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Performance of a Second-Generation PFB Pilot Plant Combustor

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DISCLAIMER

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ABSTRACT

Second-generation pressurized fluidized bed combustion (PFBC) plants promise higher efficiency with lower costs of electricity and lower stack emissions. With a conventional reheat steam cycle and a 3-percent sulfur Pittsburgh No. 8 coal, a 45-percent efficiency (HHV of coal basis) and a cost of electricity ~20 percent lower than that of a pulverized-coal-fired plant with stack gas scrubbing are being projected. This advanced plant concept incorporates three major steps: carbonization, circulating fluidized bed combustion and topping combustion.

Foster Wheeler Development Corporation has constructed and operated a second-generation PFB pilot plant at the Foster Wheeler research facility (the John Blizard Research Center) in Livingston, New Jersey. Results of the pilot plant combustor portion of the test program supporting the development of this new type of plant are presented. The fuels evaluated in this test program included several char-sorbent residues produced in a pressurized carbonizer pilot plant and their parent coals. The data confirmed the viability of the PFB combustor concept in terms of both combustion and emissions performance.

INTRODUCTION

Second-generation pressurized fluidized bed (PFB) combustion plants that generate electricity offer utilities the potential for significantly increased efficiencies with reduced costs of electricity and lower emissions, while burning the Nation's abundant supply of high-sulfur coal. Figure 1 is a simplified process block diagram of a second-generation PFB combustion plant.

In the plant, coal is fed to a pressurized carbonizer that produces a low-Btu fuel gas and char. After passing through a cyclone and ceramic barrier filter to remove gas-entrained particulates, the fuel gas is burned in a topping combustor to produce the energy required to drive a gas turbine. The gas turbine drives a generator and a compressor that feeds air to the carbonizer, a circulating pressurized fluidized bed combustor (CPFBC), and a fluidized bed heat exchanger (FBHE). The carbonizer char is burned in the CPFBC with high excess air. The vitiated air from the CPFBC supports combustion of the fuel gas in the topping combustor. Steam generated in a heat-recovery steam generator (HRSG) downstream of the gas turbine and in the FBHE associated with the CPFBC drives the steam turbine generator that furnishes the balance of electric power delivered by the plant.

The low-Btu gas is produced in the carbonizer by pyrolysis/mild devolatilization of coal in a fluidized bed reactor. Because this unit operates at temperatures much lower than gasifiers currently under development, it also produces a char residue. Left untreated, the fuel gas will contain hydrogen sulfide and sulfur-containing tar/light oil vapors; therefore, lime-based sorbents are injected into the carbonizer to catalytically enhance tar cracking and to capture sulfur as calcium sulfide. Sulfur is captured in situ, and the raw fuel gas is fired hot. Thus the expensive, complex, fuel gas heat exchangers and chemical or sulfur-capturing bed cleanup systems that are part of the coal gasification combined-cycle plants now being developed are eliminated.

The char and calcium sulfide produced in the carbonizer and contained in the fuel gas as elutriated particles are captured by high-temperature filters, rendering the fuel gas essentially particulate free and able to meet New

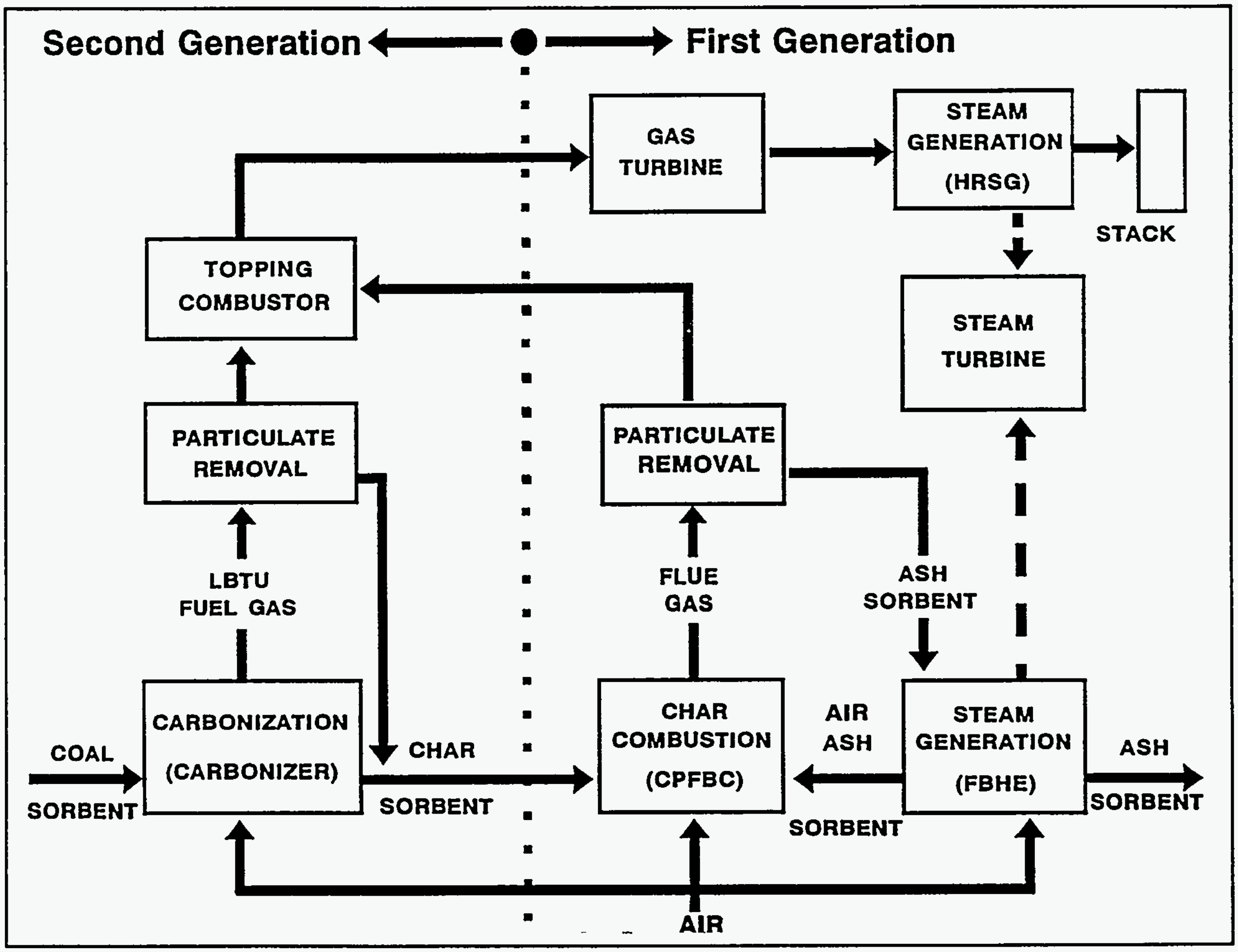

Figure 1 Simplified Process Block Diagram—Second-Generation PFB Combustion Plant

Source Performance Standards (NSPS). The captured material, with carbonizer bed drains, is collected in a central hopper and injected into the CPFBC through a nitrogen-aerated nonmechanical valve. The high excess air in the combustor transforms the calcium sulfide to sulfate, allowing its disposal with the normal CPFBC spent sorbent.

In the CPFBC, the burning char heats the high-excess-air flue gas to 1600°F; any surplus heat is transferred to the FBHE by the recirculation of solids (sorbent and coal fly ash) between the two units. Controlled recirculation is accomplished with cyclone separators and nonmechanical valves. The FBHE contains tube surfaces that cool the circulating solids. Because of the low fluidizing velocity in the FBHE ($\leq$1/2 ft/s), the risk of tube erosion is virtually eliminated.

The exhaust gases leaving the carbonizer and the CPFBC contain sorbent and fly ash particles—both of which can erode and foul downstream equipment. A hot gas cleanup (HGCU) system, consisting of ceramic cross-flow filters preceded by cyclone separators, cleans these gases to <20 ppm solids loading before they enter the fuel gas topping combustor and the gas turbine and cause erosion and fouling. Ceramic candle filters, screenless granular-bed filters, and others, are candidate alternatives for the cross-flow filter should their performance and economics be found superior. All these devices are currently under development for first-generation PFB combustion cycles. They should also be applicable to the second-generation plant.

A team of companies led by Foster Wheeler Development Corporation (FWDC)—with ■ Foster Wheeler Energy Corporation and Foster Wheeler USA ■ Gilbert/Commonwealth, Inc. ■ Institute of Gas Technology ■ Westinghouse Power Generation Business Unit (PGBU) and Science & Technology Center (STC)—has embarked upon a DOE-funded three-phase program to develop the technology for this new type of plant. A conceptual design of a 3-percent-sulfur Pittsburgh No. 8 coal-fired second-generation PFB plant with a conventional 2400 psig/1000°F/1000°F/2-1/2 in. Hg steam cycle was prepared, and its economics were determined [1]. In 1987 we estimated that, when operated with a 14-atm/1600°F carbonizer, the plant efficiency would be 44.9 percent (based on the higher heating value of the coal) and its cost of electricity would be 21.8 percent lower than that of a conventional pulverized coal-fired plant. Tests conducted in our pilot-scale carbonizer (described later) yielded performance superior to that estimated in 1987 [2]. As a result, we now expect a more energetic fuel gas and a plant efficiency of 46.2 percent with a 1600°F carbonizer.

The second-generation PFB combustion plant development effort is divided into three phases, the first of which has already been completed and documented in a series of reports available through the National Technical Information Service [3-4]. The first phase of the DOE program was aimed at plant conceptualization and optimization and identification of plant R&D needs. The second phase, involving laboratory-scale tests of the key plant components has been completed.

PFB PILOT PLANT

In November 1991 FWDC began operating a PFB pilot plant at its John Blizard Research Center in Livingston, New Jersey. The facility had a multipurpose reactor and a ceramic barrier filter. The reactor was designed to test a second-generation plant carbonizer and then, after modification, a CPFBC/FBHE. Ceramic barrier filters provided by Westinghouse STC were used with both of these units to demonstrate particulate control capabilities.

The first carbonizer test program consisted of eight bubbling fluidized bed test runs. It encompassed 37 setpoints/533 hours of operation. Portions of the collected data have been discussed in other publications [5-7]. Although highly caking Pittsburgh No. 8 coal and Ohio Plum Run dolomite were most frequently used, Illinois No. 6 and Wyoming Eagle Butte coals and Alabama Longview limestone were also tested. The Pittsburgh coal typically had a 3.5-percent sulfur content and a Free Swelling Index of 6.5; the Eagle Butte coal contained 0.7-percent sulfur and 27-percent moisture.

The bubbling bed carbonizer shown in Figure 2 was operated at approximately 3 ft/s superficial gas velocity (measured in the 10-in. ID section). Pressures, temperatures, and steam injection rates ranged from 10 to 14 atm, 1500 to 1800°F, and 0 to 0.4 lb steam/lb coal respectively.

From the standpoint of fluidized bed combustors, circulating bed performance (e.g., combustion efficiency, sulfur-capture efficiency, NO_x emissions) is generally accepted to be superior to bubbling bed performance. Although the bubbling bed carbonizer demonstrated excellent performance, an exploratory test run was made with a circulating bed carbonizer to determine whether it also offered improved performance. To achieve the higher gas velocity required for circulating bed operation, ceramic inserts were installed in the carbonizer, reducing its cross section to a constant top-to-bottom 8-in. ID. Four circulating bed carbonizer test points were completed at a nominal velocity of 10 ft/s at 5 to 9 atm pressure, with Pittsburgh No. 8 coal and limestone. Because a comparison of the circulating and bubbling bed data showed little difference in performance, no further circulating bed tests were completed.

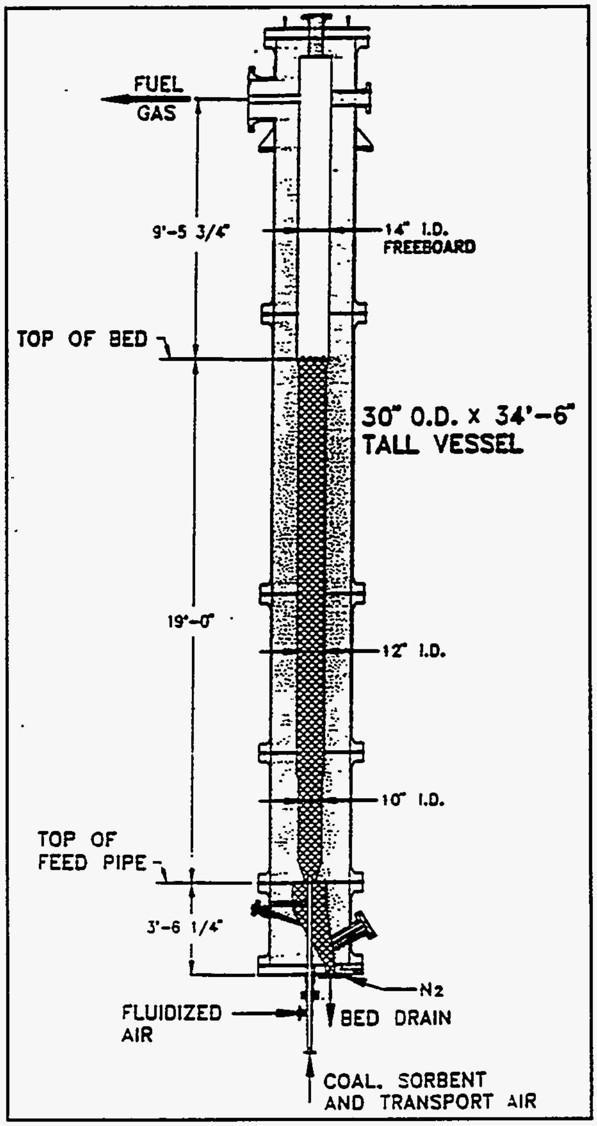

Figure 2 10-in. Carbonizer Test Unit

In summary, the carbonizer test program has been very successful [2]. It has demonstrated that carbonizer operation is smooth and controlled, emissions are lower than were previously estimated for a commercial plant, and the char/sorbent residue and fuel gas from the process appear compatible with the particle-capturing ceramic barrier filters.

Having successfully completed the carbonizer test program, the pilot plant was modified for CPFBC operation. A schematic of the CPFBC pilot plant is shown in Figure 3. Crushed coal and sorbent are loaded into and stored in separate 10-ton silos adjacent to the outside wall of the laboratory. A series of bucket elevators, vibrating feeders, belt conveyors, etc., load and transfer these materials into the building into separate lock hopper sys-

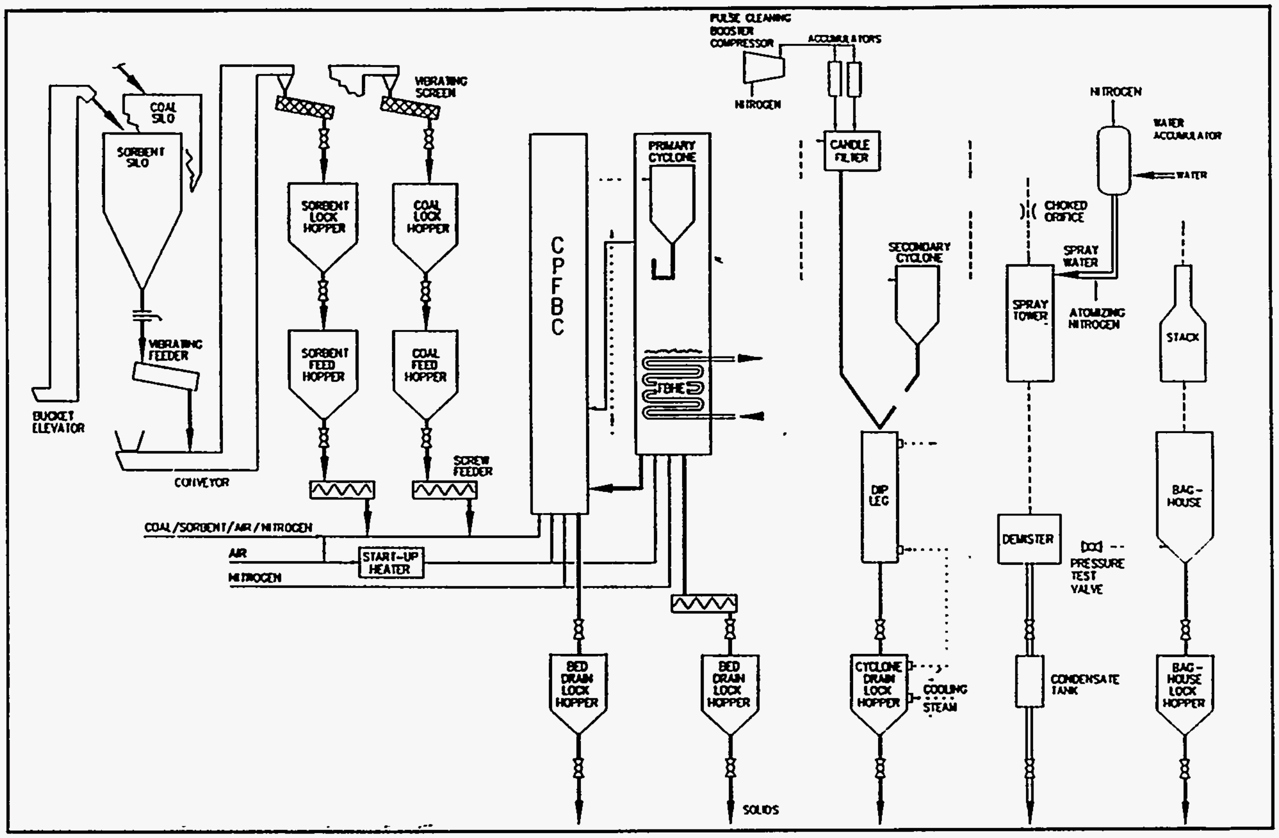

Figure 3 CPFBC Pilot Plant Schematic

tems that are pressurized to approximately 200 psig with 70°F nitrogen. From the pressurized hoppers, the coal and sorbent are fed into a pneumatic transport line via screw feeders and injected into the CPFBC.

The CPFBC is a vertical, 30-in.-OD, 34 ft-6 in.-tall pressure vessel, shown in Figure 4. The CPFBC primary zone is 12 ft-6 in. tall, and the secondary zone is 16 ft tall. The vessel is refractory lined to an 8-in. diameter. Coal, sorbent, and pneumatic transport air are injected at the bottom of the unit at a 40- to 60-ft/s jet velocity through a central, vertical 1-in. Sch 80 stainless steel pipe. At a point 10-3/4 in. below the feed pipe discharge, an outer, concentric, 2-in. Sch 40 pipe injects fluidized air around and at the base of the feed pipe. A nitrogen-aerated packed-bed cooler at the bottom of the CPFBC cools spent bed material to 300°F before lock-hopper depressuring and disposal. Two diametrically opposed secondary air injection ports are provided 12 ft-6 in. above the point of fluidized air entry.

The heat released during the combustion process is absorbed by a sorbent/fly ash mixture continuously circulated between the CPFBC and the FBHE. A cyclone separator atop the FBHE and a nonmechanical L-valve at the bottom control the circulation of solids entering the CPFBC 14-3/8 in. above the fluidizing air.

The FBHE, also shown in Figure 4, is a 42-in.-OD by 34 ft-6 in.-tall pressure vessel, refractory lined to yield a 18-in. square bed and freeboard section. A 39-in.-tall (bottom-to-top tube centerline height) water-cooled tube bundle in the bed consists of eight 1-in.-OD Incoloy 800H tubes. City water is used as the coolant, and its flow rate is adjusted as required to keep the water outlet temperature below 140°F. An air-sparger pipe injects fluidized air at the bottom of the bed and allows solids to flow downward into the L-valve or through the bed-drain cooling section. A screw feeder immediately below the FBHE controls the bed drain rate and bed height. Raising and lowering the bed height controls the amount of tube surface immersed in the bed and hence the bed and CPFBC solids return temperature. The fluidized air leaves the top of the FBHE and enters the CPFBC as secondary air.

The combustion gas/solids mixture exits the combustor and passes through a 3-in. connecting pipe into the cyclone atop the FBHE. The hot solids are separated from the gas and fall by gravity into the 6-in. Sch 40 standpipe. At the end of the standpipe, an aerated J-valve provides a gas seal between the FBHE and cyclone separator. After passing through the J-valve, the solids fall into the FBHE bed, containing tube bundles, where part of the secondary air fluidizes the solids. After passing over the heat exchanger coils, the solids are recycled to the combustor via the nitrogen-aerated L-valve. Pressure, temperature, and pressure differential ports are provided on the standpipe, J-valve, heat exchanger, and L-valve. The cyclone exhaust gas exits the FBHE and enters a ceramic barrier candle filter for final particulate cleanup.

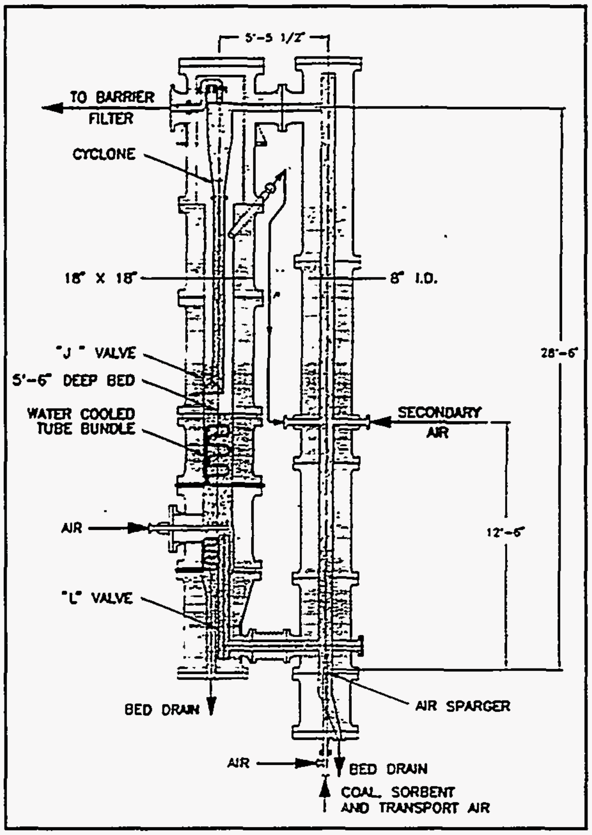

Figure 4 Integrated CPFBC/FBHE Unit—Phase 2

The gas exhausting from the ceramic-candle filter is lowered to atmospheric pressure as it passes through a choked-flow orifice. The high-velocity orifice jet discharges into an Incoloy-shrouded refractory-lined chamber, where a nitrogen-atomized nozzle injects spray water to cool the gas to approximately 350°F. Although the cooling is accomplished by a dry quench, a wire mesh demister is provided at the base of the spray tower to remove any water droplets that may be present in the gas. The cooled gas passes through a baghouse filter and is then discharged to the atmosphere via an elevated stack.

Flue gas is sampled both periodically and continuously. The periodic samples are taken from the CPFBC freeboard and from a point downstream of the demister; the continuous measurements are made at the stack via continuous emissions monitors.

CPFBC TEST RESULTS

Feedstocks and Test Conditions

A total of 23 steady-state setpoint periods were obtained from over 300 hours of operation while firing the test fuels. The coals tested in the pilot plant included Pittsburgh No. 8, Illinois No. 6, and Kentucky Andalex, all high-volatile bituminous (HVB) and Eagle Butte subbituminous. A setpoint period was also conducted with petroleum coke, which served as the pilot plant start-up fuel. Char-sorbent residues from the carbonizer test program, hereafter referred to as chars, were also tested; they included Eagle Butte with limestone, three Illinois No. 6 blends with limestone, and a Pittsburgh No. 8 with dolomite. Proximate and ultimate analyses of the test fuels are shown in Tables 1 and 2.

Sulfur contents ranged from 0.5 to 3.53 percent for the Eagle Butte subbituminous and Kentucky Andalex coals respectively. All of the coals were relatively low in ash content, with the Kentucky Andalex having the highest ash content (11.66 percent). The low ash content of some of these fuels was important from a bed maintenance standpoint; consequently, sorbent feed was often dictated by CPFBC system inventory requirements.

All three Illinois No. 6 chars contained Longview limestone sorbent, whereas, the Pittsburgh No. 8 char contained Plum Run dolomite. As shown in Table 2, all of the chars were relatively low in volatile content (less than 15 percent). The higher heating values of the chars ranged from 5961 Btu/lb for an Illinois No. 6 char to 9407 Btu/lb for the Eagle Butte char. The sulfide sulfur content of the chars ranged from 0.80 percent for the Eagle Butte to 4.30 percent for an Illinois No. 6 blend.

The major operating variables evaluated in the test program included combustor bed temperature, combustor pressure, primary air stoichiometry, and excess air. The range of these operating variables is shown below:

Combustor temperature, °F	1600 to 1700
Combustor pressure, psig	90 to 190
Primary air stoichiometry, %	60 to 90
Excess air, %	30 to 90

The target sulfur capture for all test points was 92 percent or greater. Sorbent feed rate was often dictated by system inventory requirements, not the desired level of sulfur capture.

Heat and material balances were performed for all setpoint periods to ensure the validity of efficiency and emissions calculations. Material balances were calculated based on measured and calculated input and output streams from the combustor. Input streams included measured air and nitrogen input flows and calculated fuel and sorbent rates. Output streams included measured stack gas flow and calculated ash drain rates. Both total mass flow and elemental rates (C, H, O, and N) generally showed excellent closure of less than 5 percent.

Combustion Efficiency

Carbon combustion efficiencies were in excess of 99.5 percent for the diverse types of fuels tested. Carbon combustion efficiencies were determined by measuring the

Table 1 Fuels Tested in CPFBC

Description	Petroleum Coke	Pittsburgh No. 8 (HVB)	Illinois No. 6 (HVB)	Kentucky (HVB)	Eagle Butte
Proximate Analysis, wt%					
Fixed Carbon	86.34	51.30	47.37	46.65	34.11
Volatile Matter	11.85	35.96	33.13	35.71	30.92
Ash	1.30	10.16	11.14	11.66	4.86
Moisture	0.51	2.58	8.36	5.98	30.11
Ultimate Analysis, wt%					
Carbon	90.34	71.48	62.37	66.49	47.21
Hydrogen	3.72	4.74	3.80	3.98	3.37
Oxygen	0.77	5.60	9.84	6.77	13.04
Nitrogen	1.32	1.92	1.35	1.59	0.90
Sulfur	2.04	3.52	2.84	3.53	0.51
Ash	1.30	10.16	11.14	11.66	4.86
Moisture	0.51	2.58	8.36	5.98	30.11
HHV, Btu/lb	15,382	12,799	11,532	12,216	8,245

Table 2 Char Proximate and Ultimate Analysis

Description	Eagle Butte Limestone	Pittsburgh No. 8/ Dolomite	Illinois No. 6/ Limestone Blend 2	Illinois No. 6/ Limestone Blend 3	Illinois No. 6/ Limestone Blend 10
Proximate Analysis, wt%					
Fixed Carbon	60.16	46.39	35.98	46.91	45.75
Volatile Matter	8.08	5.55	10.73	7.76	14.86
Ash	28.64	47.15	53.06	44.67	34.74
Moisture	3.12	0.91	0.23	0.66	4.65
Ultimate Analysis, wt%					
Carbon	63.54	45.97	39.33	48.31	51.25
Hydrogen	0.52	0.50	0.65	0.54	0.65
Oxygen	1.78	0	0.32	0	4.36
Nitrogen	0.90	0.96	0.70	0.81	0.89
Sulfur	1.50	4.51	5.71	5.01	3.46
Ash	28.64	47.15	53.06	44.67	34.74
Moisture	3.12	0.91	0.23	0.66	4.65
HHV, Btu/lb	9,407	8,156	5,961	8,364	8,527
Sulfide S, %	0.80	3.03	4.30	4.19	1.80

organic carbon content of the ash drains and calculating the ash drain rates. The organic carbon content of all ash drains was very low and never exceeded 0.5 percent.

A plot of carbon combustion efficiency vs. combustor bed temperature is shown in Figure 5 for the coals and chars. As shown in this figure, there appeared to be little effect from bed temperature on carbon combustion efficiency since levels were all in excess of 99.5 percent. These data are consistent with those from the literature for other pressurized CFB pilot plants [8, 9].

Average CO, SO_2, and NO_x emissions were determined for the steady-state test periods. These emissions were calculated from averages of 1-minute data over a setpoint period of between 2 and 4 hours. Carbon monoxide emissions were very low for all the fuels tested and generally ranged between 0.01 and 0.02 lb/10^6 Btu. Low CO emissions are usually an indication of high carbon combustion efficiency. A plot of CO emissions vs. combustor bed temperature is shown in Figure 6. CO emissions were considerably higher at the bed temperatures below 1600°F. These data are consistent with atmospheric CFBC experience, which also shows a strong temperature dependence on CO emissions.

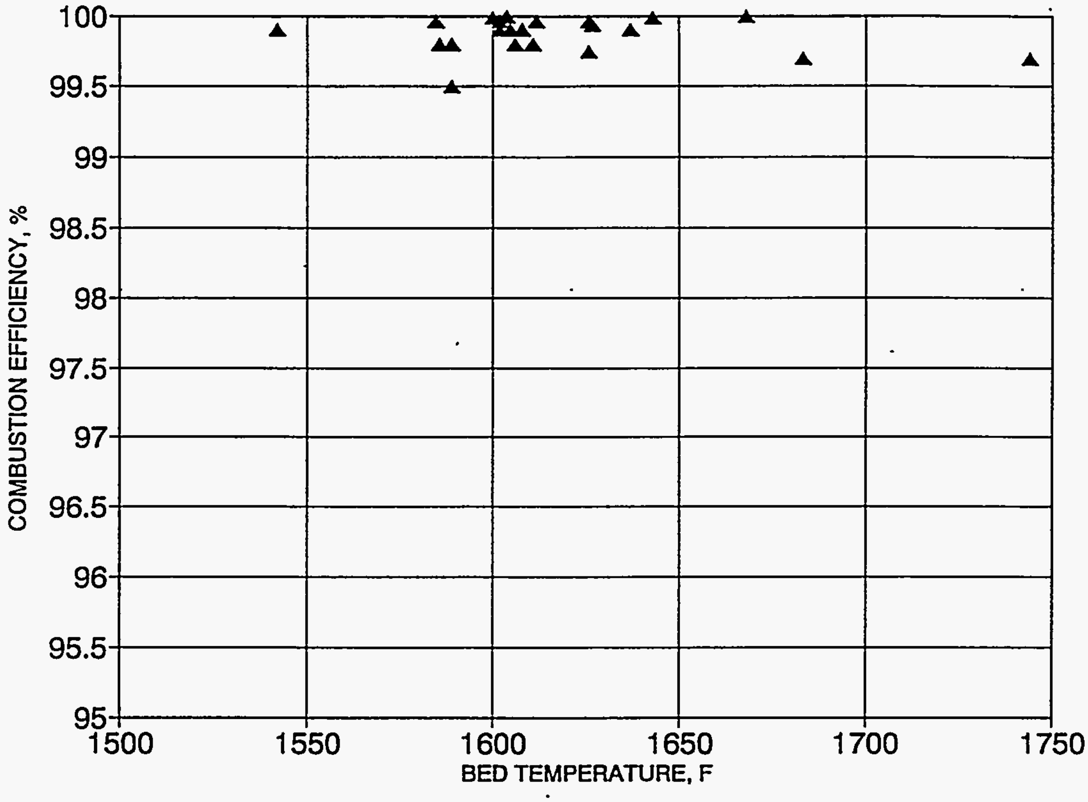

Figure 5 Carbon Combustion Efficiency vs. Combustor Bed Temperature

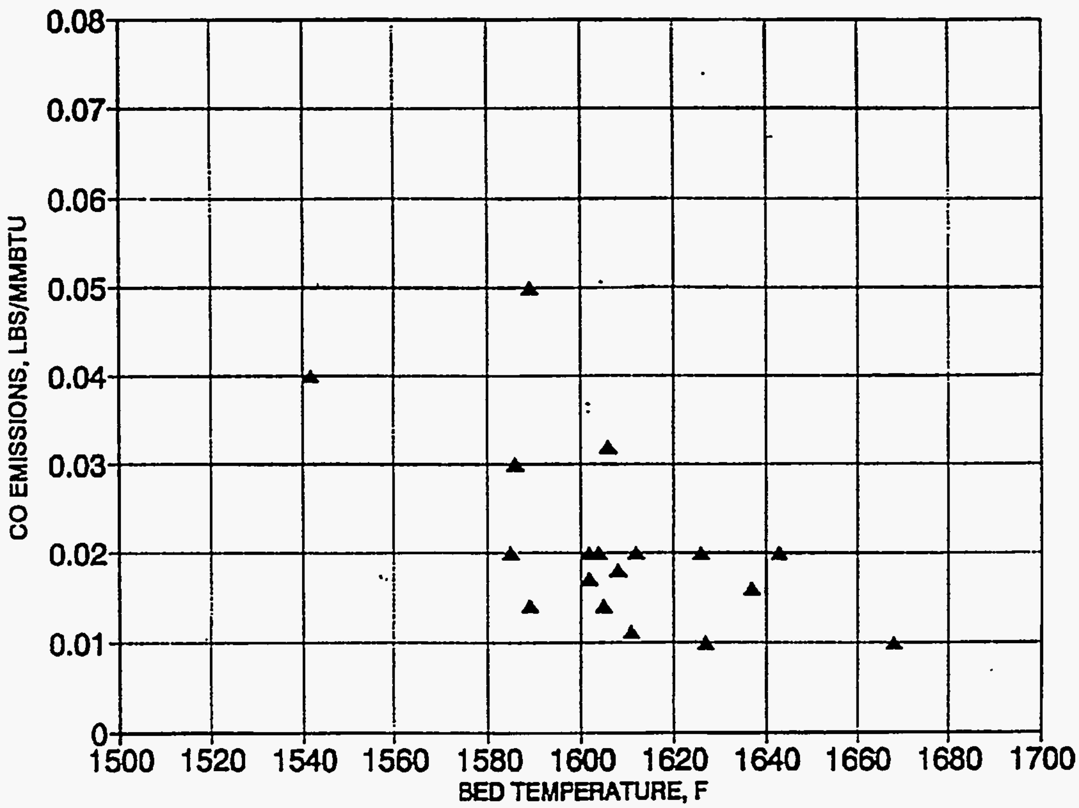

Figure 6 Carbon Monoxide Emission as a Function of Combustor Bed Temperature

Sulfur Capture

The sorbents utilized in this test program included two limestones (Genstar and Three Rivers) and one dolomite (Plum Run). Important chemical and physical properties of these sorbents are summarized in Table 3. At the beginning of each test run, the bed was sulfated by a nitrogen-SO_2 gas mixture for a period of up to 20 hours to mature the bed and provide reasonable sulfur-capture data.

Table 3 Sorbents Tested in CPFBC

Analyses	Genstar Limestone	Three Rivers Limestone	Plum Run Dolomite
Chemical Analysis, wt%			
$CaCO_3$	98.1	98.0	55.5
$MgCO_3$	0.7	1.1	42.7
Inerts	1.2	0.9	1.8
Hardgrove Index	53	49	91
TGA Ca Utilization, %	49	40	88

Sulfur-capture data for all of the test points are shown in Figure 7 as sulfur-capture efficiency vs. feed Ca/S ratio. A sulfur capture efficiency greater than 96 percent was usually achieved with Ca/S ratios ranging from 1:1 to 2:1. In some cases system inventory maintenance dictated sorbent feed rate instead of targeted sulfur capture. This was particularly true for very low ash fuels such as petroleum coke and Eagle Butte subbituminous coal. The carbonizer chars all revealed very high sulfur capture from inherent calcium and did not require additional sorbent.

NO_X Emissions

NO_X emissions generally ranged from 0.3 to 0.6 lb/10^6 Btu for the test fuels. Of all the operating parameters, primary zone stoichiometry appeared to have the greatest impact on NO_x emissions. Over the range of operating temperatures and excess air levels, no other strong dependence was observed. Some of the test chars showed exceptionally high conversions of fuel nitrogen to NO_x. This phenomenon may be attributed to the inability to control NO_x formation from nonvolatile nitrogen by air staging.

The effect of primary-zone stoichiometry on NO_x emissions is shown in Figure 8 for the Illinois No. 6 coal tests. NO_x emissions did reveal a strong dependence on primary air stoichiometry over a range of 65 to 90 percent.

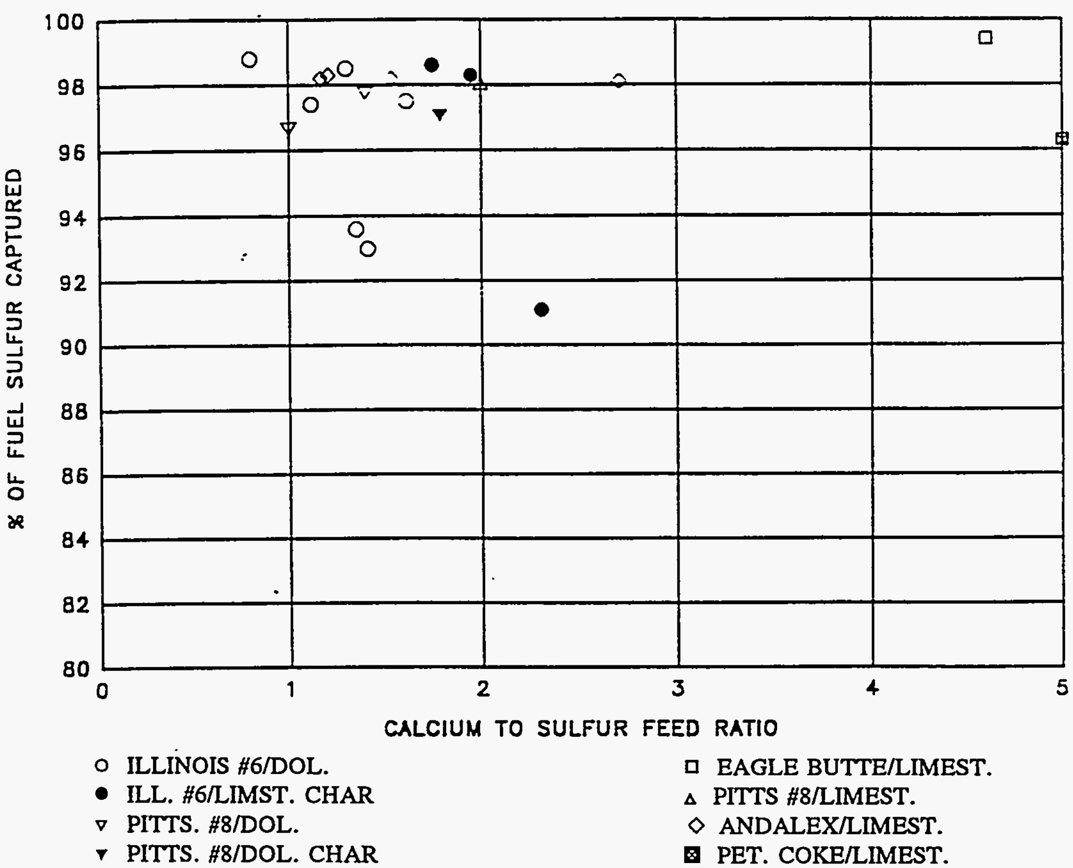

Figure 7 Sulfur Capture Efficiency vs. Primary Zone Stoichiometry

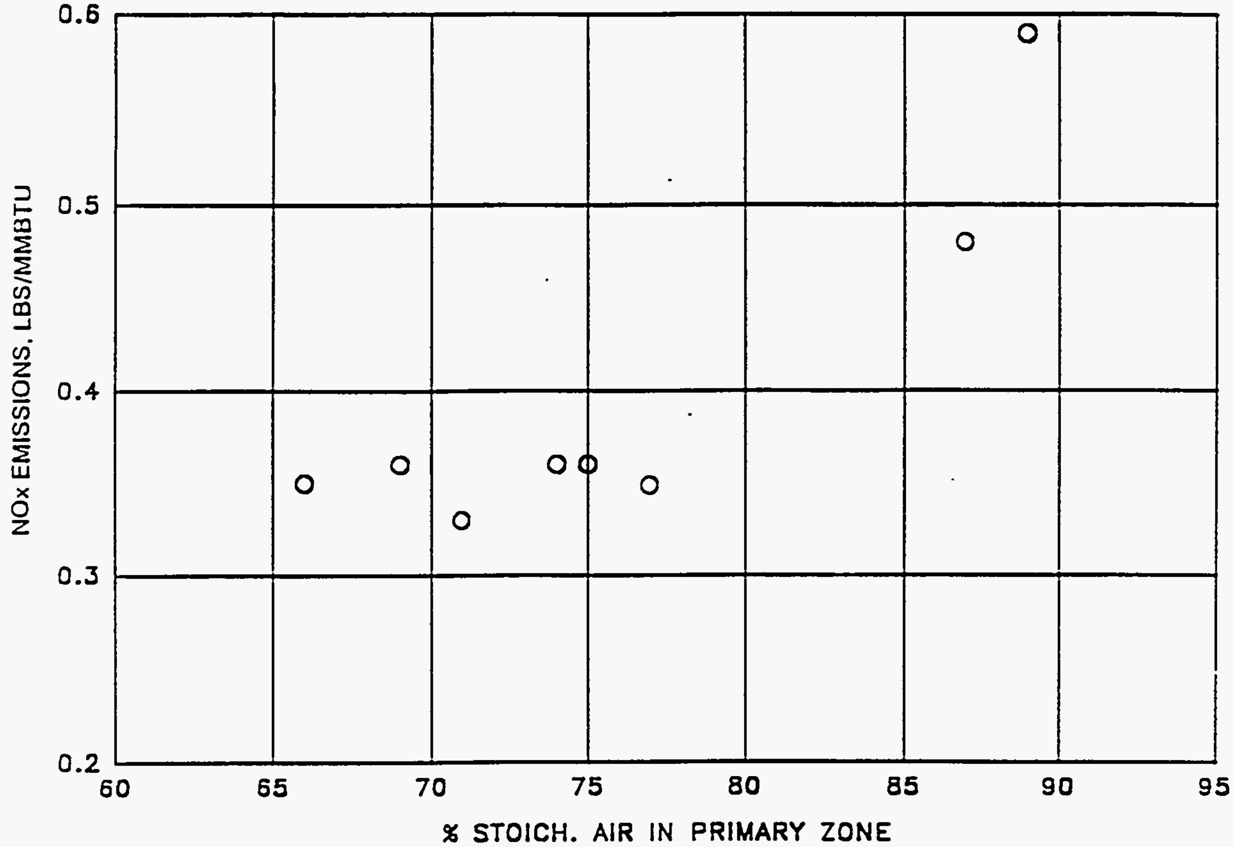

Figure 8 NO_x Emissions For Illinois No. 6 Coal vs. Primary Zone Stoichiometry

To discern the effect of fuel type, the emissions data are shown in Figure 9 as the percentage of fuel nitrogen converted to NO_x for coal and char tests. These data show similar trends with primary zone stoichiometry, with the exception of the test chars. In particular, the Pittsburgh No. 8 and Eagle Butte chars showed much higher conversions of nitrogen to NO_x than the parent coals.

As mentioned earlier, there was considerable scatter in the NO_x data correlation with primary zone stoichiometry. This scatter may be because of the variation of other operating parameters. Because of the intricate coupling of the FBHE with the combustor, difficulty was often encountered in varying one operating parameter at a time while holding all others constant. From some limited data, excess air level did not appear to have a significant effect on NO_x emissions. Figure 10 shows the effect of excess air on NO_x emissions for Illinois No. 6 coal over a narrow range of primary air stoichiometries. NO_x emissions remained fairly constant even though excess air was increased by over a factor of three (25 to 83 percent).

Emissions of NO_x from a commercial-scale CPFBC may be somewhat lower than those from the pilot plant because of increased gas residence time in the larger unit. In atmospheric CFB's NO_x emissions are generally lower in a full-scale plant compared to a pilot plant since greater reduction of NO_x by carbon and CO occurs in the taller freeboard section. The effect of increased residence time on NO_x reduction will be evaluated in Phase 3 pilot plant tests, which will utilize a significantly taller CPFBC.

Calcium Sulfide Oxidation

A major issue involving the performance of the CPFBC is the extent of char calcium sulfide conversion. Conversion of sulfide was evaluated for four different char blends (Pittsburgh No.8/dolomite and three Illinois No. 6/limestones). The sulfide sulfur contents of the chars varied from 1.8 to 4.3 percent, as shown in Table 4. The sulfide conversion ranged from 74 to 82 percent, with the high-sulfide Illinois No. 6 char having the highest conversion. As expected, the candle filter drains had the lowest concentrations of sulfide (about 1 percent). The sulfide sulfur levels were considerably higher in the FBHE and combustor drains, with the latter having the highest. Typical ash drain size distributions are shown in Figure 11 for an Illinois No. 6 char test. As shown in this figure, the combustor and heat exchanger drains were considerably coarser than the candle filter drain.

Some of the major operating parameters affecting the level of sulfide in the system inventory include temperature, excess air, and solids circulation rate. In all the char tests, relatively low firing rates and solids circulation rates (<10,000 lb/h) were used because of the limited supply of carbonizer chars. Higher circulation rates may have resulted in higher sulfide conversions for two major

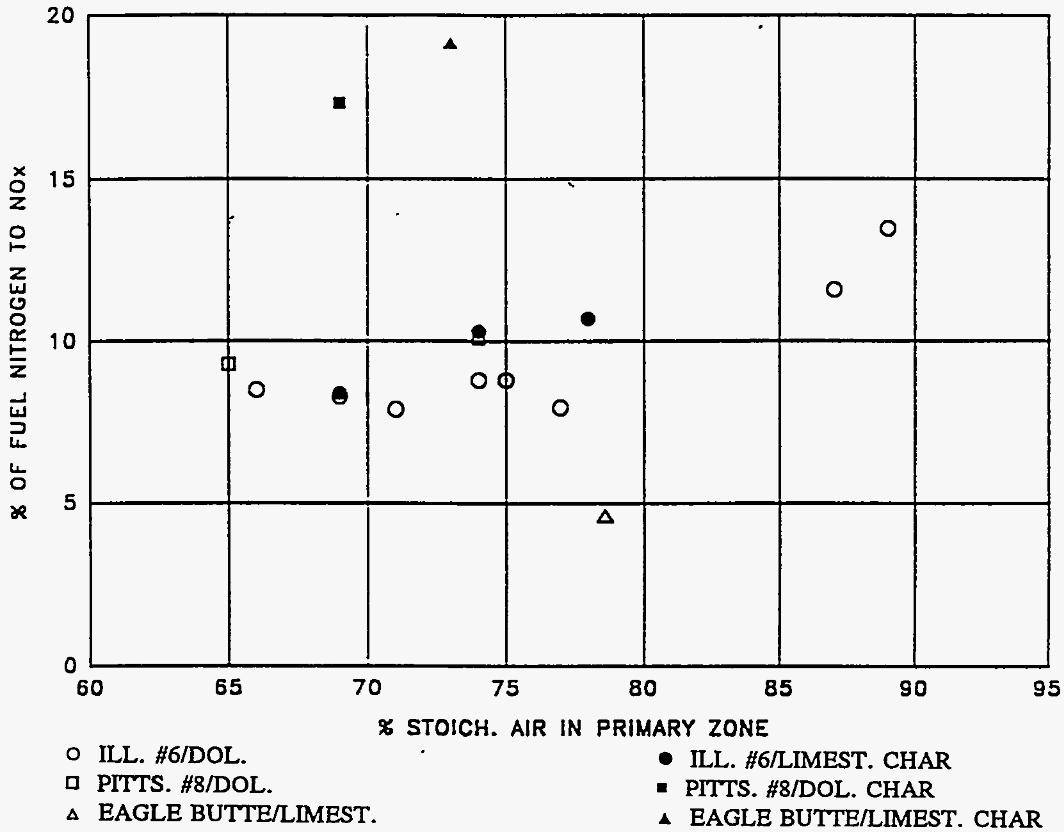

Figure 9 Nitrogen in Fuel Conversion to NO_x vs. Primary Zone Stoichiometry

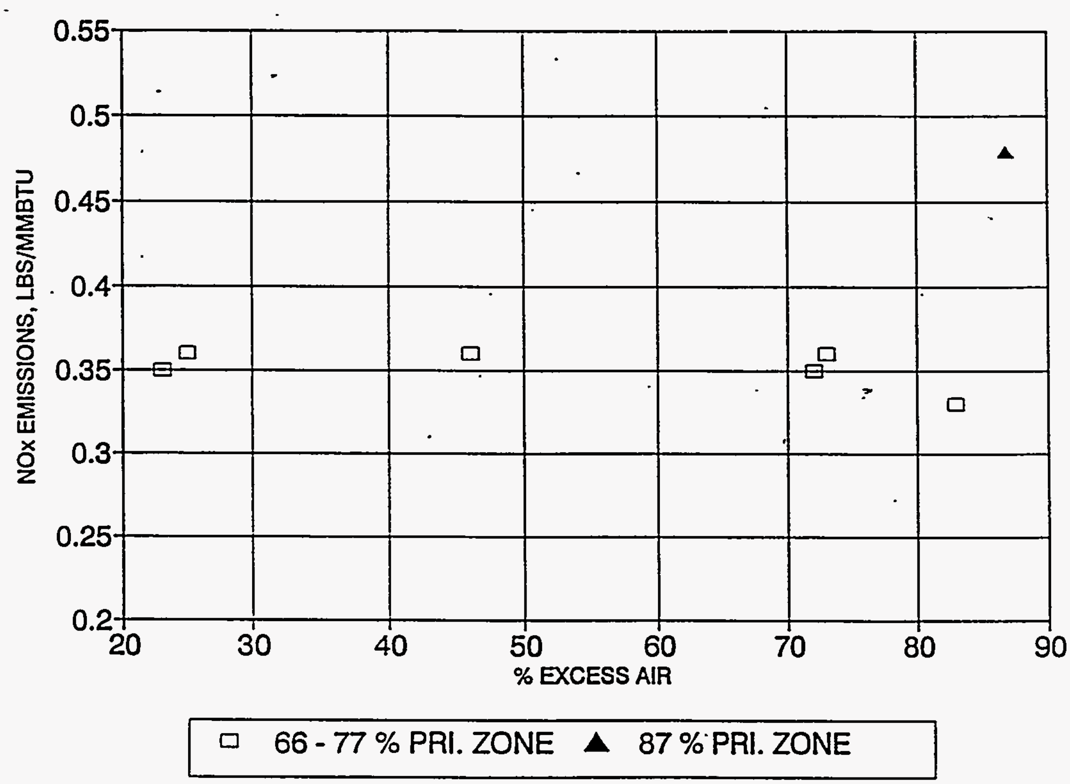

Figure 10 Effect of Excess Air on NO_x Emissions for Illinois No. 6

Table 4 PFB Char Sulfide Conversion Data

Description	Pittsburgh No. 8 (Dolomite)	Illinois No. 6 (Limestone)		
Char Rate, lb/h Sulfide S, % Sulfide S (in), lb/h	200 3.03 6.06	190 4.19 7.96	195 4.3 8.39	165 1.8 2.97
Filter Drain, lb/h Sulfide S, % Sulfide S, lb/h	47 1 0.47	29 1 0.29	21 1 0.21	18 1 0.18
Combustor Bed Drain, lb/h Sulfide S % Sulfide S, lb/h	23 1.82 0.42	12 1.96 0.23	21 2.88 0.60	16 1.71 0.27
Heat Exchanger Drain, lb/h Sulfide S, % Sulfide S, lb/h	33 1.7 0.56	55 1.61 0.89	73 1.62 1.18	30 1.89 0.32
Sulfide S (out), lb/h	1.45	1.41	1.99	0.77
Sulfide Conversion, %	76.1	82.3	76.2	73.9
Bed Temperature, °F Primary Air Stoichiometry, % Excess Air, %	1627 69 51	1612 78 68	1626 74 39	1626 69 41

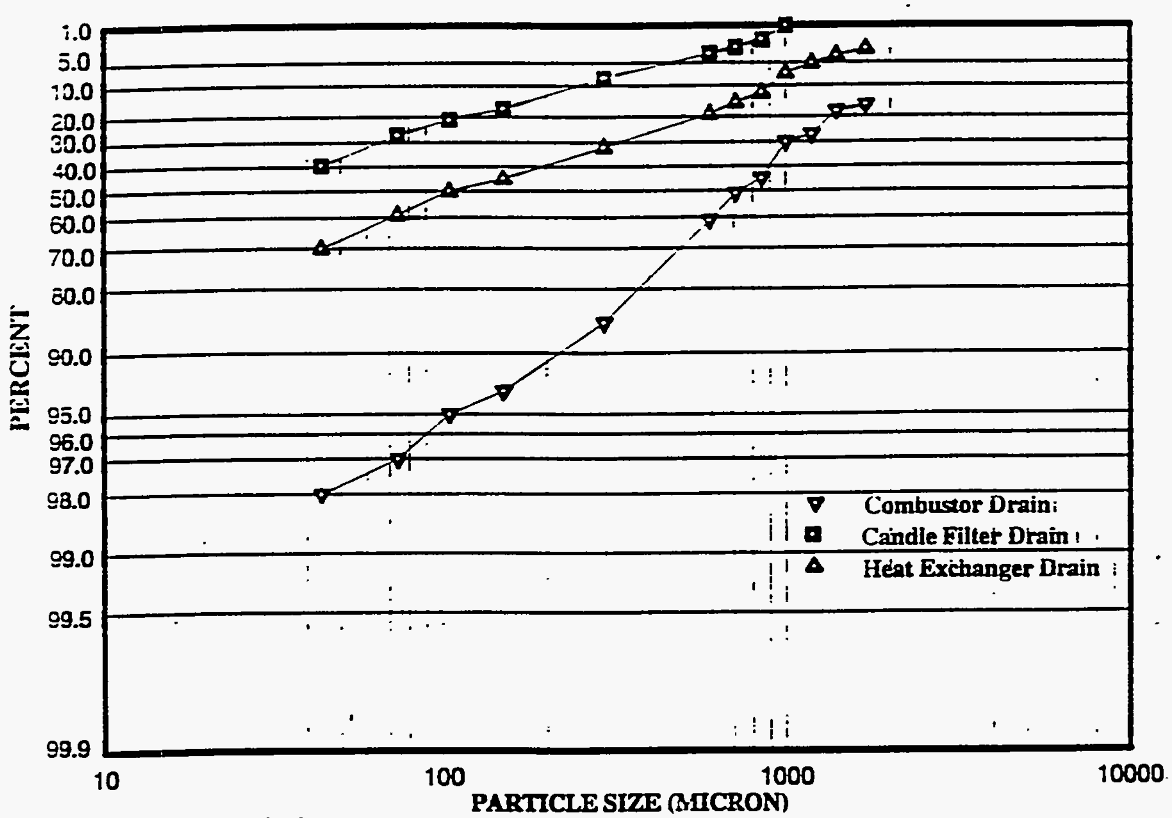

Figure 11 Run TRC-5 While Firing Illinois No. 6 Char Size Distribution

reasons. First, higher circulation rates increase the inventory residence time in the oxidizing region of the combustor secondary zone. Second, increased circulation also promotes particle attrition, which can break down the calcium sulfate shell of spent sorbent particles and allow further reaction of the exposed calcium sulfide layer.

The sulfide level (as percentage of total sulfur) was determined for selected freeboard and FBHE drain samples since they are representative of the unit inventory in circulation. The percentage of sulfur as sulfide versus solids circulation rate is shown in Figure 12 for both coal and char test runs. Solids circulation rates were calculated by performing a heat balance around the FBHE. As shown in Figure 13, the percentage of sulfur present as sulfide decreased as the solids circulation rate increased. The higher circulation rates reduced the level of sulfide probably because of attrition and the increased residence time of the circulating solids in the oxidizing secondary zone.

The effect of solids circulation rate on combustor bed particle size is shown in Figure 14 for tests with Pittsburgh No. 8 and Illinois No. 6 coals and Plum Run dolomite. As shown in this figure, the particle size of the bed ash decreased considerably with higher circulation rates because of attrition. Likewise, the amount of sulfur in the coal which exited the combustor as sulfide decreased with increasing circulation rate. As shown in Figure 13, the feed sulfur leaving the combustor in the ash drains as sulfide decreased from about 4 percent to less than 2 percent as the circulation rate was increased from 10,000 lb/h to around 30,000 lb/h. Oxidation of CaS formed in the primary zone has been shown to be diffusion limited because of the formation of a $CaSO_4$ layer around the sulfide [10]. Increased circulation rates and attrition would promote breakdown of this outer layer and allow higher levels of sulfide conversion. In the CPFBC tests, the percentage of coal sulfur exiting as sulfide was similar when compared to that in a full-scale atmospheric CFB burning high sulfur Canadian coal [11].

Conversion of sulfides during char combustion requires oxidation of both sulfide in the char feed and that formed from sulfur capture of organic char-bound sulfur. The level of sulfidation of the sorbent in a char has also been shown to have a significant effect on the eventual oxidation of calcium sulfide to sulfate in a combustion process [12]. Higher sulfidation levels yield thicker sulfide layers on sorbent particles which oxygen must penetrate for sulfation.

The sulfidation level of the chars in the carbonizer are shown in Table 5 and compared with the conversions to sulfate in the CPFBC. As shown in this table, the sulfidation levels of the Illinois No.6/ Longview limestone chars were all relatively similar ($\approx$25 percent), as were the sulfide conversions to sulfate (74 to 82 percent). The dolomitic Pittsburgh No. 8 char had a similar sulfide conversion (76 percent), but had a somewhat higher sulfidation level than the calcitic chars (41 percent). Laboratory tests have shown that relatively high conversion of sulfide to sulfate can be achieved for dolomitic sorbents at high sulfidation levels when compared to limestones [12].

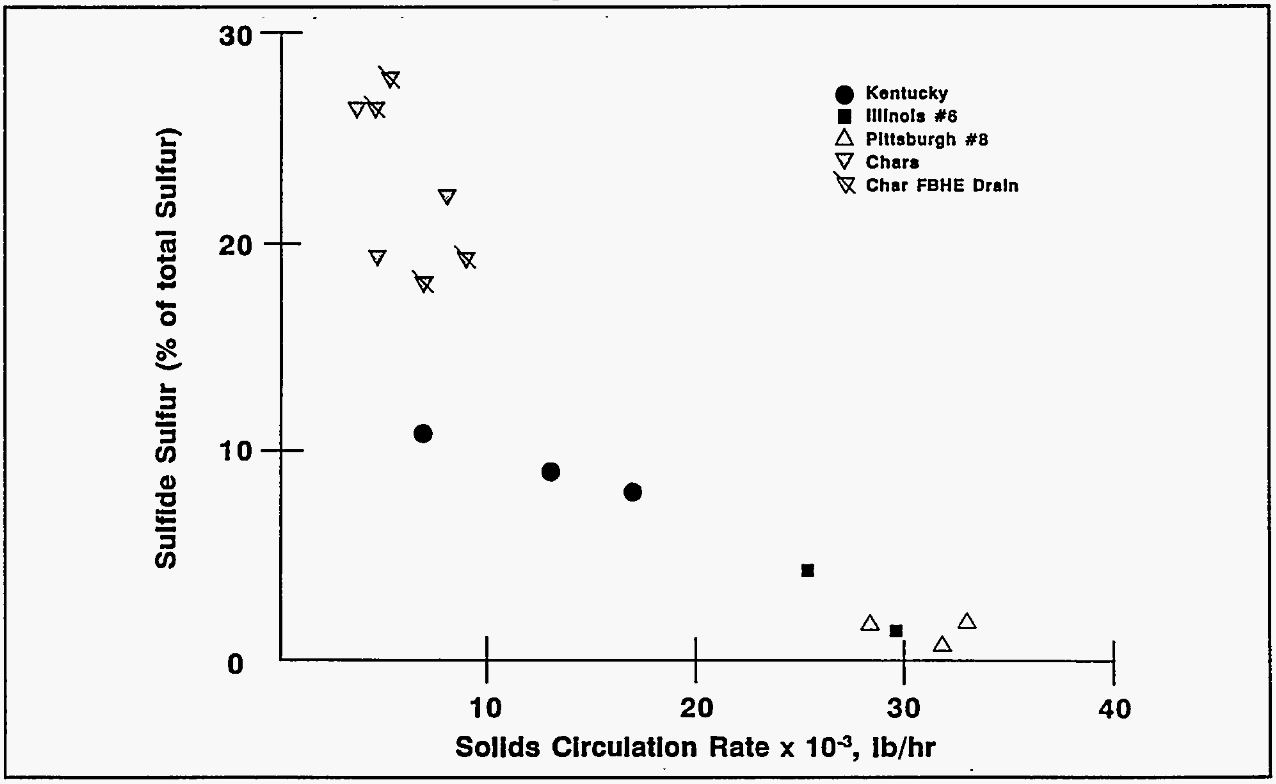

Figure 12 Freeboard Solids and FBHE Drain Sulfide as Percentage of Total Sulfur

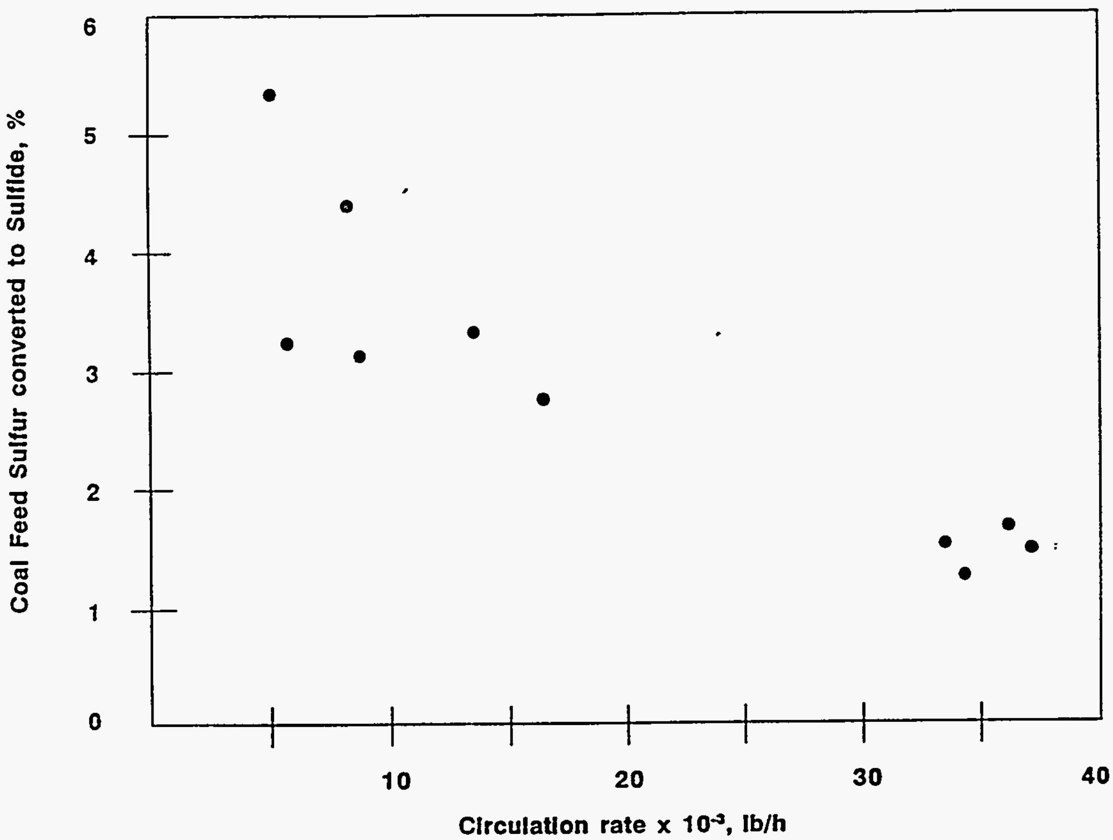

Figure 13 Coal Feed Sulfur Converted to Sulfide vs. Circulation Rate

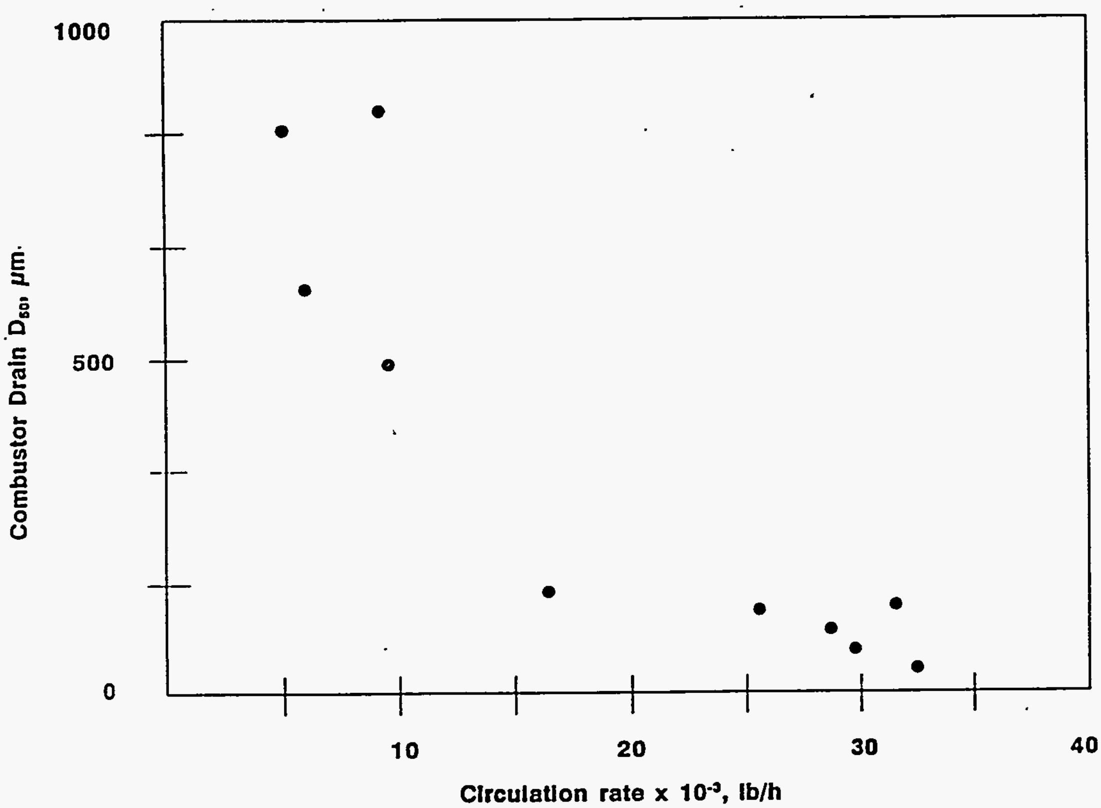

Figure 14 Effect of Circulation Rate on Combustor Bed Particle Size

Table 5 Comparison of Operating Conditions for Char Tests

Description	Pittsburgh No. 8 (Dolomite)	Illinois No. 6 (Limestone)		
Feed Sulfide S, %	3.03	4.30	4.19	1.82
Feed Ca Sulfidation, %	41.0	25.5	26.9	22.2
Sulfide Conversion, %	76.1	75.5	82.3	73.9
Bed Temperature, °F	1627	1612	1626	1626
Primary Air Stoichiometry, %	69	78	74	69
Excess Air, %	51	68	39	41
Pressure, psig	98	101	87	77
FBHE Temperature, °F	1396	1304	1261	1277
FBHE Dp, in. H_2O	6	12	9	8
Solids Circulation Rate, lb/h	9060	7396	5361	4897

SUMMARY AND CONCLUSIONS

This pilot plant program confirmed the viability of the CPFBC design and barrier candle filter from both an operational and emissions standpoint. Several HVB coals and one subbituminous coal were evaluated in this test program, in addition to chars produced in prior carbonizer pilot plant tests. Combustor temperature, primary air stoichiometry, excess air, and calcium to sulfur feed ratios were the major operating parameters evaluated in this program in order to assess their effect on combustor performance.

The following summarizes the significant results of the CPFBC pilot plant test program:

- Carbon combustion efficiency was exceptionally high and exceeded 99 percent for all the test coals and chars. Based on these results, carbon combustion efficiency should not be a major concern in commercial-scale second-generation PFB plants.

- CO emissions were very low compared to atmospheric CFB experience and were consistently less than 0.1 lb/10^6 Btu. CO emissions ranged between only 0.01 and 0.02 at combustor temperatures in excess of 1600°F.

- Sulfur capture efficiencies of greater than 96 percent were achieved for the test coals with sorbent addition rates corresponding to Ca/S ratios of between 1.0 and 2.0. Similar sulfur capture efficiencies were obtained with the carbonizer chars without the addition of fresh sorbent. The inherent Ca/S ratios were relatively high in the char from unreacted sorbent and were in excess of 1.5.

- NO_x emissions were relatively high but were generally about half the NSPS requirements (0.3 vs. 0.6 lb/10^6 Btu). Primary air stoichiometry appeared to have the most significant effect on NO_x emissions of all the operating parameters. Excess air and combustor bed temperature did not appear to have significant effects on NO_x emissions.

- Because of the short height of the Phase 2 CPFBC (about 1-s secondary zone gas residence time), calcium sulfide conversions in the CPFBC ranged from 74 to 83 percent for the char blends. Higher sulfide conversions would be expected in a commercial-scale plant because of increased gas residence time.

The carbonizer and CPFBC have been tested separately to ascertain their individual performance characteristics. In Phase 3, the multipurpose reactor will be returned to the bubbling bed carbonizer configuration, and a larger CPFBC will be installed to facilitate integrated performance tests. The CPFBC will have a 13-in. ID and, being 38 ft-3 in. tall, should exhibit improved NO_x and sulfide conversion performance. In addition, the dry lock-hopper pneumatic transport feed systems will be supplemented with a coal/water paste feed system to study the effect of a coal/water paste feed on carbonizer performance.

REFERENCES

1. A. Robertson, et al. 1988. Second-Generation PFB Combustion Plant Performance and Economics. *1988 Seminar on Fluidized-Bed Combustion Technology for Utility Applications*, Palo Alto, CA.
2. A. Robertson, et al. 1993. Second-Generation PFBC Systems Research and Development—Phase 2, Best Efficiency Approach in Light of Current Data. *Proceedings of the Coal-Fired Power Systems 93—Advances in IGCC and PFBC Review Meeting*, Don Bonk (ed.), DOE/METC 93/6131.
3. A. Robertson, et al. 1989. Second-Generation Pressurized Fluidized Bed Combustion Plant: Research and Development Needs. Foster Wheeler

Development Corporation, Livingston, NJ. Phase 1 Task 2 Report FWC/FWDC-TR-89/06 to the U.S. DOE under Contract DE-AC21-86MC21023.

4. A. Robertson, et al. 1989. Second-Generation Pressurized Fluidized Bed Combustion Plant: Integrated R&D Program Plan. Foster Wheeler Development Corporation, Livingston, NJ. Phase 1 Task 3 Report FWC/FWDC-TR-89/08 to the U.S. DOE under Contract DE-AC21-86MC21023.
5. A. Robertson, et al. 1992. Second-Generation PFBC Systems Research and Development. *Proceedings of the Twelfth Annual Gasification and Gas Stream Cleanup Systems Contractors Review Meeting*, Vol. 1, DOE/METC 92/6128.
6. A. Robertson, et al., 1992. Initial Second-Generation PFBC Carbonizer Pilot Plant Test Results. *Proceedings of the Ninth Annual International Pittsburgh Coal Conference*, University of Pittsburgh.
7. J. Van Hook, A. Robertson, and D. Bonk. 1992. Carbon Conversions Measured in a Second-Generation PFB Pilot Plant Carbonizer. *Proceedings of the 12th International Conference on Fluidized Bed Combustion*, Vol. 2, L. N. Rubow (ed.), ASME, New York.
8. K. M. Sellakumar, et al. 1993. Process Performance of Ahlstrom Pyroflow PCFB Pilot Plant. *Proceedings of the 12th International Conference on Fluidized Bed Combustion*, San Diego, pp. 423-429.
9. G. von Wedel, et al. 1993. Pressurized Fluidized Bed Combustion in a 15 MWth Test Facility—Bubbling and Circulating Experience and Future Development. *Proceedings of the 12th International Conference on Fluidized Bed Combustion*, San Diego, pp. 403-423.
10. J. Abbasian, et al., "Desulfurization of Fuels With Calcium-based Sorbents," Fuel Processing Technology 25, 1-15, 1990.
11. E.J. Anthony, "Characterization of Solid Wastes From Circulating Fluidized Bed Combustion," 10th International Conference on Fluidized Bed Combustion, San Francisco, CA, 131-139.
12. J. Abbasian, et al., "Sulfation of Partially Sulfided Calcium-Based Sorbents," I&EC Research, 30, 1991.