DOE/FETC/C--98/7288
CONF-971214--

TOPPING PCFB COMBUSTION PLANT WITH SUPERCRITICAL STEAM PRESSURE

A. Robertson
Foster Wheeler Development Corporation
Livingston, New Jersey

J. White
Parsons Power Group Incorporated
Reading, Pennsylvania

ABSTRACT

Research is being conducted under United States Department of Energy (USDOE) Contract DE-AC21-86MC21023 to develop a new type of coal-fired plant for electric power generation. This new type of plant -- called a Second Generation or Topping Pressurized Circulating Fluidized Bed Combustion (topping PCFB) plant -- offers the promise of efficiencies greater than 46 percent (HHV), with both emissions and a cost of electricity that are significantly lower than conventional pulverized-coal-fired plants with scrubbers.

The topping PCFB plant incorporates the partial gasification of coal in a carbonizer, the combustion of carbonizer char in a pressurized circulating fluidized bed combustor (PCFB), and the combustion of carbonizer fuel gas in a topping combustor to achieve gas turbine inlet temperatures of 2300°F and higher.

After completing pilot plant tests of a carbonizer, a PCFB, and a gas turbine topping combustor, all being developed for this new plant, we calculated a higher heating value efficiency of 46.2 percent for the plant. In that analysis, the plant operated with a conventional 2400 psig steam cycle with 1000°F superheat and reheat steam and a 2½-inch mercury condenser back pressure. This paper identifies the efficiency gains that this plant will achieve by using supercritical pressure steam conditions.

BACKGROUND INFORMATION

Second-Generation or Topping Pressurized Circulating Fluidized Bed Combustion (topping PCFB) plants offer electric 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 topping PCFB plant.

DISCLAIMER

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 and a packed bed of emathelite pellets to remove alkali vapors, 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 pressurized circulating fluidized bed combustor (PCFB), and a fluidized bed heat exchanger (FBHE). The carbonizer char is burned in the PCFB with high excess air. The vitiated air from the PCFB 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 PCFB 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. As this unit operates at temperatures much lower than gasifiers currently under development, it also produces a char residue. Left untreated, the fuel gas would 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 Source Performance Standards (NSPS). The captured material, together with carbonizer bed drains, is collected in a central hopper and injected into the PCFB 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 PCFB spent sorbent.

In the PCFB 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 units. Controlled recirculation is accomplished with cyclone separators and nonmechanical valves. The FBHE contains tube surfaces that cool the circulating solids. As a result of the low fluidizing velocity in the FBHE (< ½ ft/s), the risk of tube erosion is virtually eliminated.

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

The topping combustor, which consists of metallic-wall multiannular swirl burners (MASBs), will be provided in two external combustion assemblies (topping combustors) on opposite sides of the gas turbine. Each MASB contains a series of swirlers that aerodynamically create fuel-rich, quick-quench, and fuel-lean zones to minimize NO_x formation during the topping combustion process. The swirlers also provide a thick layer of air at the wall boundary to control the temperature of the metallic walls.

A team of companies -- led by foster Wheeler Development Corporation (FWDC) with Foster Wheeler Energy North America and Foster Wheeler USA; Parsons Power Group Inc.; Institute of Gas Technology; Westinghouse Power Generation Business Unit (PGBU) and Westinghouse Science & Technology Center (STC) -- has embarked upon a USDOE-funded, three-phase program to develop the technology for this new type of plant. A conceptual design of a 2.9-percent-sulfur, Pittsburgh No. 8 coal-fired topping PCFB plant with a conventional 2400psig/1000°F/1000°F/2½-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 with a stack-gas scrubber.

SEPARATE COMPONENT TESTS

In the second phase of our USDOE contract, the key components of this new type of plant were tested separately to ascertain their individual performance characteristics. Westinghouse PGBU is responsible for the design, construction and testing of the MASB. Their MASB development program started with a 12-inch-diameter test unit and has progressed to 14-inch and 18-inch-diameter sizes. Their 18-in. unit has a dual fuel capability and is a prototype of the MASBs planned for use in Westinghouse 251 and 501 combustion turbines. The 18-in. MASB was tested successfully in 1994 with both natural gas and synthesized carbonizer fuel gas and test results have been published.[2]

A 10-inch-diameter carbonizer and an 8-inch-diameter PCFB were tested separately by FWDC in the 1991-1993 time period in a single multipurpose vessel. The tests were conducted at the Foster Wheeler John Blizard Research Center in Livingston, NJ, at pressures as high as 200 psig and utilized petroleum coke, bituminous coal (Pittsburgh No. 8 and Kentucky No. 9), subbituminous coal (Wyoming Eagle Butte), and both dolomite and limestone sorbents. The fuel gas produced by the carbonizer was passed through cross-flow and candle-type ceramic barrier filters supplied by Westinghouse STC to demonstrate their compatibility with this gas. The carbonizer and PCFB test programs were successful and results have also been published.[3,4,5]

INTEGRATED CARBONIZER-PCFB PILOT PLANT

Having ascertained individual performance characteristics, the Foster Wheeler PCFB pilot plant was essentially doubled in size to permit integrated carbonizer-PCFB operation in the third and final phase of our USDOE contract. The integrated pilot plant has a maximum heat input capability of 12.1 $(10)^6$ Btu/h (3.6 MWt) and consists of two sections that are interconnected and operated in parallel. In the first or "sending" section, coal is carbonized/ partially gasified at elevated temperature (1600 to 1800°F) and pressure (≈14 atma) to produce a low Btu fuel gas and a char-sorbent residue. As shown in Figure 2, the carbonizer fuel gas is cleaned of particulate matter via a cyclone and ceramic candle filter, depressured via an orifice, cooled via a dry water-spray quench, passed through a mist eliminator and baghouse filter, and burned in a natural gas-fired incinerator. The char-sorbent residue removed from the fuel gas by the cyclone and candle filter, together with residue drained from the top and bottom of the carbonizer bed, are collected in a central hopper. The collected residue is transferred to the second or "receiving" section of the plant and burned with varying amounts of coal or coke in a PCFB, also operating at similar temperature and pressure. The PCFB flue gas is similarly depressured, cooled, and then injected into the incinerator exhaust gas in a common stack prior to their discharge to the atmosphere.

The carbonizer is a 30-in-OD x 39 ft.-6-in.-tall refractory-lined pressure vessel with a 24-ft. deep jetting fluidized bed and a 9-ft. 5-in. tall freeboard. The carbonizer ID increases from the bottom to the top in three steps to enhance solids circulation and limit slugging and elutriation. The ID is 10 in. for the first 3 ft.-7 in. of bed height, 12 in. to the top of the bed, and 14 in. in the freeboard. Air, coal, and lime-based sorbent can be injected in the unit at a 40- to 60-ft/s jet velocity through a central, vertical, 1-in. Sch 80, stainless steel feed pipe at the bottom of the unit.

The PCFB is a vertical 36-in.-OD x 44 ft.-4 in.-tall pressure vessel. The PCFB primary zone is 12 ft.-7 in. tall, and the secondary zone is 25 ft.-8 in. tall. The vessel is refractory lined to a 13-in ID. Coal, sorbent, and pneumatic transport air can be 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 feed pipe. At a point 1-3/4 in. below the top of the feed pipe, an outer concentric 3-in. Sch 80 pipe injects fluidization air around and at the base of the feed pipe; secondary air is injected 12 ft.-7 in. above this point.

A nitrogen-aerated packed-bed cooler at the bottom of the PCFB cools spent bed material to 300°F and a pressurized screw controls the withdrawal rate to a lock-hopper for depressuring and disposal. The heat released during the combustion of the char-sorbent residue is absorbed by a sorbent/fly ash mixture continuously circulated between the PCFB and a FBHE. A cyclone separator atop the FBHE and a nonmechanical J-valve at the bottom of the FBHE facilitate the circulation of these solids, with the latter entering the PCFB 26-7/8 in. above the fluidizing air nozzle.

The FBHE is a 42-in.-OD by 41 ft.-3 in.-tall pressure vessel, refractory lined to yield an 18-in. square bed and freeboard section. The fluidized bed contains a 5 ft.-6 in.-tall (bottom-to-top tube centerline height) water-cooled tube bundle consisting of eight 1-in.-OD Incoloy® 800H tubes. City water cools the tubes and its flow rate is adjusted to keep the water outlet temperature below 140°F. A series of air-sparger pipes injects fluidization air at the bottom of the bed, thus allowing solids to flow around a baffle and up to the inlet of the solids return J-valve for return to the PCFB. Bed material can flow between the air-sparger pipes to the bottom of the unit for removal through a 4-in. drain nozzle. The draining material is cooled as a packed bed to 300°F by counter flowing nitrogen. A screw feeder immediately below the FBHE controls the bed drain rate. The fluidized air leaves the top of the FBHE and enters the PCFB as secondary air.

INTEGRATED CARBONIZER-PCFB OPERATION

The construction of Foster Wheeler's integrated pilot plant was completed in 1995 and shakedown operations culminated in a 7-day commissioning run in September 1995. During this run the plant was operated with three different fuels (i.e., petroleum coke, Pittsburgh No. 8 and Kentucky No. 9 coals) and two different sorbents (i.e., Plum Run dolomite and Dravo limestone). The PCFB was started first. After a day of stable PCFB operation, the carbonizer was started, run continuously for five days, and shut down. With the PCFB free of the carbonizer, the PCFB was operated for another day to explore wide ranging operating conditions before the unit was voluntarily shut down.

The 7-day commissioning run was a success. It demonstrated that carbonizer char-sorbent residue can be continuously generated, collected at a centralized point (char collecting hopper), transferred across a reducing gas-oxidizing gas boundary, and combusted in a PCFB all at safe, smooth, and controlled rates. In addition, PCFB firing rates were adjusted to maintain stable combustion conditions (≈1600°F) as carbonizer feedstocks, operating conditions, and char-sorbent production rates were varied. Throughout the entire run, the carbonizer and PCFB candle filters operated smoothly and no candle-to-candle or hopper ash bridging was encountered. Foster Wheeler proprietary sulfur capturing techniques were demonstrated that raised the plant sulfur capture efficiency to 98.5 percent. Injection of urea into the PCFB reduced NO_x emissions, and PCFB combustion efficiencies were greater than 99.5 percent with all feedstocks. The Livingston PCFB was built primarily to combust carbonizer chars. At Foster Wheeler's research laboratory in Karhula, Finland, a PCFB with more than three times the Livingston throughput has accumulated approximately 10,000 hours of operating time in larger scale tests of alternate fuels and candle filter development activities. The collected data continues to confirm the high efficiency and low emissions we predict for the topping PCFB plant; with high-sulfur bituminous coal we anticipate NO_x emissions approaching 0.1 lbs/10^6 Btu and sulfur capture efficiencies of 95 percent at a calcium-to-sulfur molar feed ratio of 1.75.

COMMERCIAL PLANT PERFORMANCE

Tests conducted in our Phase 2 pilot-scale carbonizer yielded performance superior to that estimated in 1987, and using that test data in 1993 we projected a plant efficiency of 46.2 percent with a 1600°F carbonizer.[5] Using more advanced computer-aided design and flow field modeling programs, steam turbine manufacturers have been able to increase the efficiencies of their machines and, when incorporated into the topping PCFB plant, the 46.2 percent efficiency increases to 46.7 percent (see Table 1).

All of the plant configurations investigated to date used a conventional subcritical pressure steam cycle (2400 psig/1000°F/1000°F/2½-inch Hg). Further increases in efficiency can be achieved by using a supercritical pressure steam cycle, higher superheat/reheat steam temperatures, and/or higher gas turbine firing temperatures (≈2500°F). Since no 2500°F units are believed to be in operation as of the writing of this paper, we have limited our analyses to the more advanced but commercially proven steam conditions.

Figure 3 presents a heat and material balance for the topping PCFB plant operating with a supercritical pressure steam cycle (3500 psig/1050°F/1050°F) and a 2½-inch Hg. condenser back pressure. As in our previous studies, the plant combusts 2.9 percent sulfur Pittsburgh No. 8 coal with Ohio Plum Run dolomite supplied at a 1.75 calcium-to-sulfur molar feed ratio; and we now project, based on pilot plant tests, a 95 percent sulfur capture efficiency. The topping PCFB plant is modular; it utilizes two carbonizer-PCFB-gas turbine modules with one steam turbine. Although for simplicity Figure 3 only shows one module, the flow rates given are plant totals. Table 1 summarizes the key plant data and compares it to that of the updated subcritical pressure plant. Both plants utilize two Westinghouse 501F gas turbines, each operating with a 2350°F MASB outlet temperature and producing 139 MWe (278 MWe total). The supercritical pressure steam turbine produces 300 MWe of power compared with 288 MWe for the subcritical turbine and, as expected, the former's throttle flow is lower, i.e., 1.591 vs. 1.623 x 10^6 lb/h. Net plant outputs are 553 and 544 MWe respectively and the supercritical pressure plant efficiency is 0.8 points higher, e.g., 47.5 vs. 46.7 percent on the coal HHV basis.

Our pilot plant tests and commercial plant design updates continue to show the attractiveness of this new coal burning technology. As a result, development work is continuing and a plant approximately 7 times larger than that tested at Livingston is being constructed at the Wilsonville, Alabama, plant of Southern Company Services. The plant incorporates a 3½ MWe gas turbine integrated with a Foster Wheeler carbonizer and PCFB and Westinghouse candle filters and MASB. The plant is scheduled for a mid-1998 start up, and we look forward to the successful completion of this next milestone in the development of the topping PCFB plant.

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. W. Domeracki, et al. 1994. Development of Topping Combustor for Advanced Concept Pressurized Fluidized Bed Combustion. Proceedings of the Coal-Fired Power Systems 94, M. McDaniel, R. Staubly and V. Venkataraman, (ed.), DOE/METC 94/1008.

3. J. Van Hook, et al., "Carbon Conversions Measured in a Second-Generation PFB Pilot Plant Carbonizer," *Proceedings of the 12th International Conference on Fluidized Bed Combustion,* Volume 2, L. N. Rubow (ed.), ASME, New York, 1993.

4. R. Conn, et al., "Performance of a Second-Generation PFB Pilot Plant Combustor," *Proceedings of the 12th International Conference on Fluidized Bed Combustion,* Vol. 1, K. Heinschel (ed.), ASME, New York, 1995.

5. 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.

TABLE 1

TOPPING PCFB PLANT PERFORMANCE

basis: 1600°F Carbonizer — 280°F stack
2350°F MASB — 2½ -in. Hg. condenser

	Steam Cycle Conditions	
	2400/1000/1000	3500/1050/1050
Net Plant Output, MWe	544.1	553.4
Net Plant Efficiency, % (HHV)	46.7	47:5
Gross Power, MWe		
Gas Turbine	278.2	278.2
Steam Turbine	288.1	299.8
Steam Turbine Throttle Flow, 10^6 lb/h	1.623	1.591

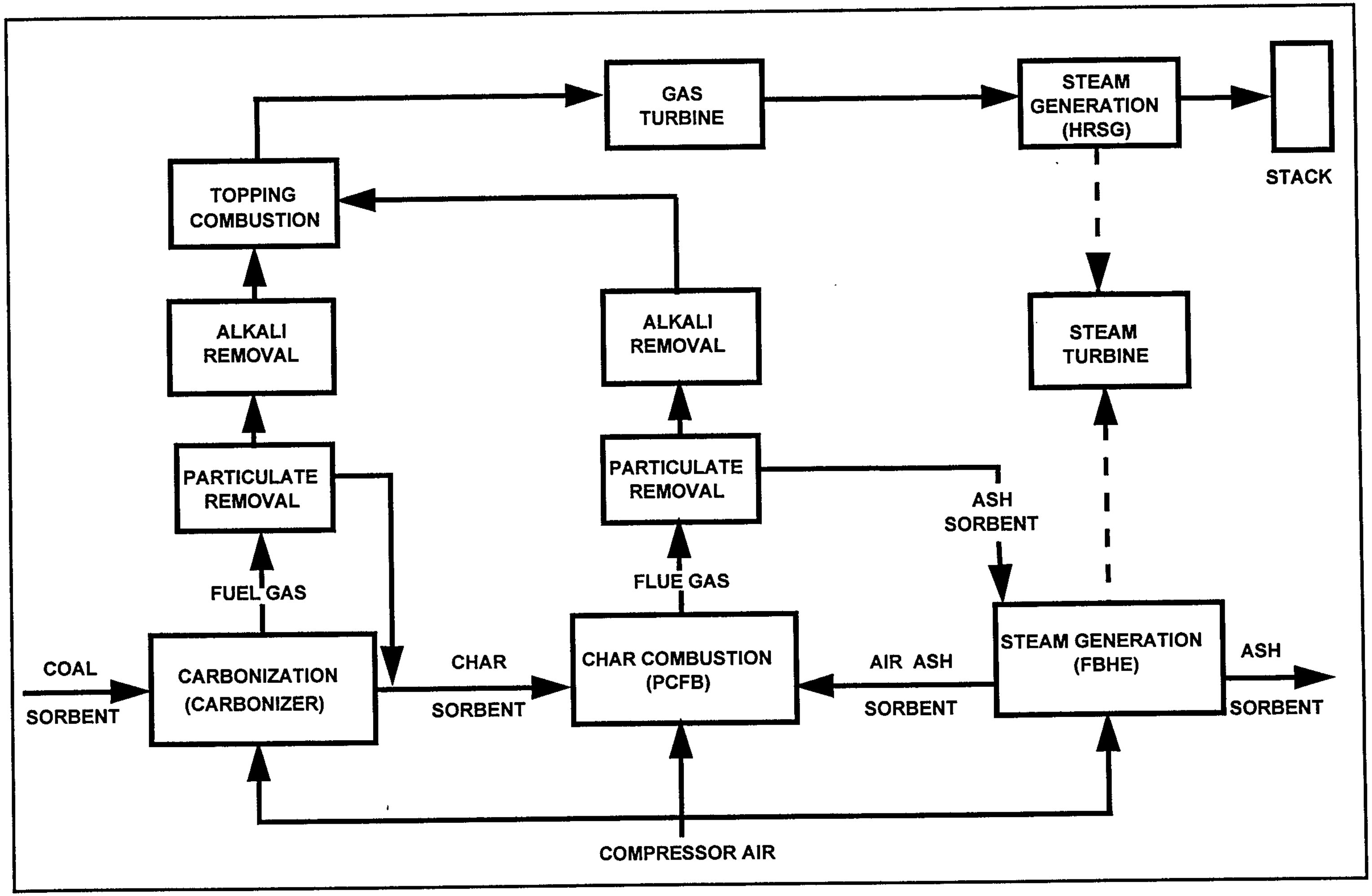

Figure 1 Simplified Process Block Diagram of a Topping PCFB Plant

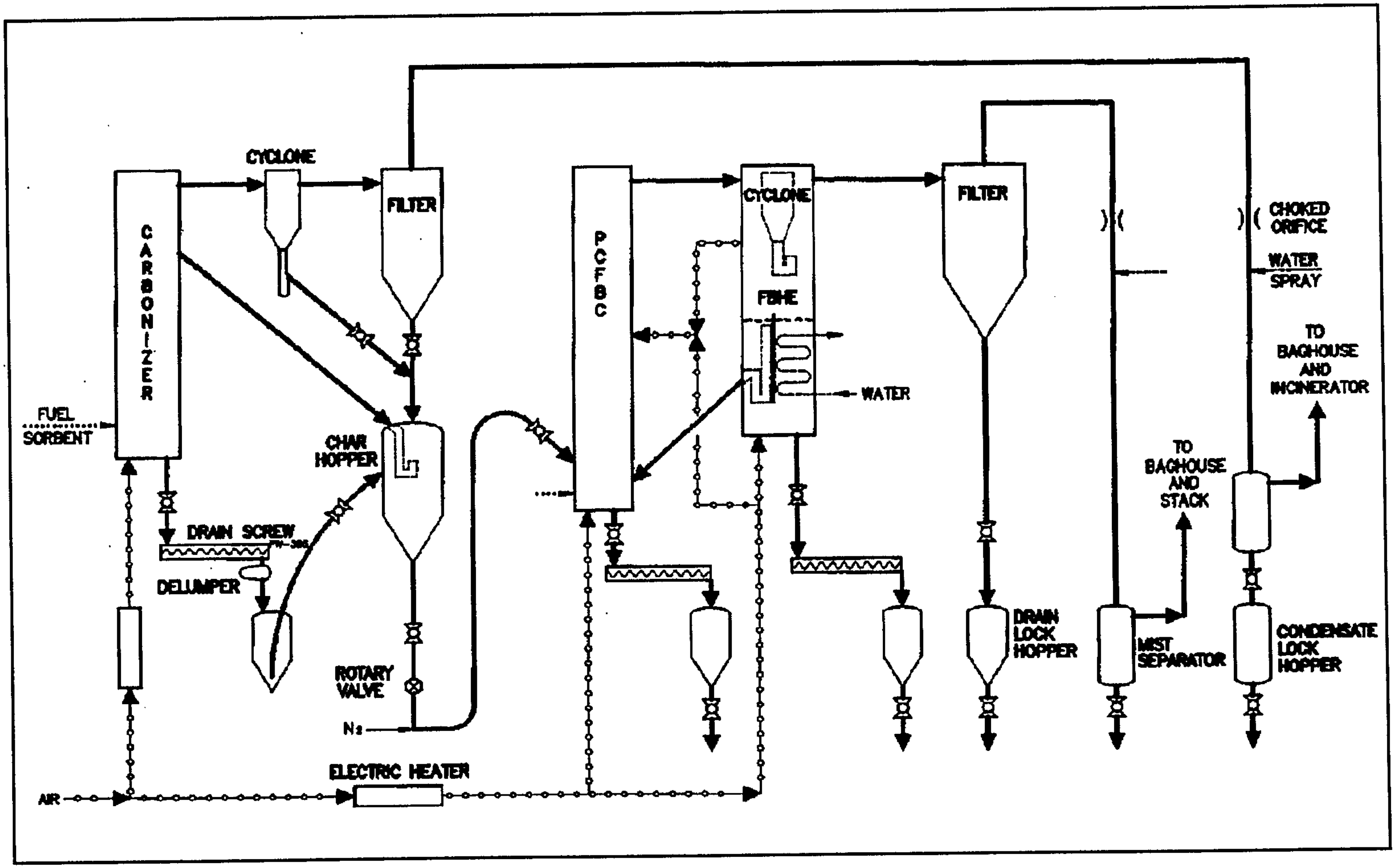

Figure 2 Integrated Carbonizer-PCFB Pilot Plant Schematic

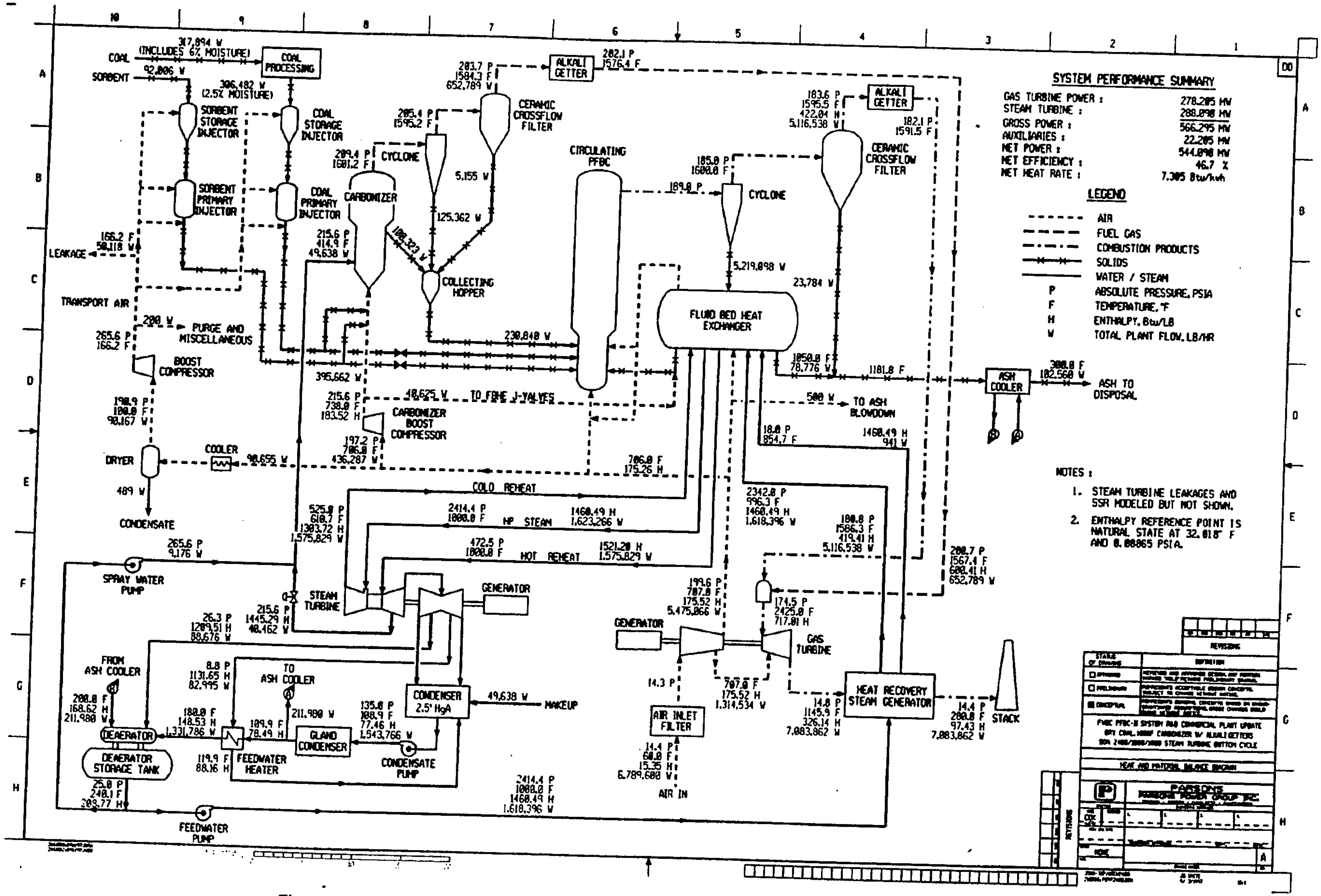

Figure 3 Topping PCFB Plant with 1600°F Carbonizer and Supercritical Steam Cycle

Report Number (14) DOE/FETC/C-- -98/7288
CONF-971214 --

Publ. Date (11) 199711
Sponsor Code (18) DOE/FE, XF
UC Category (19) UC-101, DOE/ER

DOE