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FLUIDIZED-BED COMBUSTION PROCESS**

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ABSTRACT

Under the sponsorship of the United States Department of Energy, Foster Wheeler Development Corporation, and its team members, Westinghouse, Gilbert/Commonwealth, and the Institute of Gas Technology are developing second-generation pressurized fluidized bed combustion technology capable of achieving net plant efficiency in excess of 45 percent based on the higher heating value of the coal. A three-phase program entails design and costing of a 500 MWe power plant and identification of developments needed to commercialize this technology (Phase 1), testing of individual components (Phase 2), and finally testing these components in an integrated mode (Phase 3).

This paper briefly describes the results of the first two phases as well as the progress on the third phase. Since other projects which use the same technology are in construction or in negotiation stages—namely, the Power System Development Facility and the Four Rivers Energy Modernization Projects—brief descriptions of these are also included.

INTRODUCTION

As we approach the 21st Century, we begin to reassess our global energy needs more realistically. We are vigorously studying more efficient technologies. We are already in the beginning stages of commercialization of the first generation coal gasification combined cycles, and pressurized fluidized bed combustion (PFBC) power plants. Both of these technologies yield net plant efficiencies, based on higher heating values of the coals, of approximately 40 percent. This represents a 4-point jump over those of pulverized coal and atmospheric fluidized bed combustion power plants. New and improved technologies, presently under development, promise efficiencies in excess of 40 percent. One of these new technologies is the second-generation pressurized fluidized bed combustion plant, which is capable of achieving efficiency in the 45- to 47-percent range. This paper presents a summary of the second-generation PFBC developmental efforts performed by a team headed by Foster Wheeler Development Corporation (FWDC). The program is funded by the U.S. Department of Energy (DOE) and cost-shared by FWDC and the participating team members (Westinghouse, Institute of Gas Technology and Gilbert/Commonwealth). The program entails three phases:

- Phase 1 – Design and cost estimating of a 500-MWe power plant and identification of developments needed in support of commercialization of this technology
- Phase 2 – Pilot plant testing of individual components presently not under development
- Phase 3 – Pilot plant testing of components in an integrated mode and update of the commercial plant based on test results obtained in Phases 2 and 3.

Second-Generation PFBC Concept

Schematically, the second-generation PFBC plant is shown in Figure 1. In this concept, all coal and sorbent are fed under pressure into a carbonizer/partial gasifier where a portion of the coal energy is converted into low-Btu fuel gas, and a major portion of the released sulfur is captured by the sorbent. The char-sorbent residue from the carbonizer is then fed into a circulating pressurized fluidized bed combustor (CPFBC) where the balance of the coal energy is extracted. Part of this energy is used to preheat gas turbine air to 871°C (1600°F), while the balance of energy generates steam. The flue gas from the CPFBC

Figure 1. Simplified process block diagram of the second-generation PFBC plant

and the fuel gas from the carbonizer are cleaned of particulates by cyclones and ceramic barrier filters, and both proceed to the gas turbine combustor. There the temperature of the flue gas from the CPFBC is raised by combustion of the fuel gas from the carbonizer, and then expanded in the gas turbine. Additional steam is generated in the heat recovery steam generator (HRSQ) which is located downstream of the gas turbine. The high-pressure/high-temperature steam for the HRSQ and CPFBC is fed to a steam turbine which, together with the gas turbine, generate the plant electrical output.

Design of a Commercial Plant

As mentioned previously, Phase 1 of the program addressed the design and costing of a 500-MWe net electric power plant as well as identified its R&D needs. The requirements of the plant are stated below:

- Net plant efficiency of 45 percent
- Cost of electricity 20 percent below that of pulverized coal-fired plant with scrubber
- Flexibility in burning different coals.

The plant burned Pittsburgh No. 8 coal with sulfur content of 3 percent and higher heating value of 7175 kcal/kg (12,916 Btu/lb) (as received). The sorbent was Plum Run dolomite. The cost estimate was in accordance with Electric Power Research Institute (EPRI) Technical Assessment Guide [1].

The first step in the design predicted the performance of the carbonizer. Based on limited and scattered published data [2-6], a heat and material balance of the carbonizer (shown in Figure 2) was generated. Using this as a basis, heat and material balance for a 500-MWe CPFBC plant was prepared (Figure 3). It is based on Westinghouse's 501F gas turbine with combustor outlet temperature of 1288°C (2350°F) and steam turbine conditions of 16.55 MPa/538°C/538°C/63.5 mm Hg (2400 psig/1000°F/100-0°F/2.5 in. Hg). The plant [7] is comprised of two identical carbonizer-CPFBC-gas turbine trains, each rated at approximately 250 MWe and a single steam turbine. Table 1 shows the cost and performance comparison between the second-generation CPFBC plant and a conventional pulverized coal-fired plant with scrubber, as estimated in 1987.

Figure 2. 871°C carbonizer heat and material balance

The sensitivity study revealed that the second-generation CPFBC plant performs satisfactorily with a variety of coals and sorbents provided that the solids handling equipment is properly sized. The R&D needs are summarized in Table 2. Since the high-temperature/high-pressure particulate filtration system is pursued under different DOE contracts, its development will not be directly addressed in this program.

Figure 3. Heat and material balance for a 500-MW(e) second-generation PFBC plant

TABLE 1
Phase 1 Plant Comparisons (Pittsburgh No. 8)

Summary	1.418-MPa Second- Generation PFB at Best Eff. Point 871°C Carbonizer	Conventional PC-Fired Plant with Scrubber
Net Capacity, MWe	496.3	500.9
Net Plant Efficiency, % (HHV)	44.9	35.9
Topping Combustor, °C	1288	---
GT/ST Power Split, %	45/55	0/100
TCR, 1987 \$/kW	1002	1375
COE, mills/kWh [*]	72.9	93.2
COE Advantage, %	21.8	---
Pittsburgh No. 8 Coal, kg/s	38.16	48.25
Sorbent Flow, kg/s		
Dolomite	11.04	---
Limestone	---	5.49
Ash Production, kg/s		
Ash & Spent Sorbent	12.23	0.96
Fixed Sludge	---	8.91
Water Consumption, 10 ³ m ³ /day	22.00	42.47
SO ₂ , kg/s	0.220	0.27
NO _x , kg/s	0.144	0.360
Particulate, kg/s	0.000251	0.01802

^{*} 65% capacity factor

COMPONENT TESTING

Carbonizer

A pilot plant was constructed at Foster Wheeler Development Corporation to test a carbonizer and a CPFBC. The carbonizer was tested in two modes of operation: a jetting, bubbling fluidized bed and a circulating fluidized bed. The bubbling bed tests were conducted in a jetting fluidized bed reactor of 254 mm (10-in. I.D.) (bottom section) by 9.144 m (30 ft) high, as shown in Figure 4. Coal and sorbent, crushed to 3.2 mm x 0 (1/8 in. x 0) and dried, were pneumatically fed into the carbonizer through a centrally located nozzle. Testing was conducted with and without steam addition. Table 3 shows the range of variables investigated during this portion of the testing. Typical analysis of feedstocks and sorbents are shown in Tables 4 and 5, respectively. In the jetting mode, the pilot plant operated for a total of 533 hours, during which 37 steady-state conditions were evaluated [8,9]. The effects of temperature on fuel gas composition and on carbon and energy conversion are shown in Figure 5 and Table 6, respectively.

Table 2

Second-Generation PFBC Plant R&D Needs

Component	Areas of Concern
Ceramic Barrier Filters	<ul style="list-style-type: none"> ■ Particulate Collection Efficiency with Time ■ Material Degradation ■ Effective Sealing of Filter Elements to Headers/Tubesheets ■ Effects of Thermal Shocks
G.T. Topping Combustor	<ul style="list-style-type: none"> ■ Flame Stability with Low-Btu Fuel Gas ■ Effective Cooling of Burner Components ■ Maximum Conversion of NH_3 in Fuel Gas to N_2 ■ Low Generation of Thermal NO_x
Carbonizer	<ul style="list-style-type: none"> ■ Tar Destruction ■ Formation of Agglomerates ■ Sulfur Capture ■ Fuel Gas Composition and Heating Value
CPFBC	<ul style="list-style-type: none"> ■ Char Combustion ■ Conversion of CaS to CaSO_4 ■ Sulfur Capture ■ NO_x Generation
Integrated System	<ul style="list-style-type: none"> ■ Char Transfer between Carbonizer and CPFBC ■ Load Following Capability ■ Total Environmental Emissions

Figure 4. Jetting fluidized bed carbonizer test unit

TABLE 3
Carbonizer Range of Variables Investigated

Pressures (MPa)	1.013 to 1.418	
Temperature (°C)	816 to 922	
Velocity (m/s)	0.91 and 1.1	
Steam Injection	Up to 0.4 kg/kg bituminous coal	
Fuels	Bituminous ■ Pittsburgh No. 8 ■ Illinois No. 6	Subbituminous ■ Eagle Butte, Wyoming Petroleum Coke
Sorbents	Dolomite ■ Plum Run, Ohio	Limestone ■ Longview, Alabama

* In 254-mm I.D. section

TABLE 4
Typical Carbonizer Feedstock Analysis

Description	Petroleum Coke	Coal		
		Pittsburgh No. 8	Illinois No. 6	Eagle Butte
Feed Size	-3.2 mm	-3.2/4.8 mm	-3.2 mm	-3.2 mm
Free Swelling Index	---	6.5	4	0
Proximate, wt%				
Fixed Carbon	83.96	51.06	45.06	36.16
Volatile Matter	14.97	34.23	33.49	31.39
Ash	0.94	12.61	10.59	5.58
Moisture	0.13	2.10	10.87	26.87
Ultimate, wt%				
C	89.89	69.45	62.76	50.77
H	4.42	4.62	4.40	3.60
O	0.73	5.70	6.78	11.49
N	2.30	2.03	1.57	0.98
S	1.59	3.50	3.05	0.72
Ash	0.94	12.61	10.59	5.58
Moisture	0.13	2.10	10.87	26.87
HHV, kcal/kg	8745	7068	6206	4849

TABLE 6

Carbonizer Test Unit Conversions
(Pittsburgh No. 8 Coal)

Test Run	Bed Temp. (°C)	Coal Carbon Conversion	HHV _{gas} / HHV _{coal}
1.4	822	0.30	0.23
1.1	877	0.31	0.24
2.5	922	0.41	0.26
1.2	924	0.43	0.28
2.4	978	0.50	0.33
2.3	979	0.60	0.32

Following completion of the bubbling bed tests, the carbonizer was converted to operate in a circulating bed mode, as shown in Figure 6. The I.D. of the carbonizer was reduced to 203 mm (8-in.), and it operated with a superficial gas velocity of approximately 3.3 m/sec (10 ft/sec.) Solid reinjection was via a 102 mm (4-in.) "L" valve. Since the objective of these tests was to see if circulating bed operation offered any improvement in the carbonizer performance, only one coal and sorbent was tested. The pilot plant operated for a total of 94 hours, during which four test points were completed.

The results from testing of both types of carbonizers are summarized as follows:

- No tars or oil vapors were detected with the carbonizer operating in the 816-982°C (1500-1800°F) temperature range.
- No agglomerates were found, even with high-caking Pittsburgh No. 8 coal, while operating in the temperature range of 871-982°C (1600-1800°F).
- Fuel gas and char were compatible with ceramic barrier filters.
- Up to 96 percent of the coal sulfur released in the carbonizer was captured by the sorbent.
- 22 to 66 percent of coal nitrogen was converted to ammonia.

Figure 6. Circulating bed carbonizer test unit

- More coal energy was transferred to the fuel gas than was estimated in the initial commercial plant design.
- Carbonizer operation was smooth and controlled. Both coal and sorbents could be changed without interruption.
- Very little difference was observed between the two (bubbling and circulating bed) modes of operation.

Circulating Pressurized Fluidized Bed Combustor

A CPFBC comprised of an 203 mm (8-in.) I.D. combustor, cyclone, and solids cooler (as shown in Figure 7) was constructed and tested in the Foster Wheeler's PFBC pilot plant. The cooled solids were reinjected into the combustor via an "L" valve. Similarly, as in the carbonizer tests, the fuels and sorbents, sized to 3.2 mm x 0 (1/8 in. x 0), were fed dry. In addition to the three coals previously used, one additional coal—Kentucky—as well as three chars from the carbonizer tests were combusted. The pilot plant operated in excess of 300 hours, during which a total of 23 test points were completed. The variables investigated are listed in Table 7. A summary of the test results is presented below [10].

- Carbon conversion efficiencies were in excess of 99.5 percent, as shown in Figure 8.
- Carbon monoxide emissions were very low for all fuels tested and generally ranged between 18 and 36 gr/10⁶ kcal (0.01 and 0.02 lb/10⁶ Btu). A plot of CO emissions as a function of combustor bed temperature is shown in Figure 9.
- A sulfur capture efficiency greater than 96 percent was usually achieved with Ca/S ratios ranging from 1:1 to 2:1 as shown in Figure 10.
- Of all operating parameters, primary zone stoichiometry appeared to have the greatest impact on NO_x emissions. Figure 11 presents the test data on conversion of the fuel nitrogen to NO_x for Illinois No. 6 coal and chars.
- Conversion of CaS contained in the carbonizer char-sorbent residue was evaluated for four different char blends (Pittsburgh No.8/dolomite and three Illinois No. 6/limestone). The CaS content of these chars ranged from 1.8 to 4.3 percent. The conversion ranged from 68 to 82 percent.

Figure 7. Integrated CPFBC and fluid bed heat exchanger test unit

Table 7

CPFBC Range of Variables Investigated

Pressure, MPa	0.7 to 1.4	
Temperature, °C	843 to 954	
Velocities (m/s)		
■ Primary Zone	1.22 to 1.83	
■ Secondary Zone	3.05 to 3.66	
Primary Air Stoichiometry, %	60 - 100	
Excess Air, %	30 - 90	
Solids Circulation Rate, kg/s	0.252 - 2.520	
Fuels		
	Bituminous	Subbituminous
	■ Pittsburgh No. 8	■ Eagle Butte
	■ Illinois No. 6	
	■ Kentucky	3 Carbonizer Chars
Sorbents		
	Dolomite (Plum Run)	
	Limestone (Gen Star)

Figure 8. Carbon conversion efficiency as a function of combustor bed temperature

Figure 9. Carbon monoxide emissions as a function of combustor bed temperature

Figure 10. Sulfur capture as a function of Ca/S ratio

Figure 11. Nitrogen conversion to NO_x for Illinois no. 6 coal and chars

Gas Turbine Combustor

In the commercial plant, the fuel gas from the carbonizer and the vitiated air from the CPFBC entering the gas turbine combustor can be as high as 871° (1600°F). Since any ammonia and hydrogen cyanide present in the former tend to form NO_x during combustion, NO_x emission and wall cooling of the combustor liners have precluded the use of a conventional gas turbine-type combustor. A thick layer of the hot vitiated air on the inside of the combustor liners is required to provide the necessary cooling. Low NO_x, generated in the combustor, can be achieved by staging of the combustion process. A multiannular swirl burner (MASB), based on the design by Professor J. Beér of MIT [11] and shown in Figure 12, has been selected by Westinghouse for further development.

Testing of the proposed concept is being conducted by Westinghouse at the University of Tennessee Space Institute. The fuel gas is simulated by a syngas comprised of 11.6 volume percent CH₄, 8.95 volume percent H₂, and 79.38 volume percent N₂ with a lower heating value of 1133 kcal/kg (2040 Btu/lb). The objectives of the test are to:

- Verify that the metal wall temperature did not exceed 1700°F
- Achieve stable and efficient combustion
- Minimize NO_x formation

Two series of MASB tests—one with a 301 mm (12-in.) diameter at 1149°C (2100°F) and one with a 356 mm (14-in.) diameter at 1288°C (2350°F)—were conducted. The results are presented below:

- The metal temperature of the MASB walls could be limited to 899°C (1650°F)
- Combustion efficiencies exceeded 99 percent
- Fuel gas ammonia conversions were as low as 10 percent.

Figure 12. Multiannular swirl burner (MASB)

Two more tests are scheduled for the second half of 1994. A full-size 457 mm- (18-in.) diameter MASB will be used in this series of the tests. In addition to burning synthesized fuel gas, the burner will also be tested with methane.

Integrated Subsystem

In Phase 3 of the program, presently underway, an integrated pilot plant facility comprised of carbonizer, CPFBC and their associated coal and sorbent feed and gas cleanup systems is being erected at FWDC and is scheduled to begin operation in the fourth quarter of 1994. Schematic of the pilot plant is shown in Figure 13. The plant is rated at 2.5 MWt. The significant changes from Phase 2 are listed below:

- A coal paste feed system has been added.
- Carbonizer bed height was increased to 7.3 m (24 ft).
- CPFBC I.D. was increased to 330 mm (13 in.) and height to 11.6 m (38 ft).

Operation of this pilot plant, in addition to confirming process variables investigated during Phase 2 of the testing, will provide the needed information on transfer of hot char from the carbonizer to CPFBC.

Power Systems Development Facility (PSDF)

Under sponsorship of the DOE, Southern Company Services is constructing in Wilsonville, Alabama, a 145-million dollar plant to be used for testing of advanced power system components, including long-term testing and performance evaluation of hot gas cleanup (HGCU) systems [12]. Testing of the HGCU is also supported by EPRI. One of the first systems to be tested is the second-generation CPFBC. The system is rated 7 MWe equivalent and is schematically shown in Figure 14. It will have all the major components of a commercial plant with the exception of the steam turbine and heat recovery steam generator. The carbonizer is designed to operate as a jetting-bubbling fluidized bed, similar to that tested in Phase 2. The diameter of its lower sections is 914 mm (3 ft), and the height is 14.6 m (48 ft). The upper portion of the CPFBC has an I.D. of 838 mm (33 in.).

At full-load operation, the plant will consume 0.69 kg/s (5500 lb/h) of Illinois No. 6 coal. The facility is under construction and operation is scheduled to begin in the middle of 1995.

Four Rivers Energy Modernization Project (FREMP)

Air Products has been selected in Round 5 of the DOE Clean Coal Technology Demonstration Program to build, own, and operate the first commercial second-generation CPFBC plant. The project, known as the Four Rivers Energy Modernization Project, will produce 66 MWe of electricity and 50.4 kg/s (400,000 lb/h) of process steam [13]. It will consume 33.1 metric tons/h (36.5 tons/h) of Western Kentucky high-sulfur bituminous coal. Some of the pertinent parameters of this plant are listed in Table 8.

TABLE 8

Four Rivers Energy Modernization Project

-
- Gross MWe = 70 (38 GT/32 ST)
 - Process Steam for Polymer Manufacture
 - 310,000 lb/h @ 190 psia and 420°F
 - Natural Gas Backup for Carbonizer
 - Coal Paste and Dry Sorbent Feed Systems
 - Western Kentucky Coal and Limestone
 - Independent CPFBC and GT Operation
 - 25-Year Operating Life
-

Scale-up

Any development of new technology has to undergo a reasonable scale-up process. Process parameters obtained in the pilot plant operation have to undergo stepwise confirmation before they are used to design commercial plants. Furthermore, availability and operability of larger-size peripheral equipment must be assured. Such a progression has been chartered for the second-generation CPFBC plant. Figure 15 shows, in block diagram, the scale-up from the pilot plant testing through the proposed first commercial plant. Some of the physical dimensions as well as the operating parameters are shown in Table 9. The commercialization schedule is depicted in Figure 16. Also shown in Figure 16 is the testing of the high-temperature/high-pressure particulate cleanup devices which is being performed under DOE's sponsorship at the first-generation PFBC TIDD plant in Ohio.

CONCLUSIONS

Like any new energy conversion technology, the second-generation CPFBC plant has to undergo step-by-step solutions of all technical problems, both process and mechanical. Process variables are easily determined. Solutions of mechanical problems can be much more difficult. If the technology is to succeed, a compromise between the best energy efficiency and performance of the mechanical components will have to be found. This is the compromise we are looking for as we proceed with the development of the second-generation CPFBC technology.

Figure 15. Scale-up of the second-generation PFBC

TABLE 9

Parameters in Scale-Up of Second-Generation PFBC Technology

	Phase 2	Phase 3	Wilsonville	FREMP	Commercial
Nominal MWe (or equiv.)		1.3	7	95	~250
Carbonizer Temperature, °C	816-923	816-923	871	871	871
Carbonizer Residence Time, s	5	5	5	5	5
Pressure, MPa*	1.013-1.419	1.013-1.419	1.013	1.216	1.419
Carbonizer ϕ , mm	254	254	914	2438	3505
CPFBC ϕ , mm	203	330	518	1737	2896
MASB ϕ , mm	305,357,457	---	457	457	457
Turbine	---	---	A-501 (4 MW)	W-251 (37 MW)	W-501 (107 MW)

* Air compressor discharge

Figure 16. Schedule for commercialization of the second-generation PFBC

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