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Development of Second-Generation PFB Combustion Plants

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Abstract

Research is being conducted under United States Department of Energy (USDOE) Contract DE-AC21-86MC21023 to develop a new type of coal-fueled plant for electric power generation. This new type of plant—called an Advanced or Second-generation Pressurized Fluidized Bed Combustion (APFBC) plant—offers the promise of efficiencies greater than 45 percent (HHV), with both emissions and a cost of electricity that are significantly lower than conventional pulverized-coal-fired plants with scrubbers. This paper summarizes the pilot-plant R&D work being conducted to develop this new type of plant and discusses a proposed design that should reduce demonstration-plant risks and costs.

Background Information

Advanced or Second-generation Pressurized Fluidized Bed Combustion (APFBC) 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 an APFBC 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 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 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. 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, 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 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 (< 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 barrier 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 these devices are currently under development for first-generation Pressurized Fluidized Bed (PFB) combustion plants and should also be applicable to the second-generation 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 Corporation and Foster Wheeler USA; Gilbert/Commonwealth, 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 3-percent-sulfur Pittsburgh No. 8 coal-fired second-generation PFB plant with a conventional 2400 psig/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. Tests conducted in our Phase 2 pilot-scale carbonizer yielded performance superior to that estimated in 1987. As a result, we now expect a more energetic fuel gas (Figure 2) and a plant efficiency of 46.2 percent (Figure 3) with a 1600°F carbonizer.[2]

Gas Cooling

To maximize the plant gas-turbine-to-steam-turbine power ratio and hence plant efficiency, the carbonizer fuel gas and the CPFBC flue gas/vitiated air are delivered hot to the topping combustor. If these gases are cooled prior to the topping combustor, the design requirements (i.e., 1600°F operating temperature) of the intervening equipment—i.e., filters, valves, piping—can be eased, and the need for alkali-getters eliminated. In [3] we systematically determined the effect on plant efficiency of cooling the two streams. First, the carbonizer fuel gas was cooled from 1600°F to 1450°F, with the sensible heat being transferred to the steam cycle by a heat exchanger located between the carbonizer cyclone and candle filter. In order to maintain the topping-combustor firing temperature of 2424°F, additional fuel gas had to be burned to compensate for the cooling of the fuel gas. Coal, sorbent and airflows to the carbonizer were increased, the air being diverted from the CPFBC to the carbonizer to generate additional fuel gas. Along with the additional fuel gas, additional char is also generated that is burned in the CPFBC. With less air available to absorb the increased char heat release, the steam flow to the CPFBC-FBHE subsystem is increased to maintain the CPFBC at 1600°F. Although the gas-turbine power output is essentially unchanged, steam-turbine power increases; the gas-turbine-to-steam-turbine power ratio, hence plant efficiency, decreases by 0.6 percentage points from 46.2 to 45.6, as shown in Case 1 of Table 1.

Returning the carbonizer fuel gas path to 1600°F and incorporating a heat exchanger to cool only the vitiated air path from 1600°F to 1450°F results in similar behavior. With the vitiated airflow rate being approximately 10 times larger than the original fuel-gas flow rate, a much larger increase in fuel-gas flow rate is required. As a result, the decrease in gas-turbine-to-steam-turbine power ratio and plant efficiency is greater than before, the plant efficiency decreasing by 1.3 percentage points from 46.2 to 44.9 (Case C2 in Table 1).

A 14-atmosphere, 10-inch-diameter carbonizer has been tested at the Foster Wheeler Development Corporation research center in Livingston, New Jersey,[4] and the amount of alkali vapor present in the carbonizer fuel gas has been measured. Based on these and other data, Westinghouse believes the need for alkali-getting can be eliminated by cooling the carbonizer fuel gas to 1300°F; cooling the gas condenses the alkali vapors on the gas-particulate matter, which in turn is removed by the ceramic barrier/candle filter. Although the Westinghouse candle filter uses ceramic filter elements, the elements are attached, supported and manifolded by metallic components. The 300°F reduction in carbonizer fuel gas temperature to 1300°F will improve component reliability and, via the use of lower-alloy steels, result in filter system cost savings. In addition, the lower temperature may allow the piping from the filter outlet to the gas turbine to be furnished in all-metal construction, opposed to refractory-lined pipe with metallic liners, the latter being provided to prevent spalling refractory from reaching the gas turbine. The reliability and costs of these lines together with their control valves, isolation valves, and topping combustors are similarly improved.

In Case C3 both the carbonizer fuel gas and the CPFBC flue gas/vitiated air are cooled from 1600°F to 1300°F via heat transfer to the steam cycle. As shown in Table 1, the steam turbine output increases by 63 percent and, with the decreased gas-turbine-to-steam-turbine power ratio, the plant efficiency drops by 2.4 percentage points from 46.2 to 43.8 percent. Efficiency losses generally involve parasitic losses that reduce the plant output. In our case there is no loss in power; the power output actually increases. It is the change in gas-turbine-to-steam-turbine power ratio that causes the reduction in efficiency.

Increased Carbonizer Temperature

A 1600°F carbonizer has been used in our studies because in our 1987 conceptualization of the APFBC plant, we projected it would meet the contract goal of 45 percent efficiency. Foster Wheeler Corporation has successfully operated its 14-atmosphere pressure carbonizer as high as 1815°F with Pittsburgh No. 8 coal and projects the 1700°F performance shown in Figure 4. Comparison of Figures 2 and 4 reveals that increasing the carbonizer operating temperature from 1600°F to 1700°F increases the amount of coal energy being transferred to the fuel-gas stream (the topping-combustor energy release per pound of coal carbonized increases by approximately 27 percent; whereas, the energy content of the char-sorbent residue stream reduces similarly). Hence, the additional topping-combustor heat release required to compensate for the cooling of the fuel and flue gases to 1300°F can be supplied by increasing both the carbonizer temperature and coal feed. This combination, opposed to coal feed alone, reduces the increase in CPFBC char heat release and hence the growth of the steam cycle. As a result, the efficiency decrease associated with gas cooling can be reduced. Case 4 in Table 1 reveals that this arrangement reduces the efficiency loss to 0.4 percentage points from 46.2 to 45.8 percent, and Figure 5 presents the plant heat and material balance.

CPFBC Air Bypass

An APFBC plant designed for maximum efficiency, opposed to maximum power output, operates with high excess air to minimize the steam cycle size/maximize the gas-turbine-to-steam-turbine power ratio. As a result, the CPFBC operates with relatively high excess air. A portion of this excess air can be bypassed around the CPFBC and injected into the flue gas downstream of the cyclone to quench the gas stream to 1300°F. The use of air bypass eliminates the need for a heat exchanger between the cyclone and candle filter. With less air available to absorb the CPFBC char heat release, the FBHE must be increased in size. Although the steam cycle heat pickup and plant efficiency are unchanged from Figure 5, it is expected the higher heat transfer coefficients of the FBHE (bed-to-tube, rather than gas-to-tube) will result in a less expensive heat-exchange configuration.

In summary, we believe the slight loss in efficiency (45.8 versus 46.2 percent) is well worth the improved reliability of the downstream hot-gas components. Realizing APFBC plants are an emerging technology and since we believe this gas-cooled arrangement will reduce both component risks and costs, we recommend its consideration for the first demonstration-sized plant.

Pilot Plant Testing

The move to commercialization of this new type of plant involves the five steps shown in Figure 6. Starting from the left and moving to the right, each succeeding step involves increased integration of components and increased plant size/complexity. In the first step—Phase 2 of our USDOE contract—the key components of this new type of plant were tested separately to ascertain their individual performance characteristics. The Phase 2 tests involved testing (1) a 10-inch-diameter carbonizer (Figure 7) with a cyclone and ceramic barrier filter, (2) an 8-inch-diameter CPFBC (Figure 8) with a cyclone and ceramic barrier filter and (3) 12-inch-, 14-inch- and 18-inch- (Figure 9) diameter MASBs. The first two test programs were conducted by Foster Wheeler Development Corporation at its John Blizard Research Center in Livingston, New Jersey. These programs were successful, test reports have been released to the National Technical Information Service (NTIS) for publication and test results have been presented at previous conferences.[2,4] The MASB tests were conducted at the University of Tennessee Space Institute at Tullahoma, Tennessee, under the direction of Westinghouse PGBU. Although a final report has not yet been issued (two additional tests are planned), test results have also been presented at previous conferences.[5,6,7]

In the second step to commercialization—Phase 3 of our USDOE contract—a carbonizer and CPFBC, both with their respective cyclones and ceramic candle filters, are being interconnected and operated as an integrated subsystem. The FWDC pilot plant in Livingston, New Jersey, was expanded in 1994 to permit this integrated operation. The new and previously tested units are compared in Figures 7 and 8. The new CPFBC is 13 inches in diameter by 38.3 feet tall and operates at a 2 1/2 times higher throughput than the previous Phase 2 unit. The new carbonizer is actually the previous unit lengthened by a 5-foot-tall spool piece that allows operation with a commercial-scale, 24-foot-deep bed height. The hot shakedown of the expanded/integrated carbonizer-CPFBC pilot plant is underway.

In Step 3 of Figure 6, a MASB and a gas turbine will be integrated with a carbonizer and CPFBC. This will be the first time either has operated with carbonizer fuel gas, as all previous MASB tests used gas mixtures synthesized to the composition predicted by Foster Wheeler Corporation for a commercial plant. This integration will occur at the Southern Company Services Power Systems Development Facility (PSDF) at Wilsonville, Alabama. This facility is being funded for advanced coal-based power system R&D by the USDOE, the Electric Power Research Institute and industry.

The APFBC process will be tested at the PSDF, and a simplified schematic diagram is presented in Figure 10. The plant will incorporate a 37-inch-ID CPFBC; an FBHE with two tube-bundle-containing fluidized beds, cyclones and ceramic candle filters; an 18-inch MASB and a nominal 3-MWe gas turbine. For cost savings a steam turbine will not be provided, and the FBHE heat absorption will be exhausted to atmosphere via cooling towers. The 18-inch MASB will combust 1700°F CPFBC flue gas/vitiated air to 2300°F. The gas turbine, a relatively small unit, operates with a 1975°F turbine-inlet temperature. Compressor discharge air will be injected into the 2300°F MASB exhaust to cool it to 1975°F, allowing commercial plant MASB operation to be demonstrated.

The PSDF will be operated with Illinois No. 6 bituminous and Eagle Butte subbituminous coals. Limestone from Longview, Alabama, will be injected into the APFBC fluidized beds to capture sulfur in situ. Each of these feedstocks has already been successfully tested in the Livingston Phase 2 carbonizer and CPFBC pilot plants.

The Wilsonville APFBC will be commissioned in stages. Beginning the second quarter of 1996, the plant will be operated as a first-generation PFB (no carbonizer or topping combustion), with coal being fired in the CPFBC. After this commissioning step is completed, integrated carbonizer-CPFBC operation will begin. With Wilsonville feedstocks and operating conditions having already been tested in Phase 2 and Wilsonville personnel having witnessed Phase 2 testing and Phase 3 integrated carbonizer-CPFBC pilot plant commissioning runs, we anticipate a successful two-year test program.

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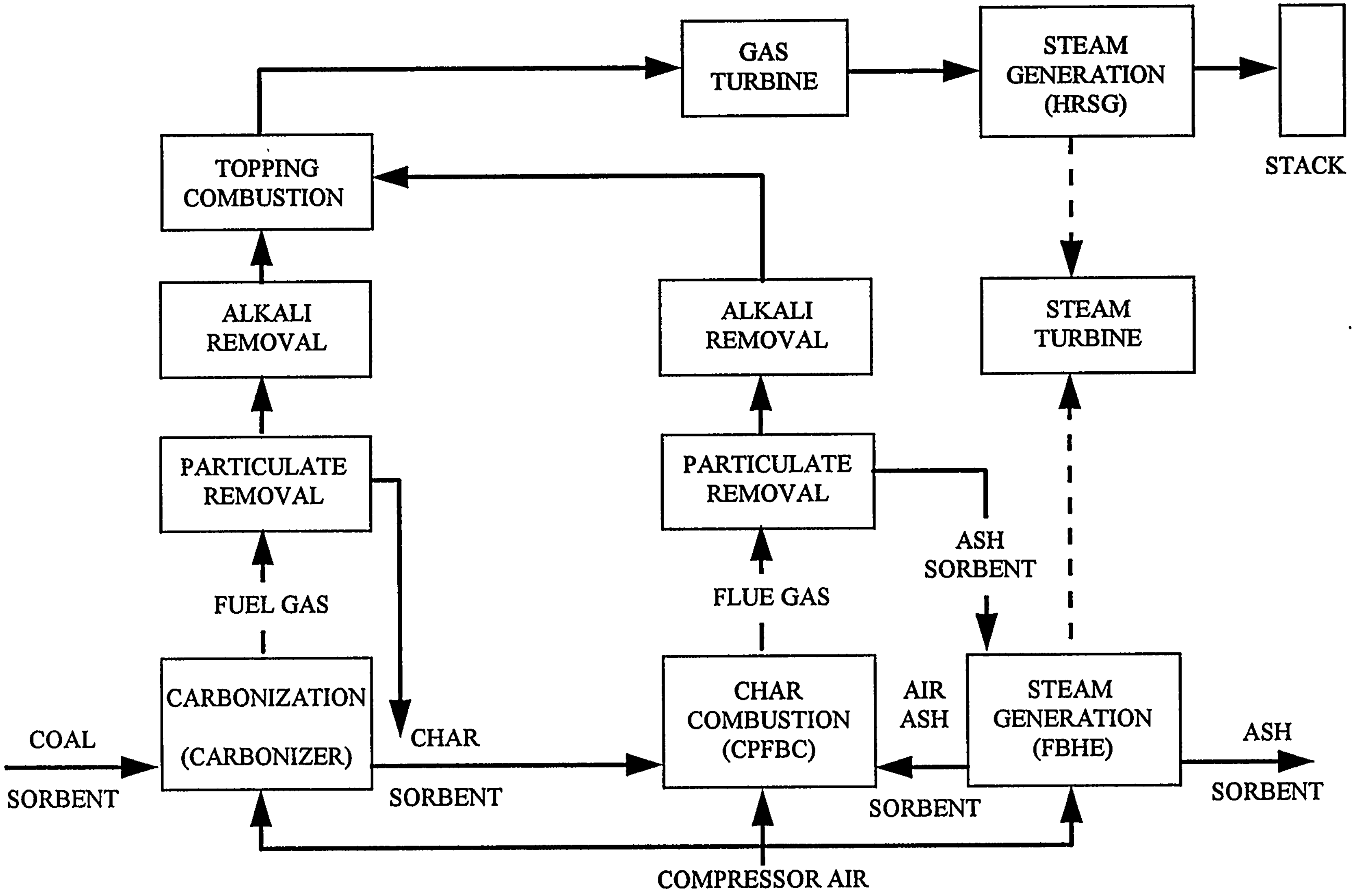

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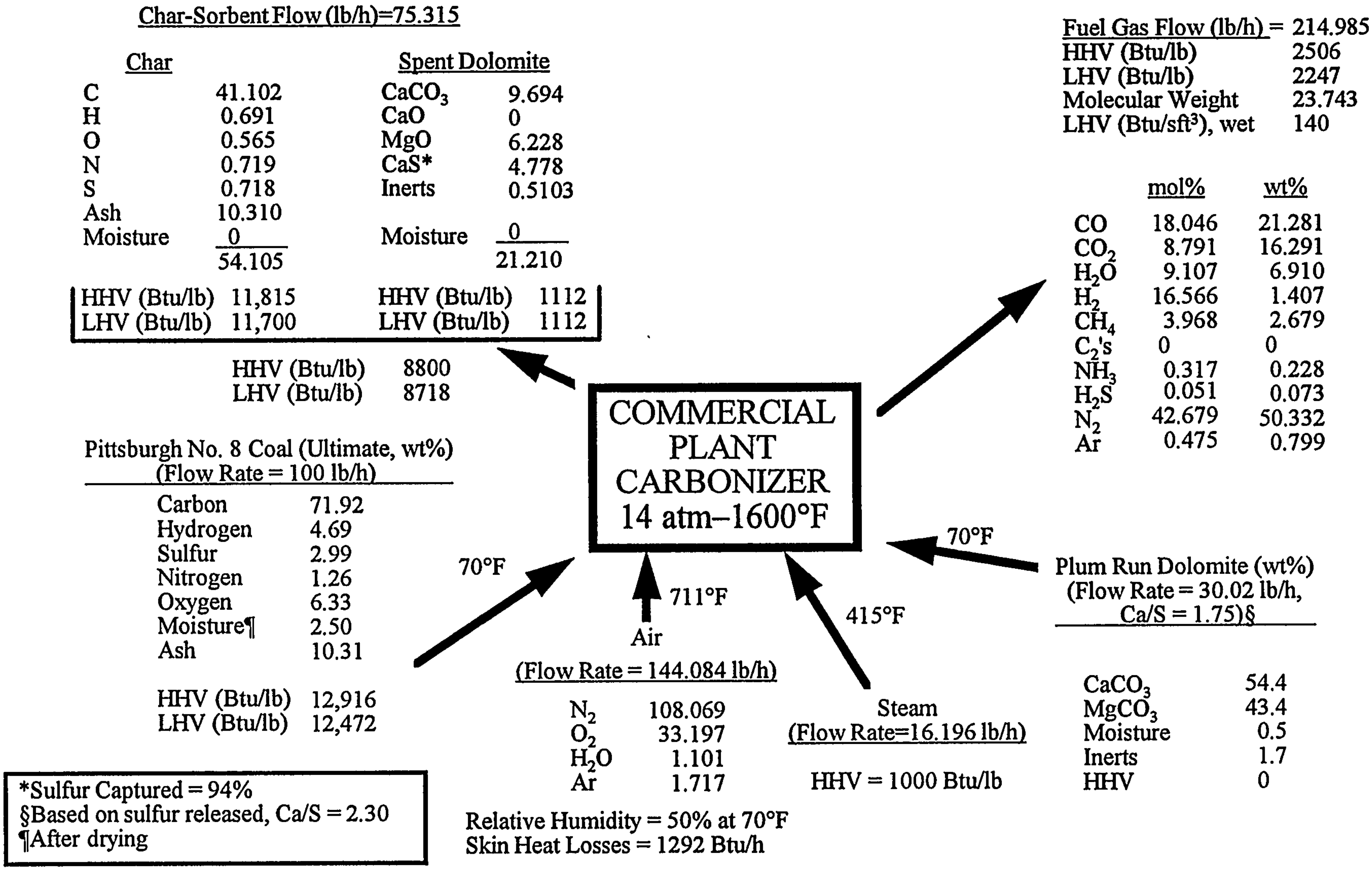
Figure 1
Simplified Process Block Diagram—APFBC Combustion Plant



Char-Sorbent Flow (lb/h)=75.315

Char		Spent Dolomite	
C	41.102	$CaCO_3$	9.694
H	0.691	CaO	0
O	0.565	MgO	6.228
N	0.719	CaS*	4.778
S	0.718	Inerts	0.5103
Ash	10.310		
Moisture	0	Moisture	0
	54.105		21.210
HHV (Btu/lb)	11,815	HHV (Btu/lb)	1112
LHV (Btu/lb)	11,700	LHV (Btu/lb)	1112

HHV (Btu/lb)	8800
LHV (Btu/lb)	8718

Pittsburgh No. 8 Coal (Ultimate, wt%)
(Flow Rate = 100 lb/h)

Carbon	71.92
Hydrogen	4.69
Sulfur	2.99
Nitrogen	1.26
Oxygen	6.33
Moisture¶	2.50
Ash	10.31
HHV (Btu/lb)	12,916
LHV (Btu/lb)	12,472

*Sulfur Captured = 94%
§Based on sulfur released, Ca/S = 2.30
¶After drying

Air
(Flow Rate = 144.084 lb/h)

N_2	108.069
O_2	33.197
H_2O	1.101
Ar	1.717

Relative Humidity = 50% at 70°F
Skin Heat Losses = 1292 Btu/h

Steam
(Flow Rate=16.196 lb/h)

HHV = 1000 Btu/lb

Fuel Gas Flow (lb/h) =	214.985
HHV (Btu/lb)	2506
LHV (Btu/lb)	2247
Molecular Weight	23.743
LHV (Btu/sft^3), wet	140

	mol%	wt%
CO	18.046	21.281
CO_2	8.791	16.291
H_2O	9.107	6.910
H_2	16.566	1.407
CH_4	3.968	2.679
C_2's	0	0
NH_3	0.317	0.228
H_2S	0.051	0.073
N_2	42.679	50.332
Ar	0.475	0.799

Plum Run Dolomite (wt%)
(Flow Rate = 30.02 lb/h,
Ca/S = 1.75)§

$CaCO_3$	54.4
$MgCO_3$	43.4
Moisture	0.5
Inerts	1.7
HHV	0

Figure 2
Phase 2 Update of 1600°F Carbonizer Performance

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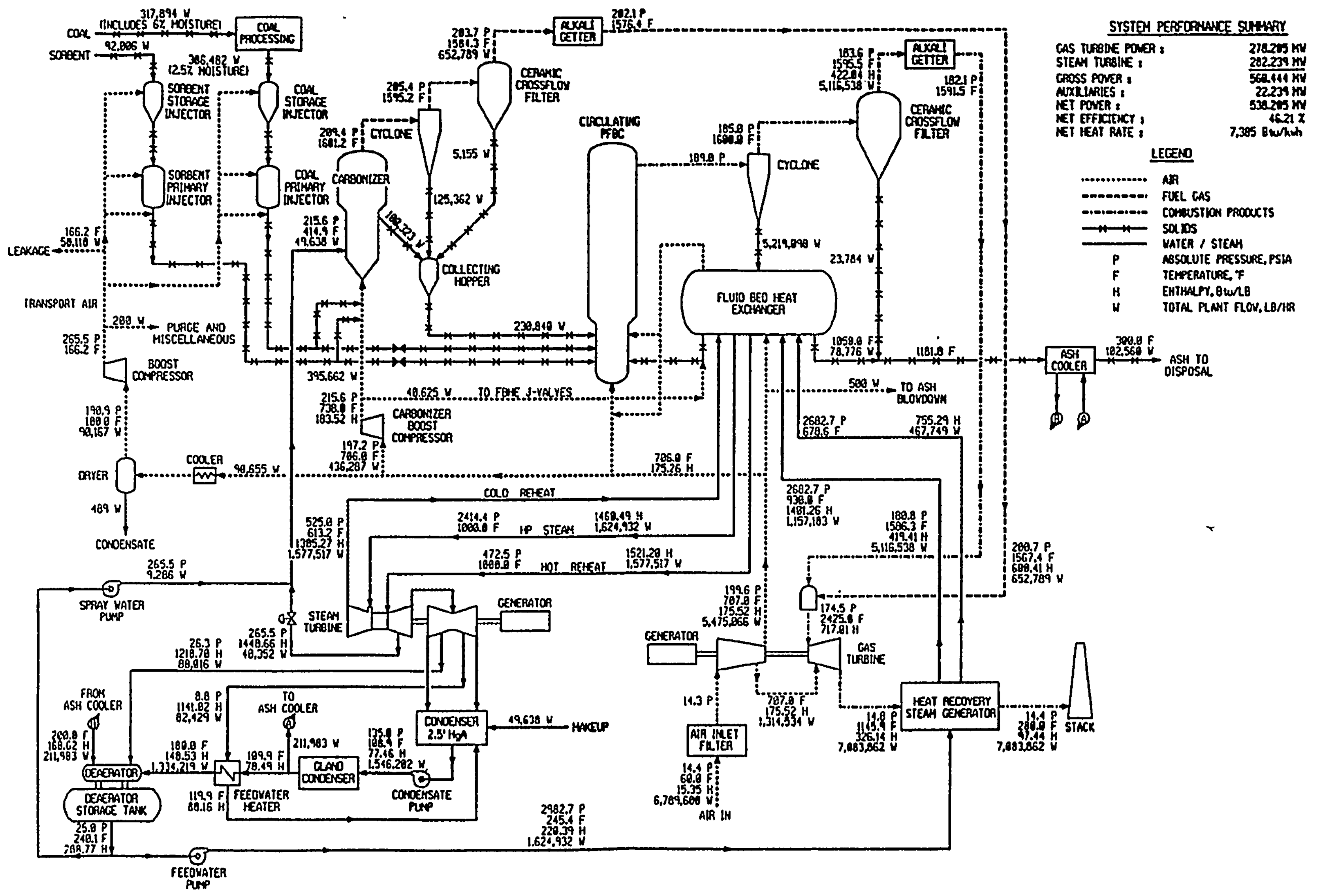

Figure 3
Phase 2 APFBC Commercial Plant Update (46.2% BEP)
14-atm/1600°F Carbonizer

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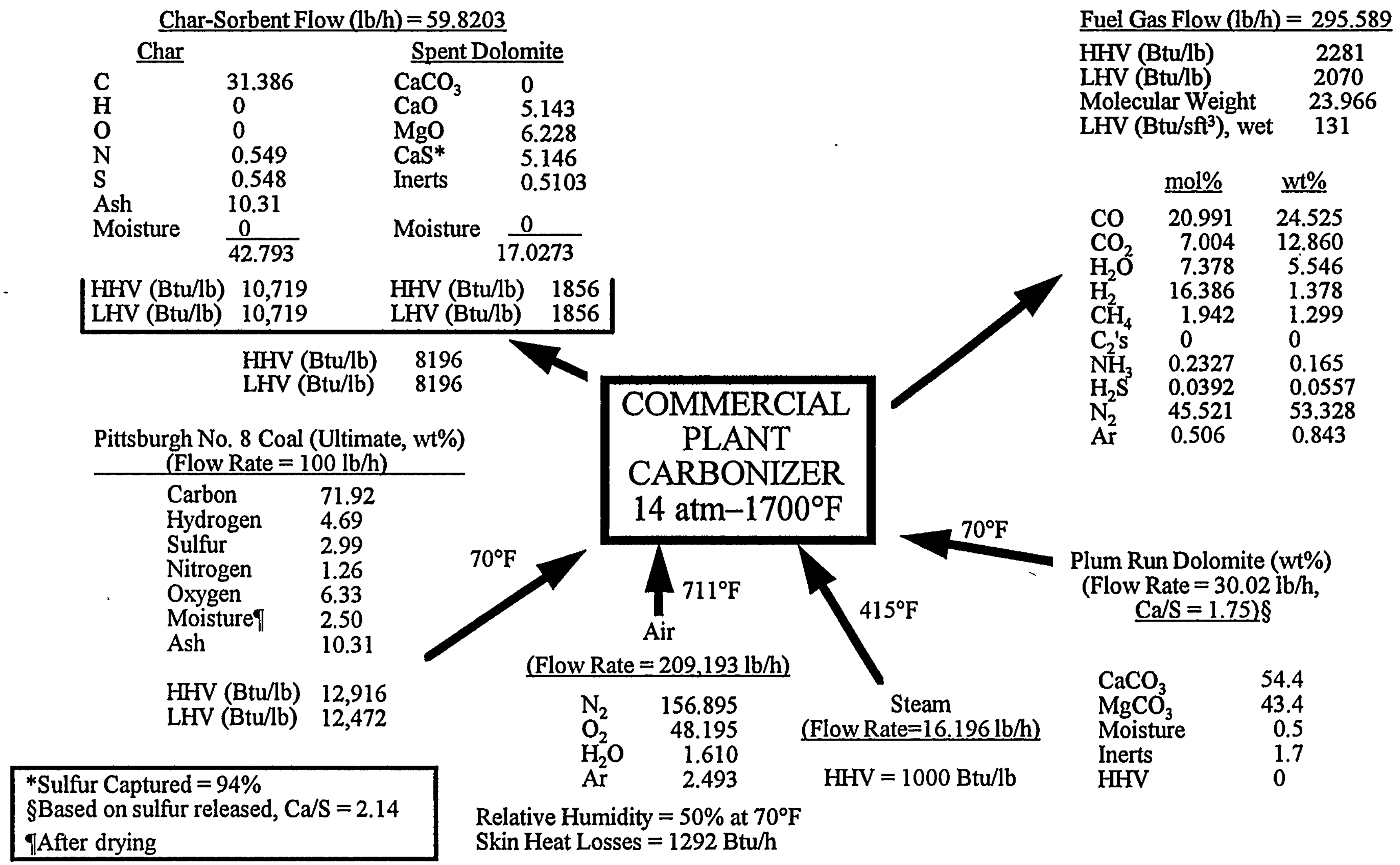

Char-Sorbent Flow (lb/h) = 59.8203

Char		Spent Dolomite	
C	31.386	$CaCO_3$	0
H	0	CaO	5.143
O	0	MgO	6.228
N	0.549	CaS*	5.146
S	0.548	Inerts	0.5103
Ash	10.31		
Moisture	0	Moisture	0
	42.793		17.0273
HHV (Btu/lb)	10,719	HHV (Btu/lb)	1856
LHV (Btu/lb)	10,719	LHV (Btu/lb)	1856

HHV (Btu/lb) 8196
LHV (Btu/lb) 8196

Pittsburgh No. 8 Coal (Ultimate, wt%)
(Flow Rate = 100 lb/h)

Carbon	71.92
Hydrogen	4.69
Sulfur	2.99
Nitrogen	1.26
Oxygen	6.33
Moisture¶	2.50
Ash	10.31
HHV (Btu/lb)	12,916
LHV (Btu/lb)	12,472

Fuel Gas Flow (lb/h) = 295.589

HHV (Btu/lb)	2281
LHV (Btu/lb)	2070
Molecular Weight	23.966
LHV (Btu/sft^3), wet	131

	mol%	wt%
CO	20.991	24.525
CO_2	7.004	12.860
H_2O	7.378	5.546
H_2	16.386	1.378
CH_4	1.942	1.299
C_2's	0	0
NH_3	0.2327	0.165
H_2S	0.0392	0.0557
N_2	45.521	53.328
Ar	0.506	0.843

Plum Run Dolomite (wt%)
(Flow Rate = 30.02 lb/h,
Ca/S = 1.75)§

$CaCO_3$	54.4
$MgCO_3$	43.4
Moisture	0.5
Inerts	1.7
HHV	0

Air
(Flow Rate = 209.193 lb/h)

N_2	156.895
O_2	48.195
H_2O	1.610
Ar	2.493

Steam
(Flow Rate=16.196 lb/h)

HHV = 1000 Btu/lb

Relative Humidity = 50% at 70°F
Skin Heat Losses = 1292 Btu/h

*Sulfur Captured = 94%
§Based on sulfur released, Ca/S = 2.14
¶After drying

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Figure 4
Phase 2 Predicted 1700°F Carbonizer Performance

SYSTEM PERFORMANCE SUMMARY

GAS TURBINE POWER:	277,306 MW
STEAM TURBINE:	315,891 MW
GROSS POWER:	593,197 MW
AUXILIARIES::	24,491 MW
NET POWER:	568,705 MW
NET EFFICIENCY:	45.80 %
NET HEAT RATE:	7,450 Btu/kwh

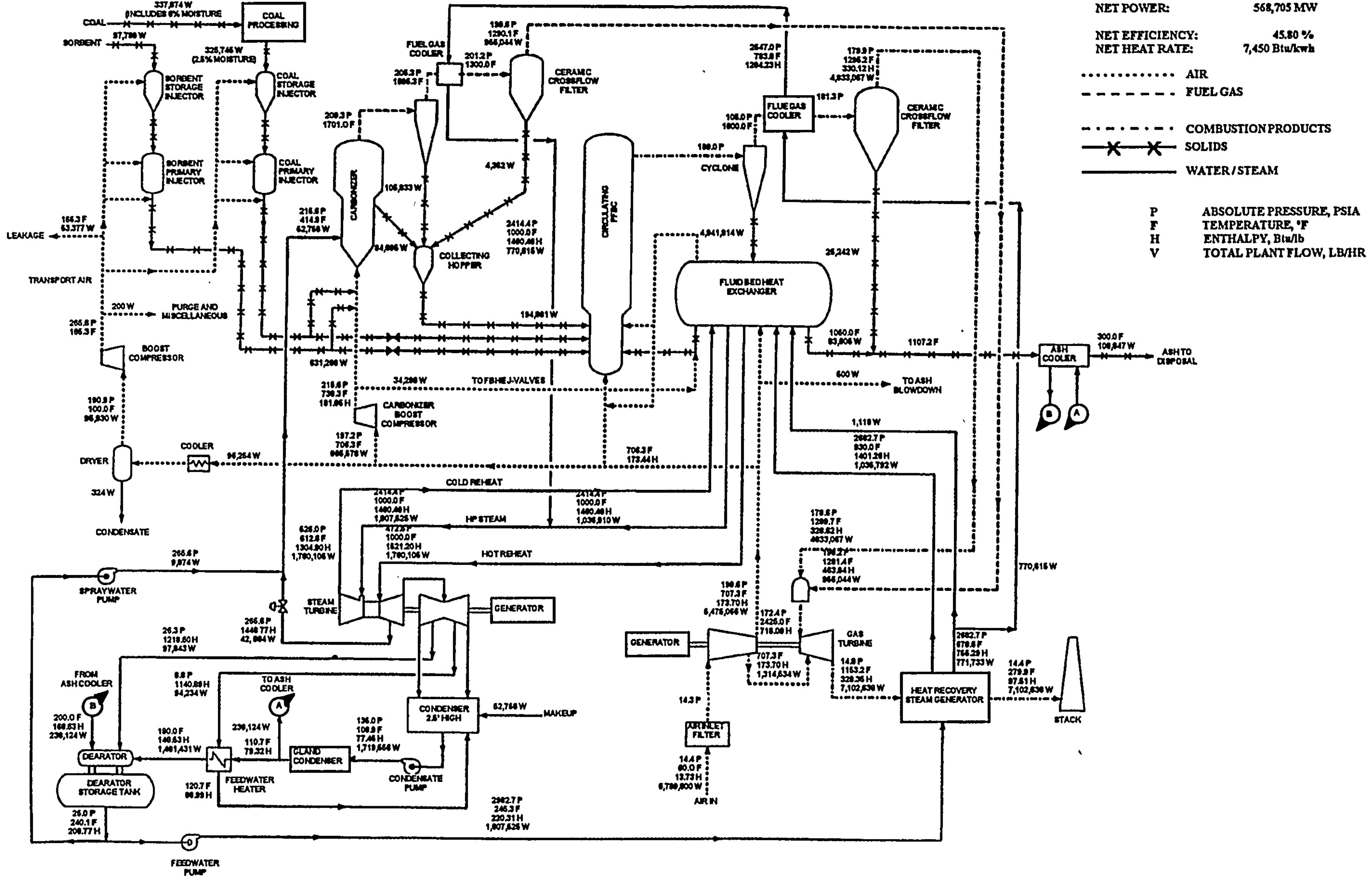

Figure 5

Phase 2 APFBC Commercial Plant with 1700°F Carbonizer and 1300°F Gas Cooling

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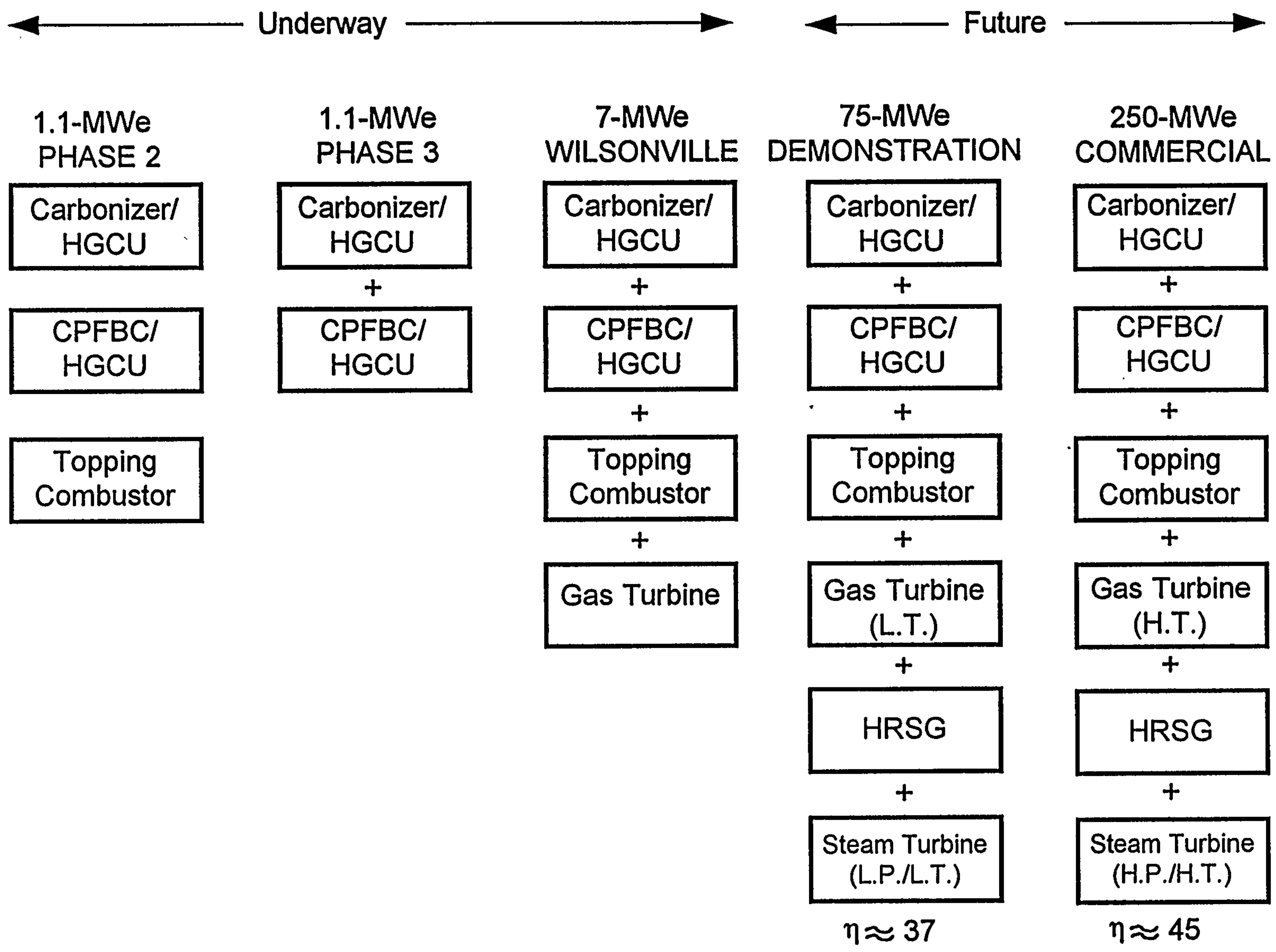
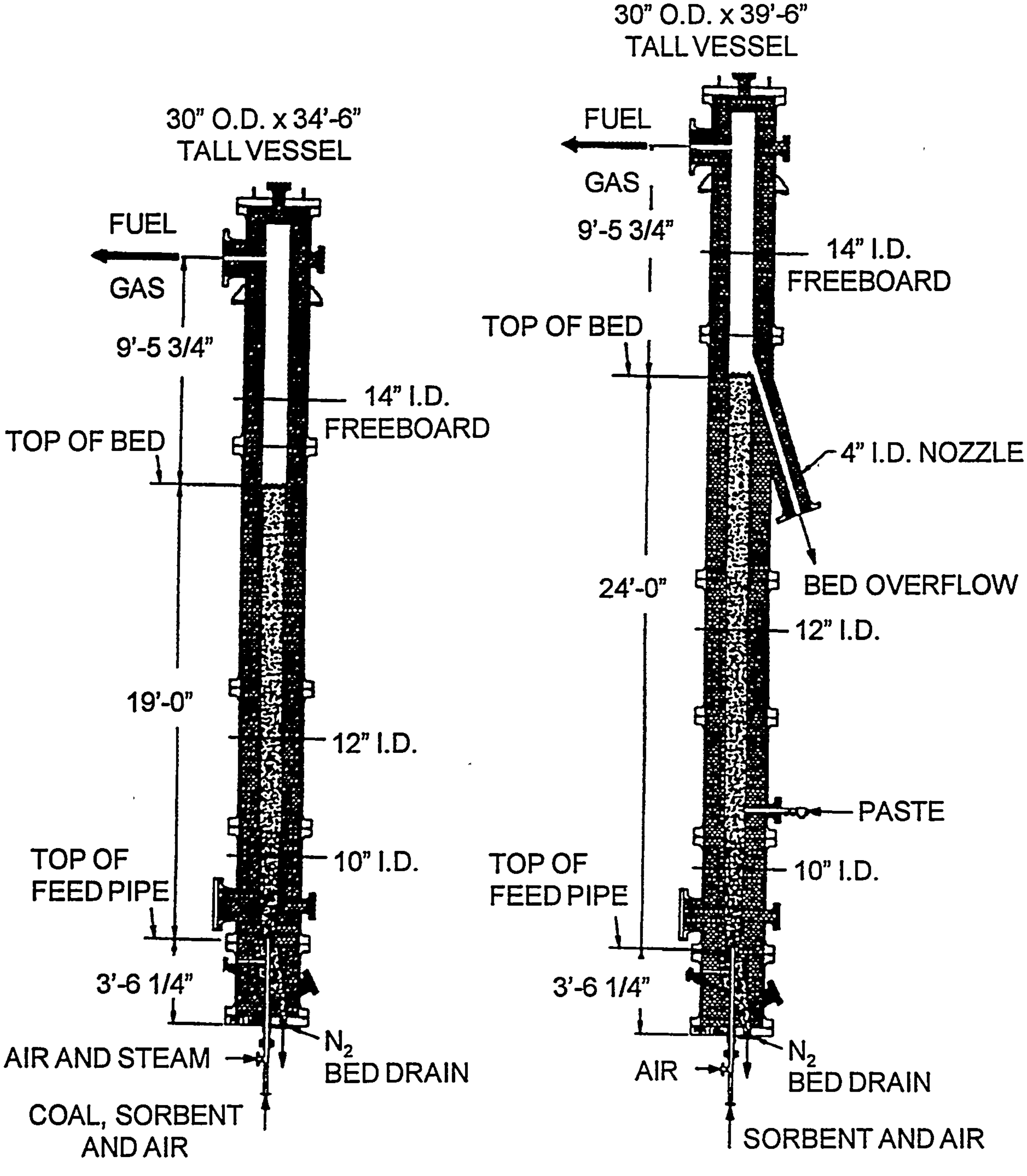
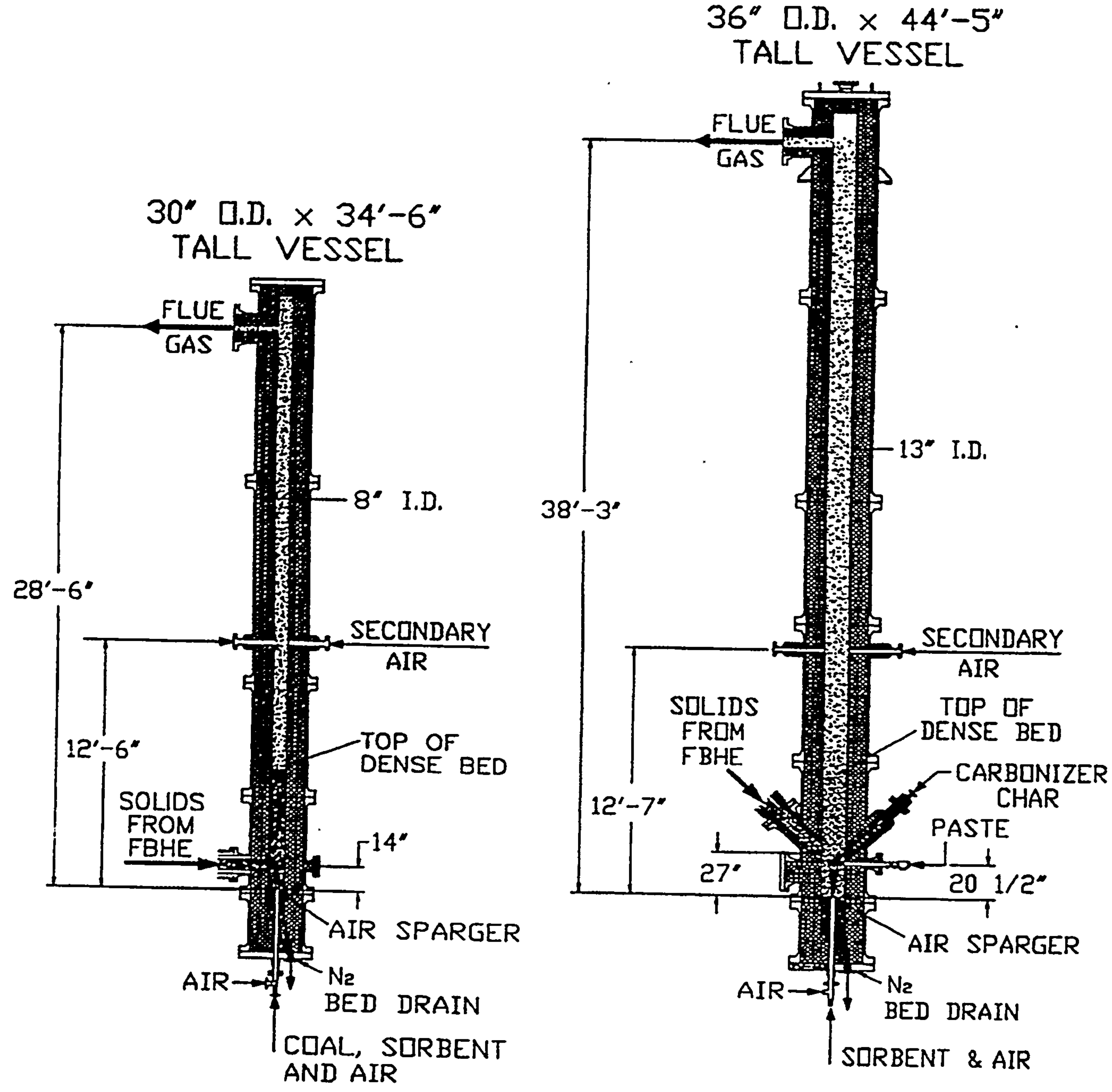


Figure 6
Second-Generation PFB Plant Development Plan



PHASE 2 **PHASE 3**

Figure 7
Carbonizer Comparison



PHASE 2 **PHASE 3**

Figure 8
CPFBC Comparison

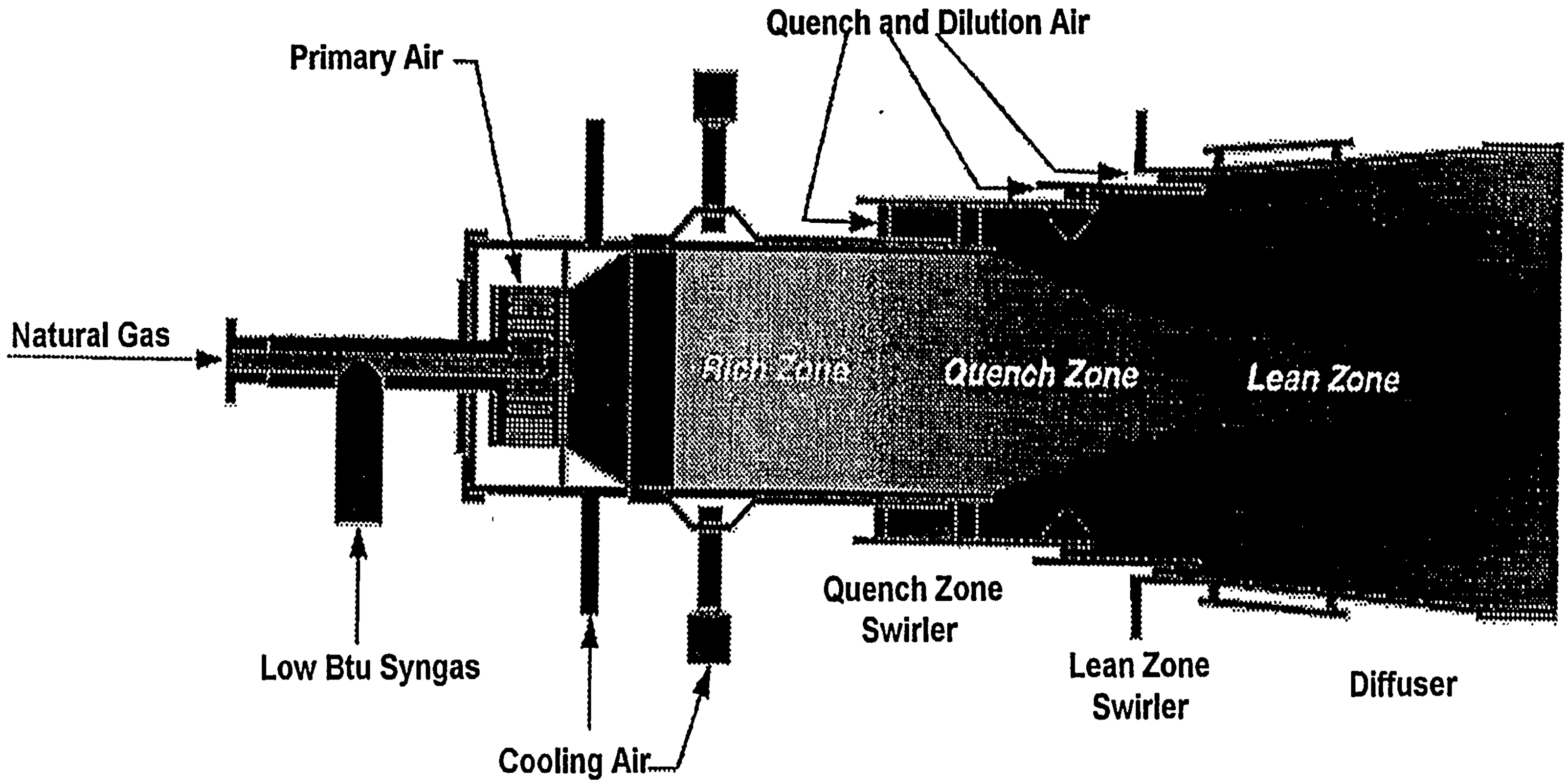


Figure 9
18-inch-diameter Westinghouse MASB Test Unit

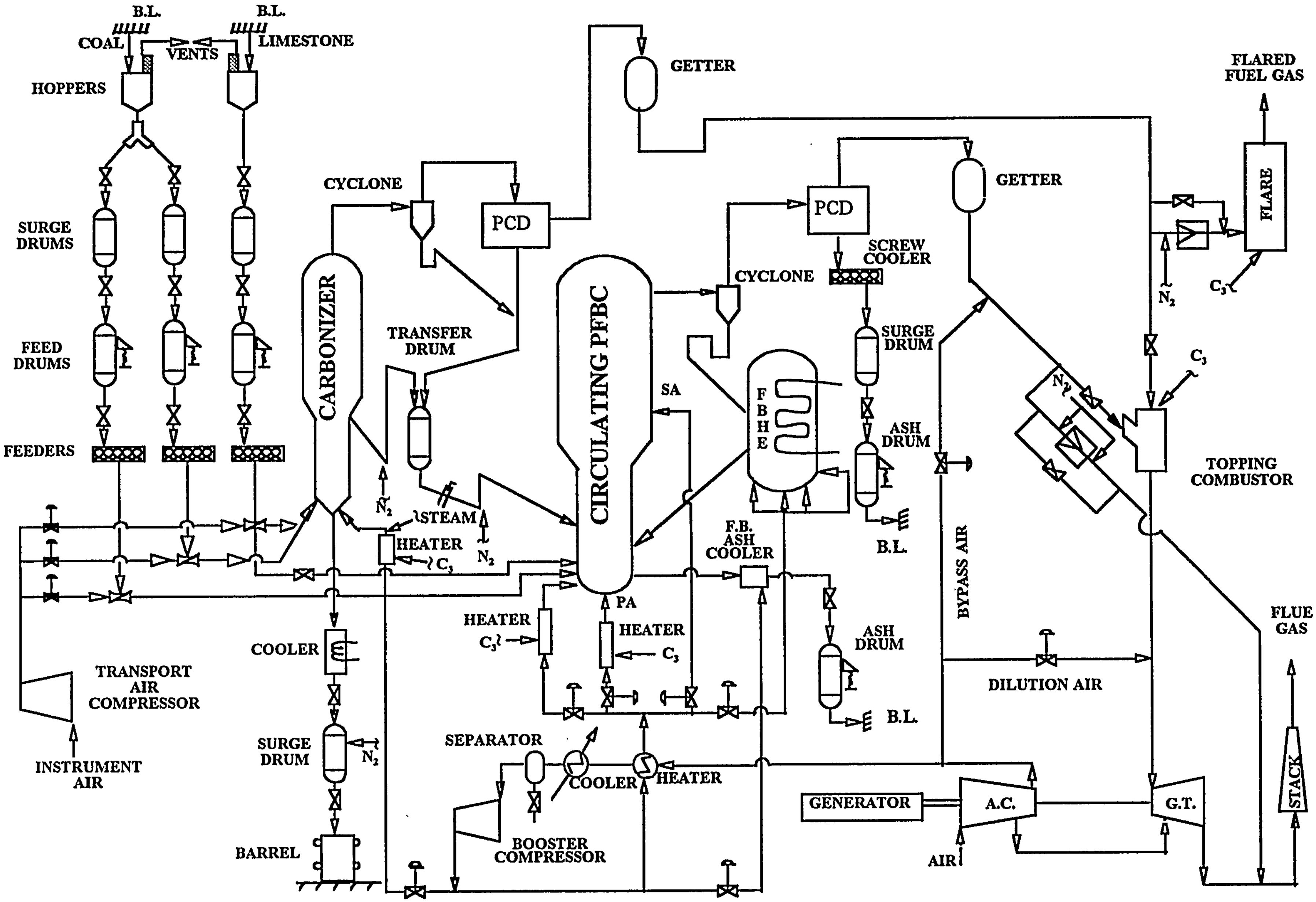


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Figure 10
Wilsonville APFBC Module

Table 1
Effect of Gas Cooling on APFBC Performance

Study Case	Baseline	C1	C2	C3	C4
Carbonizer Temperature, °F	1600	1600	1600	1600	1700
Fuel Gas Cooling, °F	0	150	0	300	400
Vitiated Air Cooling, °F	0	0	150	300	300
Fuel Gas Temperature, °F	1600	1450	1600	1300	1300
Flue Gas Temperature, °F	1600	1600	1450	1300	1300
Alkali Getters	Yes	No	No	No	No
Plant Thermal Input, MWt	1165	1190	1347	1617	1242
Plant Excees Air, %	124	119	93	61	111
CPFBC Excess Air, %	215	207	168	118	280
Gas Turbine Net Power, MWe	267.2	276.6	280.4	287.0	277.3
Steam Turbine Net Power, MWe	271.0	291.6	353.5	456.6	315.9
Net Plant Efficiency, % HHV	46.2	45.6	44.9	43.8	45.8