficult to obtain a representative sample and only broad generalizations can be made.

In Set Point 7 of Test Run VTR05 the gasifier was operating at 1956ºF with petroleum coke and five samples of the overheads were taken at approximately half hour intervals. Each sample (FD 52 through 56) was analyzed and as shown in Figures 6 and 7 char contents ranged from 56 to 69 percent by weight and mean particle diameters from 50 to 120 microns. (These variations are typical and they are the reason why carbon conversions are determined from gas rather than solids analyses). Sample FD-54 was further analyzed; it was sieved into four size fractions that were weighed and analyzed. Per Figure 8, eight percent of the sample was larger than 300 microns whereas 54 percent was finer than 75 microns. Per Figure 9 most of the 75 micron material (86 percent) was char. Based on this data Figure 10 was constructed; it shows that most of the char (2/3rds) that escaped the gasifier was finer than 75 microns. Conversely 1/3 of the char or about half of all the overheads was greater than 75 microns. The latter would appear to indicate the recycle cyclone was not performing up to expectations and that higher carbon conversions could be achieved by increasing its collection efficiency.

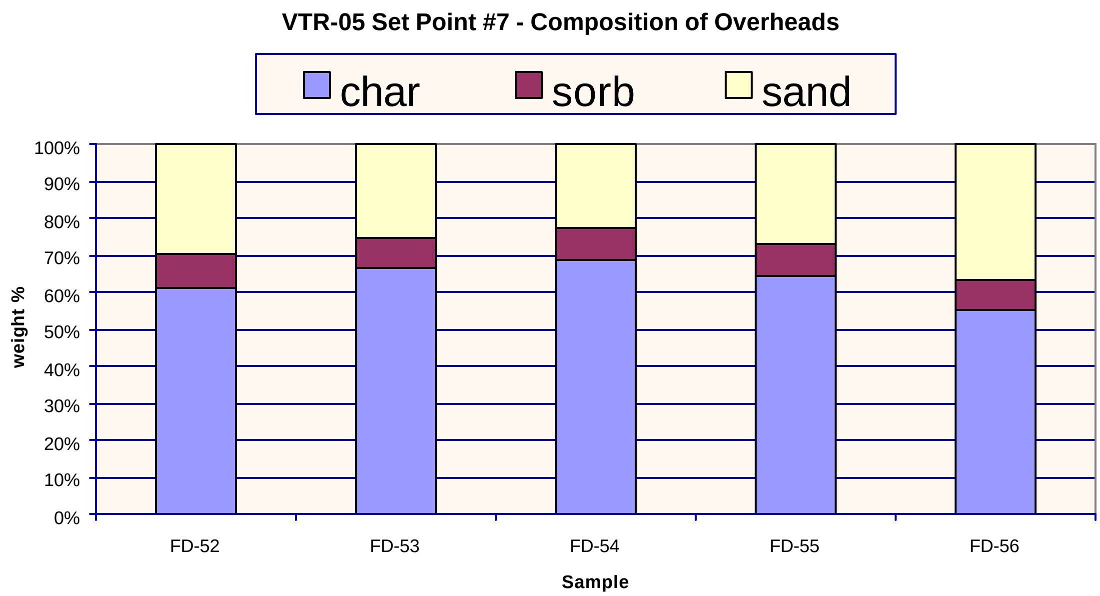

Figure 6 VTR05 Set Point 7 Composition of Overheads

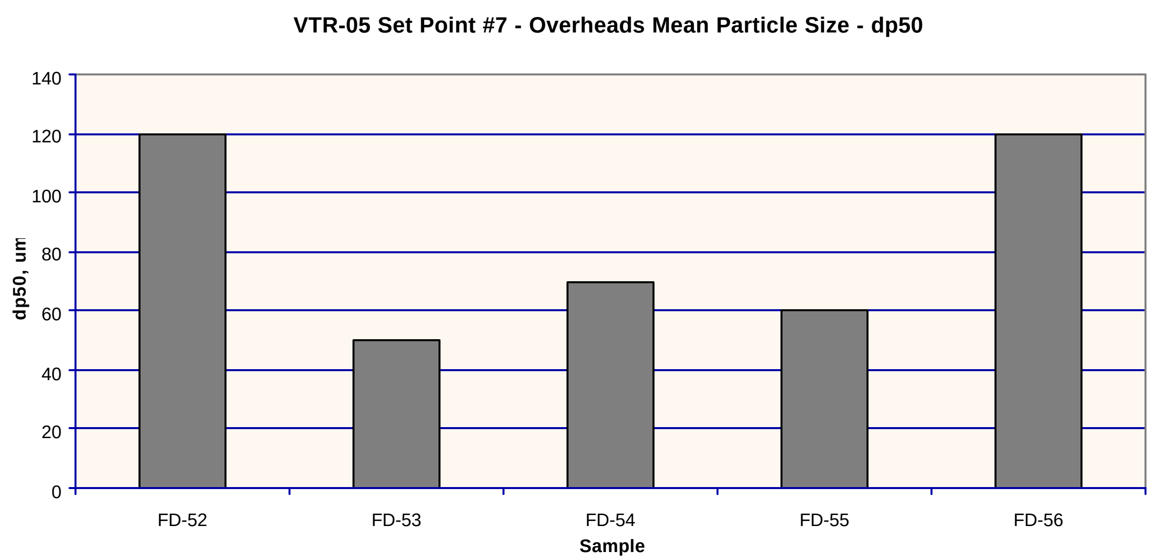

Figure 7 VTR05 Set Point 7 Overheads Mean Particle Size

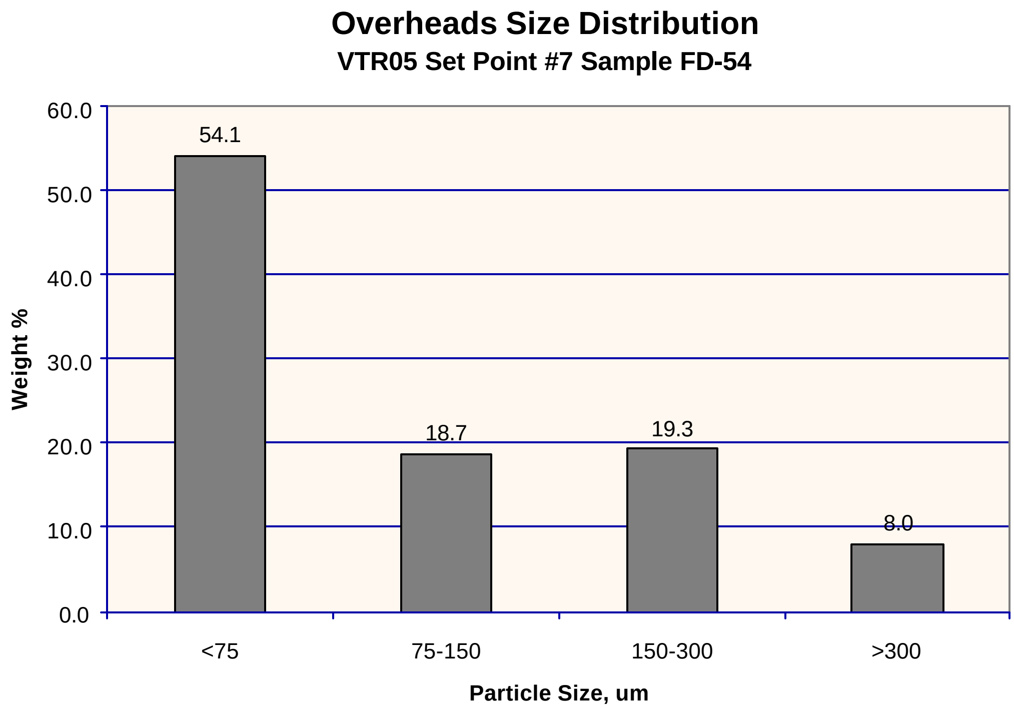

Figure 8 VTR05 Set Point 7 Overheads Size Distribution

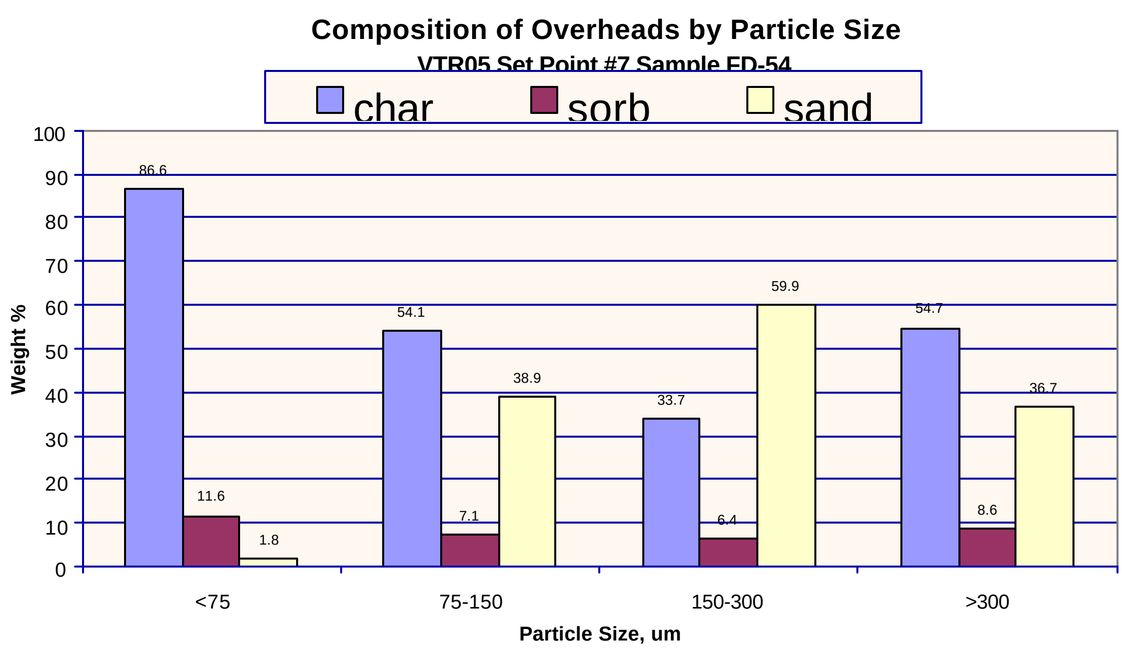

Figure 9 VTR05 Set Point 7 Composition of Overheads by Size Distribution

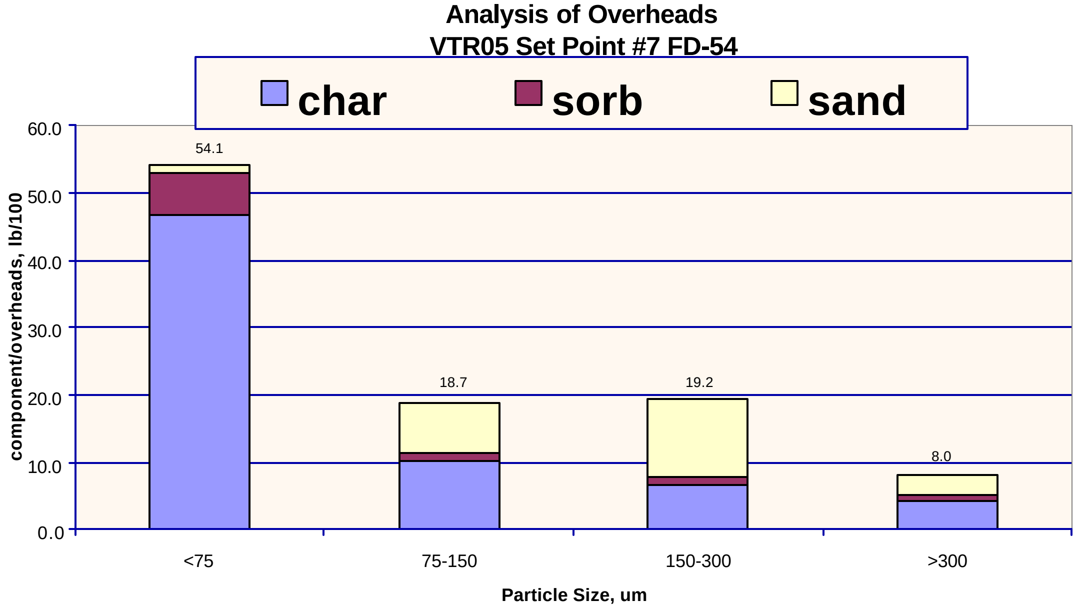

Figure 10 VTR05 Set Point 7 Analyses of Overheads

In Set Point 9 of Test Run VTR05 the PCFB gasifier was operating at 1900ºF while co-firing Dilworth coal and saw dust. After completing the set point filter pulse cleaning was put on manual control and the plant shut down. In an attempt to obtain a filter cake that was representative of the last set point, the filter was not pulse cleaned during the shut down. The filter was disassembled and a sample of the cake (PTCF) collected for analyses. Two samples of bed material (BD 11 and 12) were also collected when the PCFB gasifier bed was drained from the unit. Analyses of these samples along with the last two overheads drain samples (FD 69 and 70) collected during Set Point 9 prior to the shut down are presented in Figures 11 through 13. The data reveal:

1.) the bed had a 300 micron mean particle size and was mostly sand in a 70/20/10 sand/char/limestone weight ratio.
2.) the overheads had about a 40 micron mean particle size and was mostly char in roughly an 80/15/5 char/sand/limestone weight ratio.
3.) the filter cake had a 14 micron mean particle size and was primarily char in roughly a 90/10 char/limestone weight ratio.
4.) the char in the bed, which was expected to be relatively coarse, evidenced high carbon conversion at over 95 percent.
5.) the overheads, being finer, evidenced about 70 percent carbon conversion.
6.) the filter cake char, being the finest in size, had the lowest carbon conversion at about only 20 percent.

From the above it appears that coarser coal particles remain in the gasifier recycle loop longer than finer coal particles and, as a result, experience higher carbon conversion. Since the finest char particles had only about 20 percent carbon conversion, it appears the finer fraction of the coal feed may have escaped the gasifier system in their first pass through the unit. Should it become desirable to increase the carbon conversion efficiency of the PCFB gasifier this can be achieved by increasing the collection efficiency of the recycle cyclone and reducing the amount of fines in the coal feed.

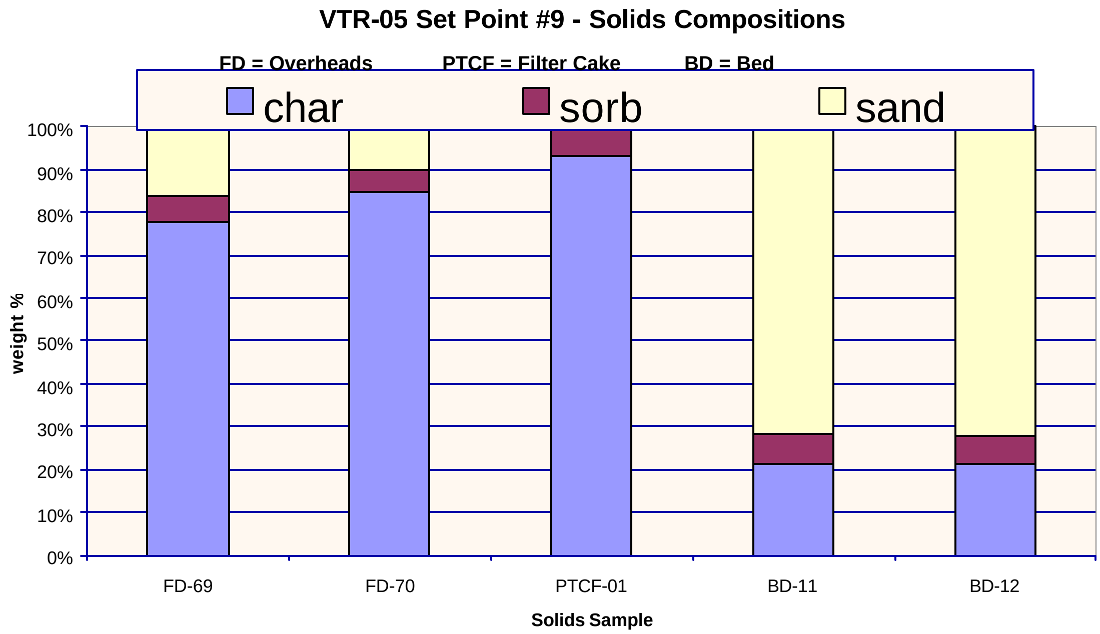

Figure 11 VTR05 Set Point 9 Solids Composition

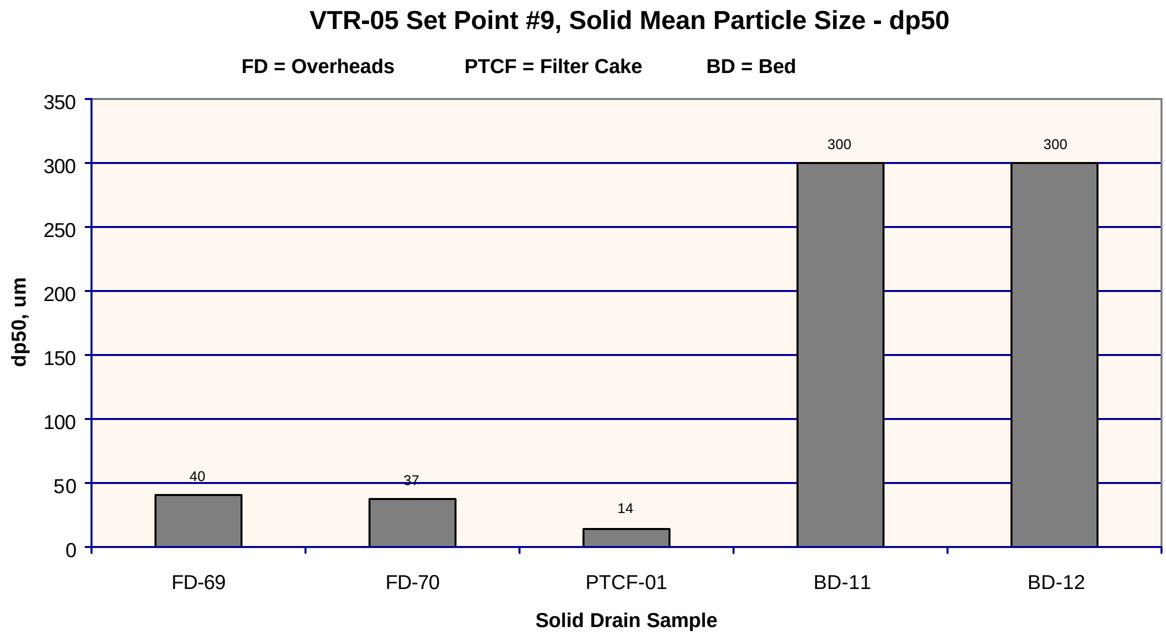

Figure 12 VTR05 Set Point 9 Solids Mean Particle Size

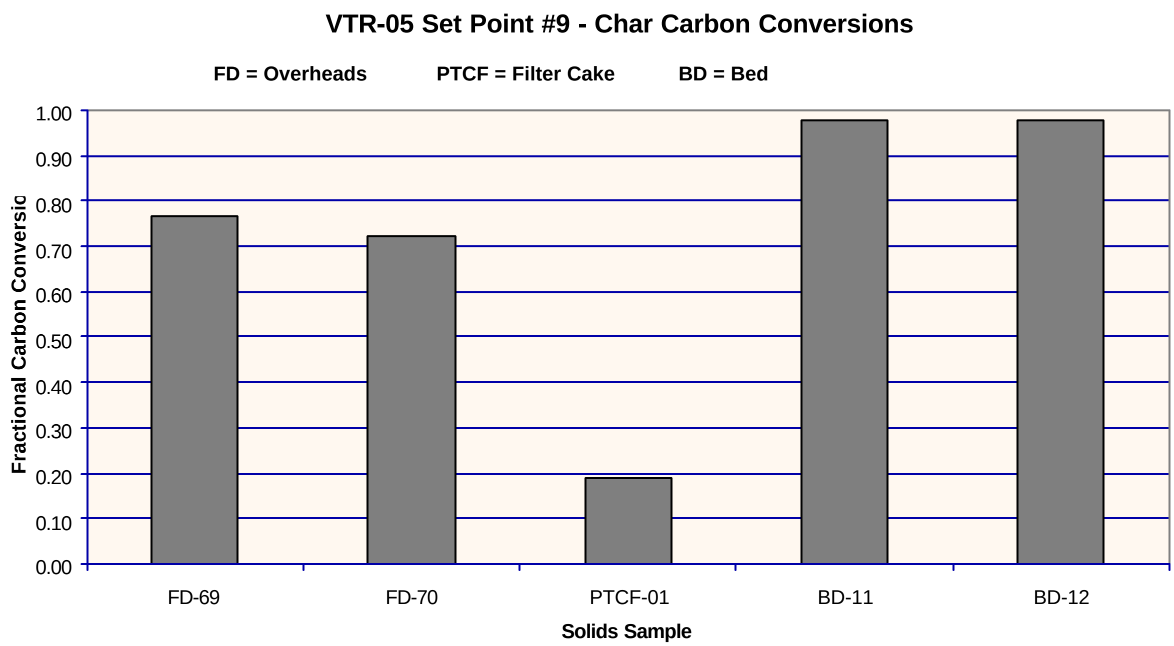

Figure 13 VTR05 Set Point 9 Char Carbon Conversions

Analyses of the test data has been completed and preparation of a test report are underway. As previously reported general observations are that the test program was very successful in that:

a. it has confirmed commercial plant predictions;
b. it has demonstrated that a PCFB can gasify a wide variety of fuels ;
c. it can handle highly caking coals without agglomeration problems;
d. it can operate in a co-firing biomass-coal mode;

e. it can operate with oxygen and carbon dioxide enriched air;
f. porous metal filters can be used to filter particulate without tar/oil blinding;
g. the char residue produced by the PCFB can be easily handled.

Task 5 – Project Management

With analysis of the test data having been completed a final report is in preparation and is proceeding toward an October 31, 2003 submittal.

6.0 Conclusions

Analyses of all twenty two test points have been completed. As expected the Eagle Butte subbituminous coal yielded the highest carbon conversions (ranged from 80 to 90%) and its syngas lower heating values ranged from 110 to 120 Btu/SCF. Most of the bituminous coal carbon conversions were in the 60 to 80% range with syngas lower heating values ranging from 90 to125 Btu/SCF. With petroleum coke being low in volatile content its syngas heating values were lower ranging from 80 to 90 Btu/SCF; operation with oxygen enriched air raised the coke values to 117 and 129 Btu/SCF. Since commercial plant syngas heating values will be higher, all of these fuels should be suitable for a gas turbine with a combustor designed for low Btu gas.

7.0 References

N/A

8.0 Bibliography

N/A

9.0 Acronyms and Abbreviations

ACFM	Atmospheric Pressure Circulating Fluidized Bed
ATS	Advanced Turbine System
D50	Mass Mean Particle Size in Microns
DOE	U.S. Department of Energy
FW	Foster Wheeler Power Group, Inc.
HITAF	High-Temperature Air Heater
PCFB	Pressurized Circulating Fluidized Bed
PGM	Partial Gasification Module
SOFC	Solid Oxide Fuel Cell