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**DEVELOPMENT OF A HIGH-PERFORMANCE
COAL-FIRED POWER GENERATING SYSTEM WITH
PYROLYSIS GAS AND CHAR-FIRED
HIGH TEMPERATURE FURNACE (HITAF)**

DE-AC22-91PC91154

**Quarterly Progress Report 5
January through March 1993**

**Prepared for
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania**

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FOSTER WHEELER DEVELOPMENT CORPORATION

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QUARTERLY PROGRESS REPORT 5 (January through March 1993)

INTRODUCTION

A concept for an advanced coal-fired combined-cycle power generating system is currently being developed. The first phase of this three-phase program consists of conducting the necessary research and development to define the system, evaluating the economic and technical feasibility of the concept, and preparing an R&D plan to develop the concept further.

Foster Wheeler Development Corporation is leading a team of companies involved in this effort. The team consists of:

- AlliedSignal Aerospace Company—AiResearch Division
- Bechtel Corporation
- Research-Cottrell
- TRW, Inc.
- Foster Wheeler Energy Corporation.

The power generating system being developed in this project will be an improvement over current coal-fired systems. Goals have been specified that relate to the efficiency, emissions, costs, and general operation of the system. These goals are:

- Total station efficiency of at least 47 percent.
- No more than:
 - 0.15 lb NO_x/10⁶ Btu fuel heat input
 - 0.15 lb SO_x/10⁶ Btu fuel heat input
 - 0.0075 lb of particulates/10⁶ Btu fuel heat input.
- All solid wastes must be benign. Generation of solid wastes is minimized through production of usable by-products.
- Over 95 percent of the total heat input is ultimately from coal, with initial systems capable of using coal for at least 65 percent of the heat input.
- Efficient and economic baseload power generation:
 - Operation with a range of U.S. coals
 - Annual capacity factor of 65 percent
 - Load following with minimal degradation in efficiency

- Net electrical output as low as 100 MW
 - 10-percent lower cost of electricity (COE) relative to a modern coal-fired plant conforming to NSPS.
-
- Safety, reliability, and maintainability to meet or exceed conventional coal-fired power plants.
 - Amenable to construction using factory-assembled modular components based upon standard design.

The system proposed to meet these goals is a combined-cycle system where air for a gas turbine is indirectly heated to approximately 1800°F in furnaces fired with coal-derived fuels and then directly heated in a natural-gas-fired combustor to about 2400°F. The system is based on a pyrolyzing process that converts the coal into a low-Btu fuel gas and char. The fuel gas is relatively clean, and it is fired to heat tube surfaces that are susceptible to corrosion and problems from ash deposition. In particular, the high-temperature air heater tubes, which will need to be a ceramic material, will be located in a separate furnace or region of a furnace that is exposed to combustion products from the low-Btu fuel gas only. A simplified process flow diagram is shown in Figure 1.

PROJECT WORK

Task 1—Project Work Plan

A Project Work Plan was developed, and this plan was approved by DOE. The work effort was divided into subtasks organized to achieve the project objectives.

Task 2—Concept Definition and Analysis

Subtask 2.7—Define Cycle Analysis Model

The plant size has been established at approximately 290 MWe. In a previous report (Quarterly Progress Report 4), two basic arrangements of the system were discussed. These arrangements were the natural-gas HITAF (NG-HITAF) and the fuel-gas HITAF (FG-HITAF). The NG-HITAF would fire natural gas for topping combustion, and the FG-HITAF would use fuel gas from the pyrolyzer for topping combustion.

Figure 1 Simplified Process Block Flow Diagram

The NG-HITAF has been chosen as the base-case system. The detailed plant design will be done for this arrangement. Thus a decision was made to concentrate on the NG-HITAF configuration. Fuel gas firing in the gas turbine will still be investigated as a means of reaching the project long-term goal of less than 5 percent natural gas consumption.

The plant heat and material balances reported in Quarterly Progress Report 4 have been reviewed by the team members. We again analyzed the design and operation of the various subsystems with the data from that heat and material balance. As a result of these analyses, updated information was fed to Bechtel to revise the heat and material balances. The flow streams for the NG-HITAF and FG-HITAF are shown in Figures 2 and 3. The revised balances are listed in Tables 1 and 2. Some of the changes from the previous balance follow:

- Amount of char transport gas was reduced—The char transport system was analyzed in more detail, and we determined that less fuel gas would be required to transport the char to the char combustor. The current estimates are a char-to-fuel gas weight ratio of 20 for the NG-HITAF system and 16 for the FG-HITAF system.
- Argon was added to the list of gas components being monitored—Previous balances included argon in the nitrogen flow. Since GATE has the capability of tracking argon, and since the noble gases have unique thermodynamic properties, we decided to include argon in subsequent heat and material balance determinations.
- Limestone replaced dolomite as the system sorbent—Experimental work at FWDC has indicated that limestone is as effective as dolomite in the pyrolyzer. The use of limestone instead of dolomite will reduce cost because a lower flow rate of limestone is needed to achieve the same Ca/S ratio.
- Ca/S ratio was reduced—The Ca/S criteria for determining the sorbent flow rate to the pyrolyzer were also reduced based on FWDC experiments. This reduction lowered the limestone flow rate further.
- Limestone to the char combustor was eliminated—Since a flue gas desulfurization system will be required to remove sulfur from the dirty flue gas, sulfur capture in the char combustor is less critical. For the char combustor system, emphasis will be placed on combustion of the char with minimum NO_x production while generating a benign solid product (slag). The net changes in sorbent demands between the pyrolyzer and char combustor provide significant savings in variable cost for the plant.
- Water-cooled fuel gas furnace was added—The fuel gas-fired furnace will be of tubewall construction with refractory coating. The tubes will be the evaporator surface, and 8 percent of the heat input will go to the steam cycle.

Figure 2 NG-HITAF Flow Diagram
(Support Diagram for
Table 1)

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Figure 3 FG-HITAF Flow Diagram
(Support Diagram for
Table 2)

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Stream No.		1		2		3
Stream		Coal to Carbonizer		V. Air to Carbonizer		Sorbent to C
		%wt	lb/hr	%wt	lb/hr	%wt
	Carbon	71.92%	79,327			
	Hydrogen	4.69%	5,173			
	Oxygen	6.33%	6,977			
	Nitrogen	1.26%	1,385			
	Sulfur	2.99%	3,301			
Solids	Ash	10.32%	11,383			0.95%
	Moisture	2.50%	2,756			2.00%
	CaCO ₃					95.50%
	MgCO ₃					1.55%
	CaO					
lb/h	MgO					
	CaS					
	CaSO ₄					
	CH ₄					
	C ₂ H ₄					
Gases	C ₂ H ₆					
	C ₃ H ₈					
	CO					
	H ₂					
	CO ₂			2.18%	6,242	
lb/h	H ₂ O		17,846	2.56%	7,321	
	O ₂			19.67%	56,282	
	N ₂			74.32%	212,642	
	H ₂ S					
	COS					
	SO ₂					
	C ₆ H ₆ +					
	Argon			1.27%	3,627	
	NH ₃					
	NO ₂					
Total Gas, lb/h		100.00%	128,145	100.00%	286,114	100.00%
					9,898	
					28.91	
Pressure, psia			49.40		32.34	
Temperature, °F			70.00		350.00	
Temperature, °C			21.11		176.67	
Sens. Heat, MM Btu/hr			3.22		22.48	
Lat. Heat, MM Btu/hr			18.74		7.69	
LHV, Btu/lb			12,454.70			
HHV, Btu/lb			12,915.96			
LHV, MM Btu/hr			1,373.73			
HHV, MM Btu/hr			1,424.61			
Total Energy, LHV			1,376.95		22.48	
MM Btu/h, HHV			1,446.57		30.17	

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Table 1 NG-HITAF (Dry Feed to Pyrolyzer)

4		5		6		7	
Carbonizer	Char fm Carbonizer	Fuel G. fm Carbonizer		Fuel Gas to Combust		V. Air to Combust	
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt
	61.82%	30,663					
	0.39%	193					
	0.97%	483					
	2.14%	1,064					
82	23.11%	11,465					
173							
8,238							
134							
	1.89%	938					
	0.13%	64					
	9.54%	4,732					
			1.36%	5,086	1.36%	5,052	
			21.95%	81,904	21.95%	81,360	
			1.21%	4,498	1.21%	4,466	
			12.02%	44,833	12.02%	44,535	2.18% 13,611
			5.17%	19,288	5.17%	19,159	2.56% 15,984
						19.67%	122,732
			57.13%	213,167	57.13%	211,750	74.32% 463,705
			0.04%	143	0.04%	142	
			0.97%	3,627	0.97%	3,603	1.27% 7,910
			0.16%	590	0.16%	586	
8,626	100.00%	49,601	100.00%	373,139	100.00%	370,659	100.00% 623,922
				15,209		15,108	21,584
				24.53		24.53	28.91
34.40		29.40		29.40		29.40	29.40
70.00		1,700.00		1,700.00		1,200.00	715.70
21.11		926.67		926.67		648.89	379.83
0.02		21.16		198.65		132.86	102.36
				20.25		20.12	16.76
		9,666.22		1,881.02		1,881.02	
		9,700.95		2,073.79		2,073.79	
		479.45		701.88		697.22	
		481.17		773.81		768.67	
0.02		500.61		900.54		830.08	102.36
0.02		502.34		992.72		921.64	119.12

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Stream No.		8		9		10
		Flue Gas to HTHE		Air to Compressor		Bypass
Stream		%wt	lb/hr	%wt	lb/hr	%wt
	Carbon					
	Hydrogen					
	Oxygen					
	Nitrogen					
	Sulfur					
Solids	Ash					
lb/h	Moisture					
	CaCO ₃					
	MgCO ₃					
	CaO					
	MgO					
	CaS					
	CaSO ₄					
	CH ₄					
	C ₂ H ₄					
	C ₂ H ₆					
	C ₃ H ₈					
	CO					
Gases	H₂					
lb/h	CO₂	20.09%	199,837	0.05%	1,840	0.05%
	H₂O	8.79%	87,393	0.82%	28,331	0.82%
	O₂	1.86%	18,527	22.95%	795,438	22.95%
	N₂	67.91%	675,455	74.90%	2,595,720	74.90%
	H ₂ S					
	COS					
	SO ₂	0.03%	268			
	C ₆ H ₆ +					
	Argon	1.16%	11,513	1.28%	44,276	1.28%
	NH ₃					
	NO ₂	0.16%	1,584			
Total Gas, lb/h		100.00%	994,576	100.00%	3,465,405	100.00%
			34,121		119,128	
			29.15		29.09	
	Pressure, psia		15.60		14.70	
	Temperature, °F		2,918.00		60.00	
	Temperature, °C		1,603.33		15.56	
	Sens. Heat, MM Btu/hr		858.63		0.83	
	Lat. Heat, MM Btu/hr		91.76		29.75	
	LHV, Btu/lb					
	HHV, Btu/lb					
	LHV, MM Btu/hr					
	HHV, MM Btu/hr					
Total Energy, LHV			858.63		0.83	
MM Btu/h, HHV			950.39		30.58	

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Table 1 (Cont) NG-HITAF (Dry Feed to Pyrolyzer)

	11		12		13		14	
	Air to Recuperator		Air to Air Heater		Flue Gas to Furnace		Air to HTHE	
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
262	0.05%	1,377	0.05%	1,377	20.09%	199,837	0.05%	1,377
4,533	0.82%	23,798	0.82%	23,798	8.79%	87,393	0.82%	23,798
127,270	22.95%	668,168	22.95%	668,168	1.86%	18,527	22.95%	668,168
415,315	74.90%	2,180,405	74.90%	2,180,405	67.91%	675,455	74.90%	2,180,405
					0.03%	268		
7,084	1.28%	37,192	1.28%	37,192	1.16%	11,513	1.28%	37,192
					0.16%	1,584		
554,485	100.00%	2,910,940	100.00%	2,910,940	100.00%	994,578	100.00%	2,910,940
19,061		100,068		100,068		34,121		100,068
29.09		29.09		29.09		29.15		29.09
205.40		205.40		203.30		15.40		198.20
680.40		680.40		1,030.00		1,923.50		1,400.00
360.22		360.22		554.44		1,050.83		760.00
84.51		443.66		707.25		533.25		997.91
4.76		24.99		24.99		91.76		24.99
84.51		443.66		707.25		533.25		997.91
89.27		468.65		732.24		625.02		1,022.90

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Stream No.		15		16		17		18
		Air to GT Combustor		Nat Gas to GT Comb.		FG fm GT Combustor		Gas to Re
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt
	Carbon							
	Hydrogen							
	Oxygen							
	Nitrogen							
	Sulfur							
Solids	Ash							
lb/h	Moisture							
	CaCO3							
	MgCO3							
	CaO							
	MgO							
	CaS							
	CaSO4							
	CH4			100.00%	27,176			
	C2H4							
	C2H6							
	C3H8							
	CO							
Gases	H2							
lb/h	CO2	0.05%	1,377			2.58%	75,929	2.18%
	H2O	0.82%	23,798			2.89%	84,833	2.56%
	O2	22.95%	668,168			19.05%	559,758	19.67%
	N2	74.90%	2,180,405			74.21%	2,180,405	74.32%
	H2S							
	COS							
	SO2							
	C6H6+							
	Argon	1.28%	37,192			1.27%	37,192	1.27%
	NH3							
	NO2							
Total Gas, lb/h		100.00%	2,910,940	100.00%	27,176	100.00%	2,938,116	100.00%
			100,068		1,694		101,762	
			29.09		16.04		28.87	
	Pressure, psia		191.30		250.00		191.70	
	Temperature, °F		1,800.00		200.00		2,418.00	
	Temperature, °C		982.22		93.33		1,325.56	
	Sens. Heat, MM Btu/hr		1,323.25		2.11		1,904.38	
	Lat. Heat, MM Btu/hr		24.99				89.07	
	LHV, Btu/lb				21,502.00			
	HHV, Btu/lb				23,861.00			
	LHV, MM Btu/hr				584.33			
	HHV, MM Btu/hr				648.44			
Total Energy, LHV			1,323.25		586.44		1,904.38	
MM Btu/h, HHV			1,348.23		650.55		1,993.45	

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Table 1 (Cont) NG-HITAF (Dry Feed to Pyrolyzer)

19		20		21		22	
Operator	Gas fm Recuperator	Coal to Precomb.	Char to Char Comb.	Prim. Air to Char C.			
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt
		71.92%	7,381	58.88%	30,863		
		4.69%	481	0.37%	193		
		6.33%	649				
		1.26%	129	0.93%	483		
		2.99%	307	2.04%	1,084		
		10.32%	1,059	22.01%	11,485		
		2.50%	256				
				1.80%	938		
				0.12%	64		
				9.09%	4,732		
				0.06%	34		
				1.05%	544		
				0.06%	30		
81,385	2.18%	81,385		0.57%	298	2.18%	9,871
71,999	2.56%	71,999		0.25%	128	2.56%	11,577
553,521	19.67%	553,521				19.67%	89,005
1,091,305	74.32%	2,091,305		2.72%	1,417	74.32%	336,277
				0.00%	1		
35,672	1.27%	35,672		0.05%	24	1.27%	5,736
				0.01%	4		
813,883	100.00%	2,813,883	100.00%	10,263	100.00%	52,081	100.00%
97,343		97,343					15,653
28.91		28.91					28.91
18.40		18.40		18.40			18.40
1,093.20		740.00		60.00		1,700.00	1,093.20
589.56		393.33		15.56		928.87	589.56
743.68		479.39		0.00		28.20	119.58
75.60		75.60					12.16
				12,454.70		9,295.50	
				12,915.96		9,337.75	
				127.82		484.11	
				132.56		486.31	
743.68		479.39		127.83		512.32	119.58
819.28		554.99		132.56		514.52	131.74

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Stream No.		23		24		25
		Sec. Air to Char C.		FG to DSH #1		Slag fm Char
Stream		%wt	lb/hr	%wt	lb/hr	%wt
	Carbon					
	Hydrogen					
	Oxygen					
	Nitrogen					3.36%
	Sulfur					
Solids	Ash					68.90%
lb/h	Moisture					
	CaCO3					
	MgCO3					
	CaO					18.45%
	MgO					0.35%
	CaS					8.93%
	CaSO4					
	CH4					
	C2H4					
	C2H6					
	C3H8					
	CO					
Gases	H2					
lb/h	CO2	2.18%	4,935	21.51%	155,450	
	H2O	2.56%	5,789	3.10%	22,402	
	O2	19.67%	44,502	3.44%	24,849	
	N2	74.32%	168,138	70.00%	505,832	
	H2S					
	COS					
	SO2			0.76%	5,501	
	C6H6+					
	Argon	1.27%	2,868	1.19%	8,604	
	NH3					
	NO2			0.00%	11	
Total Gas, lb/h		100.00%	228,233	100.00%	722,648	100.00%
					23,695	
					30.50	
Pressure, psia					15.80	
Temperature, °F			1,093.20		3,317.00	
Temperature, °C			589.56		1,825.00	
Sens. Heat, MM Btu/hr			59.79		680.89	
Lat. Heat, MM Btu/hr			6.08		23.52	
LHV, Btu/lb						
HHV, Btu/lb						
LHV, MM Btu/hr						
HHV, MM Btu/hr						
Total Energy, LHV			59.79		680.89	
MM Btu/h, HHV			65.87		704.41	

Date: May 1993

Table 1 (Cont) NG-HITAF (Dry Feed to Pyrolyzer)

Comb.	26		27		28		29	
	FG to Air Htr. #1		Tot Gas to Air Htr. #2		F. Gas to Air Htr.		F. Gas to Stack	
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
612								
12,524								
3,354								
64								
1,624								
	21.51%	155,450	20.69%	355,287	20.69%	355,287	10.96%	396,820
	3.10%	22,402	6.39%	109,795	6.39%	109,795	4.38%	158,509
	3.44%	24,849	2.53%	43,376	2.53%	43,376	11.54%	417,883
	70.00%	505,832	68.79%	1,181,286	68.79%	1,181,286	71.70%	2,596,244
	0.76%	5,501	0.34%	5,768	0.34%	5,768	0.16%	5,768
	1.19%	8,604	1.17%	20,117	1.17%	20,117	1.22%	44,252
	0.00%	11	0.09%	1,595	0.09%	1,595	0.04%	1,595
18,177	100.00%	722,848	100.00%	1,717,224	100.00%	1,717,224	100.00%	3,621,071
		23,695		57,816		57,816		123,678
		30.50		29.70		29.70		29.28
15.80		15.70		15.50		15.00		14.70
400.00		2,437.00		1,923.50		1,588.00		165.00
315.56		1,336.11		1,050.83		864.44		73.89
20.29		480.62		900.48		723.39		94.47
		23.52		115.28		115.28		166.43
20.29		480.62		900.48		723.39		94.47
20.29		504.14		1,015.77		838.68		260.90

FOSTER WHEELER DEVELOPMENT CORPORATION

Stream No.		1		2		3
		Coal to Carbonizer		Air to Carbonizer		Sorb. to C
Stream		%wt	lb/hr	%wt	lb/hr	%wt
	Carbon	47.94%	108,502			
	Hydrogen	3.13%	7,075			
	Oxygen	4.22%	9,547			
	Nitrogen	0.84%	1,898			
	Sulfur	2.00%	4,515			
Solids	Ash	8.88%	15,565			0.95%
lb/h	Moisture	35.01%	79,238			2.00%
	CaCO ₃					95.50%
	MgCO ₃					1.55%
	CaO					
	MgO					
	CaS					
	CaSO ₄					
	CH ₄					
	C ₂ H ₄					
	C ₂ H ₆					
	C ₃ H ₈					
	CO					
Gases	H ₂					
lb/h	CO ₂			0.05%	205	
	H ₂ O			0.82%	3,549	
	O ₂			22.95%	99,644	
	N ₂			74.90%	325,163	
	H ₂ S					
	COS					
	SO ₂					
	C ₆ H ₆ +					
	Argon			1.28%	5,548	
	NH ₃					
	NO ₂					
Total Gas, lb/h		100.00%	228,329	100.00%	434,107	100.00%
lbmole/h					14,923	
MW					29.09	
	Pressure, psia		279.92		285.91	
	Temperature, °F		70.00		750.00	
	Temperature, °C		21.11		398.89	
	Sens. Heat, MM Btu/hr		1.32		74.33	
	Latent Heat, MM Btu/hr					
	LHV, Btu/lb		7,948.32			
	HHV, Btu/lb		8,609.23			
	LHV, MM Btu/hr		1,798.93			
	HHV, MM Btu/hr		1,948.51			
Total Energy, LHV			1,800.25		74.33	
MM Btu/h, HHV			1,949.83		74.33	

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Table 2 FG-HITAF (Slurry Feed to Pyrolyzer)

4		5		6		7	
Donizer	Char fm Carbonizer	Fuel G. fm Carbonizer	Fuel Gas to Comb.	Air to Compressor			
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt
	51.96%	29,975					
	0.33%	189					
	0.82%	472					
	1.80%	1,028					
129	27.21%	15,694					
271							
12,958	5.42%	3,126					
210							
	0.17%	100					
	12.29%	7,091					
			0.89%	5,508	0.89%	5,478	
			18.21%	112,188	18.21%	111,529	
			1.34%	8,243	1.34%	8,195	
			18.38%	100,912	18.38%	100,321	0.05%
			9.22%	58,807	9.22%	58,475	0.82%
							22.95%
			52.88%	325,774	52.88%	323,888	74.90%
			0.06%	347	0.06%	345	2,595,720
			0.90%	5,548.45	0.90%	5,514	44,278
			0.12%	739	0.12%	734	
13,568	100.00%	57,685	100.00%	618,068	100.00%	612,482	100.00%
				25,567		25,417	120,237
				24.10		24.10	28.82
285.91		259.92		259.92		249.92	14.70
70.00		1,700.00		1,700.00		1,000.00	60.00
21.11		926.67		926.67		537.78	15.56
0.04		22.72		340.48		185.31	0.84
				59.65		59.30	29.75
		8,264.71		1,683.49		1,683.49	
		8,293.90		1,820.80		1,820.80	
		476.75		1,037.14		1,031.07	
		478.44		1,121.73		1,115.17	
0.04		499.47		1,377.62		1,218.38	0.84
0.04		501.15		1,521.86		1,359.78	30.59

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Stream No.		8		9		10		11	
		Bypass Air		Air to Recuperator		Air to Furnace		Air to GT Cor.	
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	
	Carbon								
	Hydrogen								
	Oxygen								
	Nitrogen								
	Sulfur								
Solids lb/h	Ash								
	Moisture								
	CaCO3								
	MgCO3								
	CaO								
	MgO								
	CaS								
	CaSO4								
	CH4								
	C2H4								
	C2H6								
	C3H8								
	CO								
Gases lb/h	H2								
	CO2	0.05%	262	0.05%	1,172	0.05%	1,172	0.05%	
	H2O	0.82%	4,533	0.82%	20,249	0.82%	20,249	0.82%	
	O2	22.95%	127,270	22.95%	568,524	22.95%	568,524	22.95%	
	N2	74.90%	415,315	74.90%	1,855,242	74.90%	1,855,242	74.90%	1
	H2S								
	COS								
	SO2								
	C6H6+								
	Argon	1.28%	7,084	1.28%	31,646	1.28%	31,646	1.28%	
	NH3								
	NO2								
Total Gas, lb/h		100.00%	554,465	100.00%	2,476,833	100.00%	2,445,187	100.00%	2
lbmole/h			19,238		85,937		85,937		
MW			28.82		28.82		28.45		
Pressure, psia			205.40		205.40		204.80		
Temperature, °F			680.60		680.60		1,030.00		
Temperature, °C			360.33		360.33		554.44		
Sens. Heat, MM Btu/hr			85.08		380.07		605.60		
Latent Heat, MM Btu/hr			4.76		21.26		21.26		
LHV, Btu/lb									
HHV, Btu/lb									
LHV, MM Btu/hr									
HHV, MM Btu/hr									
Total Energy, MM Btu/h,	LHV		85.08		380.07		605.60		
	HHV		89.84		401.33		626.86		

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Table 2 (Cont) FG-HITAF (Slurry Feed to Pyrolyzer)

12		14		15		17	
Combus	FG fm GT	Combus	Gas fm GT	Coal to Precombust.	Char to Char Comb.		
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt
				71.91%	12,483	48.91%	29,975
				4.69%	814	0.31%	189
				6.33%	1,098		
				1.26%	218	0.77%	472
				2.99%	520	1.69%	1,038
				10.32%	1,791	25.61%	15,894
				2.50%	434		
						5.10%	3,126
						0.16%	100
						11.57%	7,091
						0.05%	32
						1.07%	656
						0.08%	48
1,172	9.44%	291,750	8.01%	292,013		0.96%	590
20,249	5.30%	163,607	4.61%	168,140		0.54%	332
568,524	13.43%	415,032	14.88%	542,302			
855,242	70.54%	2,179,110	71.20%	2,594,425		3.11%	1,906
						0.00%	2
	0.02%	648	0.02%	648			
31,646	1.20%	37,160	1.21%	44,244		0.05%	32
						0.01%	4
	0.06%	1,984	0.05%	1,984			
478,833	100.00%	3,089,291	100.00%	3,843,756	100.00%	17,359	100.00%
85,937		107,453		126,690			
28.82		28.75		28.76			
197.60		191.70		16.40			
1,400.00		2,424.00		1,162.70	60.00		1,700.00
760.00		1,328.89		628.17	15.56		926.67
854.37		2,078.29		1,053.50	0.01		34.18
21.26		171.79		176.55			
					12,454.56		7,877.71
					12,915.83		7,913.26
					216.20		482.82
					224.21		487.62
854.37		2,078.29		1,053.50	216.20		516.99
875.63		2,250.07		1,230.05	224.21		521.80

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Stream No.		18		19		20		21	
		Prim. Air to Char C.		Sec. Air to Char C.		FG to DSH #1		Slag fm Char C	
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	
	Carbon								
	Hydrogen								
	Oxygen								
	Nitrogen								2.37%
	Sulfur								
Solids	Ash								59.97%
lb/h	Moisture								
	CaCO3								
	MgCO3								
	CaO								4.14%
	MgO								0.34%
	CaS								19.46%
	CaSO4								13.72%
	CH4								
	C2H4								
	C2H6								
	C3H8								
	CO								
Gases	H2								
lb/h	CO2	8.01%	62,447	8.01%	19,702	22.36%	240,257		
	H2O	4.81%	35,957	4.81%	11,344	5.35%	57,539		
	O2	14.88%	115,971	14.88%	36,589	2.72%	29,263		
	N2	71.20%	554,815	71.20%	175,045	68.10%	731,766		
	H2S								
	COS								
	SO2	0.02%	139	0.02%	44	0.25%	2,676		
	C6H6+								
	Argon	1.21%	9,462	1.21%	2,985	1.16%	12,479		
	NH3								
	NO2	0.05%	424	0.05%	134	0.05%	570		
Total Gas, lb/h		100.00%	779,214	100.00%	245,843	100.00%	1,074,550	100.00%	
lbmole/h			27,093		8,548		36,056		
MW			28.76		28.76		29.80		
	Pressure, psia		15.78				16.70		
	Temperature, °F		1,162.70		1,162.70		2,759.00		2
	Temperature, °C		628.17		628.17		1,515.00		1
	Sens. Heat, MM Btu/hr		226.59		71.49		846.71		
	Latent Heat, MM Btu/hr		37.75		11.91		60.42		
	LHV, Btu/lb								
	HHV, Btu/lb								
	LHV, MM Btu/hr								
	HHV, MM Btu/hr								
Total Energy, LHV			226.59		71.49		846.71		
MM Btu/h, HHV			264.34		83.40		907.13		

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Table 2 (Cont) FG-HITAF (Slurry Feed to Pyrolyzer)

	22		23		26		27	
Comb.	DFG to Air Htr		DFG fm Air Htr		Gas to Recuperator		Gas fm Recuperator	
lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
690								
7,484								
1,207								
100								
5,673								
3,999								
	22.36%	240,257	22.36%	240,257	8.01%	209,884	8.01%	209,884
	5.35%	57,539	5.35%	57,539	4.61%	120,839	4.61%	120,839
	2.72%	29,263	2.72%	29,263	14.88%	389,742	14.88%	389,742
	68.10%	731,766	68.10%	731,766	71.20%	1,864,565	71.20%	1,864,565
	0.25%	2,678	0.25%	2,678	0.02%	466	0.02%	466
	1.16%	12,479	1.16%	12,479	1.21%	31,797	1.21%	31,797
	0.05%	570	0.05%	570	0.05%	1,426	0.05%	1,426
9,153	100.00%	1,074,550	100.00%	1,074,550	100.00%	2,618,699	100.00%	2,618,699
		36,056		36,056		91,050		91,050
		29.60		29.60		28.76		28.76
16.70		16.20		15.70		16.40		16.40
100.00		2,374.00		1,830.70		1,162.70		851.30
915.56		1,301.11		888.17		628.17		455.17
45.12		713.72		464.96		761.49		535.57
		60.42		60.42		126.68		126.68
45.12		713.72		464.96		761.49		535.57
45.12		774.14		525.37		888.37		662.45

- Cooler vitiated air was used in the pyrolyzer—Until now, the vitiated air to the pyrolyzer was assumed to be about 700 to 750°F. This value was based on an early trade-off study that examined the impact of 1100°F vs. 700°F vitiated air and showed that the lower temperature yielded a higher overall performance. The nominal 700°F was assumed to be available either following the recuperator or following the evaporator section of the clean HRSG. During a closer examination of the overall system, it became apparent that the auxiliary power requirements from a booster compressor with an inlet temperature that high were not only prohibitive, but yielded a temperature after compression that was much too high. Even if air were extracted from the high-pressure economizer at a nominal 525°F so that the final compressed air temperature was about 760°F (and therefore closer to the assumed values), the power consumption was estimated to be about 5.7 MWe. It also became apparent that lower temperature vitiated air should be used and that it might as well come from the exhaust leaving the low-stage economizer. At the time this analysis was being done, this stream was at about 180°F. After compression up to 2 atm, the gas temperature to the pyrolyzer was calculated at about 350°F. More important, the power consumption was almost 2 MWe lower, increasing the net power produced by about 0.7 percent.
- Temperatures, pressures, and stream compositions were updated—After the material balances were issued in December, several comments were received from team members, correcting or updating information related to their systems. Most of these corrections have been incorporated into the current balance. Those related to pressure were noted, but until a better definition of the equipment arrangement is available, a detailed analysis of the system pressure drops cannot be made. A preliminary analysis should be available during the next reporting period.
- Flue gas desulfurization utility requirements were updated—Research-Cottrell has estimated utility requirements for the flue gas desulfurization system. This information is based on work performed in previous studies. These estimates have been refined to reflect the HiTAF conditions more accurately.
- Fuel gas cooler operating conditions were modified—The design of the fuel gas cooler was developed further by FWDC. We determined that the original steam- and gas-side parameters could be changed slightly to greatly lower the cost of the cooler. Using this heat exchanger for final superheating put outlet metal temperatures in a range where corrosion from the fuel gas could be a problem. Also, at the cold end of the heat exchanger the temperature difference between the steam and the fuel gas was low, causing a large surface requirement. The final superheater surface was moved to the main furnace, and intermediate superheater surface was placed in the fuel gas cooler. The fuel gas is now cooled to only 1200°F instead of 1000°F (see Subtask 3.2). The effect of these changes was to reduce the fuel gas cooler surface requirement by about 50 percent.

These changes were directly incorporated into the system model. In addition, there was some modeling done at the subsystem level. The subsystems involved were the char combustor and the fuel gas furnace.

Work done on the char combustor subsystem involved modifications to both TRW's and Bechtel's heat and material balance programs. Initial attempts to match TRW's slagging combustor simulations were based on overall heat and material balance results provided by TRW. It became evident during the reporting period that more-detailed modeling was required to better simulate TRW's work. A new stream was added to determine the flow and energy of the material leaving the precombustor before the char is added.

At the same time, modifications were made to allow the total primary air stream to enter the char combustor through the precombustor. The amount of primary air required is based on the stoichiometric requirements of both coal and char and is set by TRW between 0.8 and 1.0. Current balances are based on a stoichiometry of 0.9.

Bechtel and TRW agreed that, until additional experimental data are available, 80 percent of the sulfur in the CaS entering the char combustor with the char/spent sorbent stream would be released as sulfur dioxide into the flue gas. This is consistent with values currently being used by Research-Cottrell in their work with the FGD system. The calcium would revert to CaO and leave with the slag. The captured 20 percent of sulfur would be converted to CaSO_4 . Some CaS would leave in the slag unconverted, but the degree should not significantly change the material and energy balance.

TRW estimated a value of 990 Btu/lb for the amount of additional energy leaving in the slag over the sensible energy of the ash entering the char combustor system. This value includes sensible heat, as well as energy required for the change of state during slagging. The Bechtel models have been revised to include this level of heat loss. As a result of the work done this quarter, the Bechtel and TRW slagging combustor models are now in good agreement.

A study was also done on the fuel gas combustion system and the ceramic air heater. Excess air levels and vitiated air temperatures were varied to determine the impact on flue gas temperatures entering and leaving the ceramic air heaters. The results of this study are presented in Table 3.

Option 4 represents the parameters that are currently being used in the plant heat and material balances. As the table shows, the higher temperature vitiated combustion air will increase the ceramic air heater log mean temperature difference and thereby reduce the surface requirement. The trade-off is that this temperature increase will also increase NO_x generation. Since the need for a back-end DeNO_x system is borderline, the trade-off decision is difficult. If we end up needing a DeNO_x system anyway, raising the vitiated combustion air temperature and reducing the ceramic air heater surface would clearly be beneficial. However, if the additional temperature pushes us over the NO_x limit, there would probably be no benefit. More analysis is required before this decision can be made.

**Table 3 Impact of Fuel Gas Combustion Operation on Ceramic Air Heater
Operating Conditions**

Parameters	Option 1	Option 2	Option 3	Option 4
Vitiated air temperature, °F	1110	1110	1110	720
Excess air in fuel gas combustor, %	23.0	28.8	35.1	20.0
Flue Gas to Ceramic Air Heater				
Flow, 10 ³ lb/h	1010	1040	1073	995
Temperature, °F	3050	3000	2950	2883
Flue Gas From Ceramic Air Heater				
Temperature, °F	2077	2050	2026	1887
Air to Ceramic Air Heater				
Flow, 10 ³ lb/h	2911	2911	2911	2911
Temperature, °F	1400	1400	1400	1400
Air From Ceramic Air Heater				
Temperature, °F	1800	1800	1800	1800
ΔT hot, °F	1250	1200	1150	1083
ΔT cold, °F	677	650	626	487
LMTD, °F	934	897	861	758

Task 3—Preliminary R&D**Subtask 3.1—Analytical Determination of Pyrolyzer Yields**

The City College of New York (CCNY) pyrolyzer computer model is being used to predict the pyrolyzer heat and material balances. This model best matched the results of the FWDC Second-Generation PFB pyrolyzer pilot plant tests.

The latest pyrolyzer heat and material balances for the NG-HITAF and FG-HITAF arrangements are listed in Tables 4 and 5. These balances are based on limestone instead of the dolomite used in previous balances.

The vitiated air inlet temperature was also changed for the NG-HITAF pyrolyzer. The current balance is based on 350°F vitiated air. Previous balances were based on 711°F vitiated air. The change has been made to increase plant efficiency. Analysis showed that auxiliary power required to compress the vitiated air at 711°F was significant and that an increase in plant efficiency would result if lower temperature vitiated air were used. The vitiated air temperature is now 350°F after compression. This situation does not exist for the FG-HITAF pyrolyzer because its higher operating pressure requires air from the gas turbine compressor discharge. Also, limestone is now being used as the sorbent instead of dolomite. The lower calcium content of the dolomite increases the required sorbent flow rate which is an economic penalty. Under the reducing conditions that exist in the pyrolyzer, the limestone should be as effective as dolomite for sulfur capture. We are not anticipating any additional sulfur capture during the combustion of the char and sorbent, so it will be of benefit to reduce costs by using the limestone.

Subtask 3.2—Characterization of Ceramic Air Heater Gas-Side Environment

Potential flue gas alkali levels in the ceramic air heater were analyzed and were reported in Quarterly Report 3. Based on these analyses, we decided to include a fuel gas cooler in the cycles being investigated. Cooling the fuel gas removes most of the alkalis in the fuel gas; there are other benefits to this approach as well. The pyrolyzer operates at 1700°F. If the fuel gas is cooled below 1400°F, unlined alloy pipe can be used to transport the fuel gas to the burners, and valves are available for control of this flow. Also, steam superheat tube surface can be placed in the fuel gas cooler, and it is thermodynamically efficient to transfer the heat at these temperatures.

Sodium concentration in the fuel gas vs. temperature is plotted in Figure 4. For the initial plant heat and material balances, we chose 1000°F for the fuel gas leaving the cooler. This was a conservatively low temperature which would yield only 0.3 ppm(w) of sodium in the fuel gas if all the soluble sodium were released during pyrolysis. After the last plant heat and material balance was completed, a preliminary design analysis was prepared for the fuel gas cooler. This analysis revealed that, with the available steam conditions, the log mean temperature difference was low if the fuel gas was cooled to 1000°F. When the fuel gas was cooled to 1200°F, the cooler was substantially smaller.

Table 4 NG-HITAF Pyrolyzer Heat and Material Balance

Table 5 FG-HITAF Pyrolyzer Heat and Material Balance

Figure 4 NG-HITAF—Fuel Gas Sodium Concentration vs. Temperature

If all the soluble sodium in the coal were released during pyrolysis, this level of cooling (1200°F) would result in about 10 ppm(w) in the fuel gas. The resultant sodium concentration in the flue gas to the ceramic air heater would be less than 4 ppm(w). Alkali concentrations could be significantly lower than are predicted by assuming that all the soluble alkalies are released in the fuel gas. There can be considerable alkali gettering by the ash. The corrosion testing being done in Subtask 3.8 will give us more information on allowable alkali levels; but pending these results, 1200°F fuel gas will be used in the cycle analysis.

Subtask 3.5—Char Reactivity and Transport Gas Requirements

Two types of char transport systems have been investigated. One system is based on pulverizing the char between the pyrolyzer and the char combustor. The other system is based on designing and operating the pyrolyzer subsystem so that the char leaving the pyrolyzer will be sized correctly for the char combustor. The two types of systems were compared in Quarterly Report 3.

A major drawback to the pulverized char alternative is that no commercial equipment could be found that could pulverize the char while it was hot. Cooling and then pulverizing the char turned out to be very complicated. It required a lot of equipment and raised concerns about cost and reliability.

Work then focused on the design of a pyrolyzer and char transport system that would not require char cooling or pulverizing. This approach requires finer coal feed to the pyrolyzer and makes a circulating fluidized bed a better choice than a jetting fluidized bed. A circulating fluidized bed pyrolyzer subsystem is shown in Figure 5. This type of a system uses higher superficial velocities than a jetting fluidized bed. Two of these trains are required for a 290-MWe plant. The pyrolyzer and primary cyclone particle-gas dynamics were modeled and reported in Quarterly Report 4. Modeling showed that the char flow rates and size distributions required by the char combustors can be achieved by this type of a system. The primary cyclone and pyrolyzer will act as a classifier to control the size of particles transported to the char combustor.

The char that escapes capture in the primary cyclone is collected in the secondary cyclone and the barrier filter. This char is pneumatically fed to the char combustors with fuel gas being used as the transport medium. To determine the fuel gas required to transport the char, a proprietary equation for saltation velocity recommended by Particulate Solids Research Institute (PSRI) was used [11].

Using this equation, Figure 6 shows saltation velocities in a horizontal pipe vs. solids flow rate. These velocities are plotted for pipe inside diameters of 2, 4, and 6 in. The transport gas velocity should be kept as low as possible to minimize erosion, but it must be higher than the saltation velocity. With the current NG-HITAF char/sorbent flow rate of 24,800 lb/h per pyrolyzer train, a 120-ft/s gas velocity in a 5-in. I.D. pipe will yield a mass flow ratio of 20 lb solids/lb gas. This mass flow ratio is reasonable for pneumatic transport.

Figure 5 Fuel Gas Generation System

Figure 6 Char Sorbent Transport (Saltation Velocity vs. Solids Flow Rate)

The char transport piping will be carbon steel pipe with a refractory lining. The lining will consist of two layers. The outside layer will be chosen for its insulation properties, the inside layer for its erosion resistance.

Subtask 3.6—Char Combustor Technical Assessment

The overall objective of this task is to perform a technical assessment of the char combustor to determine preliminary performance and operating requirements and to identify char combustor development issues.

The char combustor must be capable of operating with pyrolyzed char from the pyrolyzer as its primary fuel. Together, the char combustor and furnace are required to complete combustion of the char in a manner that minimizes the formation of NO_x , removes most of the ash from the gas stream, and facilitates the removal of SO_2 from the gas stream.

During the previous two quarters (Quarterly Reports 3 and 4), the performance and operating requirements of the char combustor were addressed. These issues include the size and combustion characteristics of the char feed, the method of char transport to the combustor, the combustor air preheat temperature, the need for precombustor auxiliary fuel, combustor emissions and slag rejection requirements, and combustor heat loads and cooling water requirements.

During the last quarter, the char combustor heat and material balances for both the baseline NG-HITAF plant and the alternative FG-HITAF plant were updated to reflect the most current combustor requirements. In addition, the issue of char combustor NO_x formation was addressed through both a review of slagging combustor operating experience and a literature search of experimental studies of NO_x formation for low-volatile coals and chars. These two topics are discussed in the following sections.

NG-HITAF Char Combustor Heat and Material Balance. A preliminary char combustor heat and material balance was performed for the NG-HITAF case in support of Bechtel's plant heat and material balance activities. A schematic of the combustor, shown in Figure 7, indicates the various process streams. Coal is burned in the precombustor with vitiated air from the gas turbine. (A further refinement of this heat and material balance is required to include the coal carrier flow.) The precombustor flow exhausts tangentially into the slagging stage, creating a highly turbulent, confined vortex flow. A mixture of char and fuel gas is injected in the head end of the combustor. Molten slag is tapped from the combustor following the completion of combustion at slightly fuel-rich conditions. The flow is then exhausted into a furnace. The combustor is cooled with high-temperature boiler feedwater.

Figure 7 NG-HITAF Char Combustor Heat and Material Balance

Table 6 lists the baseline combustor operating conditions for the NG-HITAF case. The total fuel thermal input is 619×10^6 Btu/h, in which the char and fuel gas account for 79 percent of the fuel thermal input, while the coal accounts for the remaining 21 percent. The precombustor exit temperature is 2006°F , with a cooling load requirement of 4.0×10^6 Btu/h, or 3 percent of the coal thermal input. The main combustor is operated under fuel-rich conditions, at a stoichiometry of 0.8. The combustor exit temperature is approximately 3200°F , with a cooling load requirements of 105×10^6 Btu/h, or 17 percent of the total fuel thermal input.

Table 6 Combustor Operating Conditions—NG-HITAF Case

Thermal Input	
Coal	133×10^6 Btu/h
Char	486×10^6 Btu/h
Total	619×10^6 Btu/h
Precombustor	
Chamber Stoichiometry	0.9
Exit Stoichiometry	3.85
Exit Temperature	2006°F
Cooling Load	4.0×10^6 Btu/h
Char Combustor	
Stoichiometry	0.8
Exit Temperature	3211°F
Cooling Load	105×10^6 Btu/h
Total Heat to Steam Cycle	109×10^6 Btu/h

The total heat to the steam cycle from the cooling circuit is 109×10^6 Btu/h. Table 7 lists the process flow rates, temperatures, pressures, and compositions for the NG-HITAF inlet flows.

Char Combustor NO_x Formation. The char combustor design is based on the successful development of the TRW atmospheric slagging coal combustor, which has demonstrated high combustion efficiency in combination with low NO_x emissions. To achieve low NO_x emissions (0.2 to 0.4 lb $\text{NO}_2/10^6$ Btu), the combustor utilizes both fuel and air staging. In the precombustor, coal is burned under substoichiometric (fuel rich) conditions. Additional combustion air is added downstream of the primary precombustor combustion zone to raise the stoichiometry to between 2 and 4, depending on combustor operating conditions. The resultant flow stream then enters tangentially into the main, or slagging, stage of the combustor, creating a highly turbulent, confined vortex flow. The remaining fuel (coal or char) is injected in the head-end region of the slagging stage, where devolatilization and char oxidation occur under overall fuel-rich conditions. Once char oxidation is complete and the majority of molten ash has been centrifuged to the walls of the combustor, the combustion products enter the furnace, where additional air is added to complete combustion while further minimizing NO_x formation.

Typically, a very high percentage of the NO_x formed in the precombustor is destroyed, or "reburned" in the slagging stage of the combustor under fuel-rich conditions. The conversion of fuel nitrogen to NO_x or NO_x precursors (HCN, NH_3 , and others) in the slagging stage is usually quite sensitive to the overall slagging-stage stoichiometry. In general, high-temperature operation at near stoichiometric conditions results in excessive NO_x formation, while lower-temperature, fuel-rich conditions result in the formation of excessive NO_x precursors, which are

Table 7 NG-HITAF Char Combustor Inlet Flows

Stream	Stream No.					
	20: Coal to Precombustor		21: Char to Char Combustor		22: Primary Air to Precombustor	
	wt%	lb/h	wt%	lb/h	wt%	lb/h
Carbon	71.92	7,381	58.9	30,662		
Hydrogen	4.69	481	0.37	193		
Oxygen	6.33	650				
Nitrogen	1.26	129	0.93	484		
Sulfur	2.99	307	2.04	1,062		
Ash	10.32	1,059	22.02	11,463		
Moisture	2.5	257				
CaO			1.8	937		
MgO			0.12	62		
CaS			9.09	4,732		
CH ₄			0.06	31		
CO			1.05	547		
H ₂			0.06	31		
CO ₂			0.57	297	2.16	9774
H ₂ O			0.25	130	2.56	11,584
O ₂					19.67	89,007
N ₂			2.72	1,416	74.32	336,300
AR					1.27	5,747
NH ₃			0.01	5		
Total Gas	100.0	10,263	100.0	52,057	100.0	452,503
Pressure, in. H ₂ O		20		10		20
Temperature, °F		60		1700		1110
Temperature, K		289		1200		872
Sensible Heat, 10 ⁶ Btu/h				26.19		
HHV, Btu/lb		12,915.96		9341.12

subsequently oxidized once additional air is introduced into the flow. An example of this trade-off for the TRW slagging combustor is shown in Figure 8, where overall combustor NO_x emissions are plotted as a function of combustor stoichiometry. Note that a minimum is achieved at a stoichiometry ratio of 0.7 (fuel rich), where a balance has been favorably achieved between NO_x formation in the combustor and NO_x formation in the secondary burner as a result of NO_x precursor oxidation.

There are two primary issues related to adapting a slagging coal combustor to burn low-volatile pyrolyzed char in a manner that minimizes NO_x formation. First, the nature of pre-combustor NO_x destruction in the slagging stage of the combustor may be different because of the lower level of volatiles present during the initial combustion phase. Second, the formation of NO_x and NO_x precursors from char nitrogen is likely to be different than from the fuel nitrogen in the parent coal. These issues are presented in more detail in the discussion that follows.

Several different researchers have shown that NO_x produced in the coal flame is reduced to N_2 through heterogeneous char/ NO_x reactions, either directly or through combination with CO at the char surface [1-3]. However, the contribution of this NO_x destruction mechanism relative to the homogeneous reduction of NO_x by hydrocarbon species is likely to depend strongly on local gas conditions and has not been well characterized in a slagging combustor flame environment.

In addition, a number of studies have indicated that the conversion of fuel nitrogen to NO_x is lower for char nitrogen than for coal nitrogen [3-5]. Indeed, the contribution of char nitrogen to overall NO_x emissions may be as much as three times lower than that for the volatile nitrogen compounds released during the devolatilization of coal particles. Again, much depends on the nature of the pyrolysis process, as well as the local gas temperature and composition in the flame zone.

To initiate the evaluation of NO_x formation in the char combustor, it is interesting to compare the char outlet from the pyrolyzer with the coal inlet flow. This comparison is presented in Table 8 for a pyrolyzer operated on Pittsburgh No. 8 at 2 atm/1700°F.

Approximately 40 percent of the coal is converted to char. The hydrogen and oxygen species are almost completely released, with partial release of the sulfur, nitrogen, and carbon species. Only 35 percent of the original nitrogen from the coal remains in the char. The ratio of nitrogen to carbon remains approximately constant, suggesting that most of the volatile nitrogen compounds are released during the pyrolysis process, while the remaining nitrogen is well-bound within the char matrix.

Figure 8 Typical Dependence of Combustor NO_x Emissions on Combustor Stoichiometry
(Source: TRW Slagging Combustor Development Testing)

Table 8 Comparison of Pyrolyzer Coal and Char Flows—2 atm/1700°F

Constituents	Coal Feed Inlet Flow (lb/h)	Char Outlet Flow	
		(lb/h)	(% of Inlet Flow)
Carbon	71.92	27.8	38.7
Hydrogen	4.69	0.175	3.7
Oxygen	6.33	0	0
Nitrogen	1.26	0.438	34.8
Sulfur	2.99	0.964	32.2
Ash	10.32	10.32	100
Moisture	2.5	---	---
Total	100.00	39.7	

A comparison of coal and char analyses for these pyrolyzer operating conditions is presented in Table 9. Two char analyses are listed: sorbent-free char in the second column and char with sorbent in the third column. Note that although the nitrogen content in the fuel decreases as a result of pyrolysis, lb NO₂/10³ Btu fuel (assuming 100-percent conversion of fuel nitrogen to NO₂) actually increases slightly. However, if the conversion of char nitrogen to NO_x is considerably less than the conversion of coal nitrogen to NO_x, overall NO_x emissions for the char combustor will be lower.

In summary, a review of recent experimental NO_x studies, along with an evaluation of coal and char compositions, appears to indicate that the potential for NO_x emissions from the char combustor is as low, or lower, than from a comparable coal-fired combustor [3-5]. Much, of course, depends on the nature of the pyrolysis process; the coal type; and the thermodynamic, chemical, and mixing conditions within the combustor. Future activities related to char combustor NO_x formation encompass an evaluation of the nature of nitrogen release during char oxidation tests, as well as NO_x kinetics modeling, as part of the overall char combustor analytical modeling activity.

Table 9 Comparison of Pittsburgh No. 8 Coal and Char Analysis

Constituents, %	Parent Coal	Char*	Char and Sorbent
Carbon	71.92	69.91	58.9
Hydrogen	4.69	0.44	0.37
Oxygen	6.33	---	---
Nitrogen	1.26	1.10	0.93
Sulfur	2.99	2.42	2.04
Ash	10.32	26.13	22.02
Moisture	2.5	---	---
Sorbent, Fuel Gas	---	---	15.74
Total	100.00	100.00	100.00
HHV, Btu/lbm	12,916	10,557	9,341
lb NO ₂ /10 ⁶ Btu [†]	3.21	3.43	3.28
*Produced under 2 atm/1700°F conditions.			
†Assumes 100% conversion of fuel nitrogen to NO ₂ .			

Subtask 3.10—Fuel Characterization Testing

During the last quarter, fuel characterization testing at Brigham Young University (BYU) continued. Testing is being performed at BYU's Advanced Combustion Engineering Research Center (ACERC), with close cooperation between personnel at TRW and BYU. The overall objective of the testing is to obtain experimental data on high-temperature char reactivity and combustion characteristics in support of combustor analytical modeling and conceptual design activities.

Preliminary analysis of the char produced from FWDC's second-generation PFB combustion project indicates that, although the char contains only a fraction of the original coal volatiles, it still appears to be fairly reactive, apparently because of the conditions under which it is pyrolyzed.

Analyses and experiments are being performed at BYU to provide information on:

- Expected volatile yields at high heating rates (and comparison with ASTM tests)
- Char reaction rates as a function of particle size and gas environment
- Expected rates of NO_x formation (preliminary)

Description of Experiments. The rates of char combustion, sulfur release, and nitrogen release will be determined in a flat flame burner (FFB) experiment as a function of flame temperature, gas composition, particle residence times, and particle size. Both parent coal and char will be characterized. Gas temperatures and compositions will be similar to the actual slagging stage combustor environment (approximately 2000 K/3000°F). Since the slagging combustor design calls for complete conversion of the char particle in 70 to 90 percent of stoichiometric air, reactivities are desired in both oxygen environments and in steam/ CO_2 environments. The post-flame gases in the FFB experiment can be adjusted to contain 0 to 20 mol% O_2 by changing the stoichiometry of the flame. These post-flame gases generally contain 13 mol% steam and 6 mol% CO_2 . CO_2 concentrations of up to 15 mol% may be required, which can be achieved by adding additional CO_2 gas at the burner inlet. Char samples will be collected in the FFB at different residence times to determine kinetic rates. Residence times in the FFB will be determined by streak photography. Maximum residence time in the FFB is 500 ms.

A schematic of the FFB test configuration is shown in Figure 9. Air and methane are transported separately through a monolithic structure, as shown in Figure 10. A steady, flat flame is produced at the top of the structure. Coal or char is fed pneumatically upward through

Figure 9 Char Combustion Test Configuration

Figure 10 Flat Flame Burner

the middle of the FFB. An adjustable collection probe with a nitrogen quench above the FFB collects and extinguishes the burner char particles. The char particles are then separated in a cyclone and retained for post-test analyses.

A preliminary test matrix is presented in Table 10. Key tests parameters include coal type, particle diameter, flame temperature, gas concentration, and particle residence time. Tests are also being performed at a previously characterized gas composition and flame temperature to provide a baseline for comparison with an existing database.

Table 10 Char Combustion Experiments

Test Parameter	Nominal	Test Range
Coal Type	Pittsburgh No. 8	Coal and Char From Three Different Coals
Particle Diameter	65 microns	30 - 120 microns
Flame Temperature	3000°F	1600 - 3300°F
O ₂ Concentration	6%	0 - 15%
CO ₂ Concentration	6%	6 - 15%
H ₂ O Concentration	13%	8 - 15%
Particle Residence Time	100 ms	10 - 500 ms

Post-test fuel analyses are being performed on collected char and compared with pre-test analyses to determine carbon, sulfur, and nitrogen losses. Results will be compared with those obtained with the parent coal. Analyses being performed on the parent coal and collected char samples include:

- Proximate analysis (ASTM volatiles, fixed carbon, moisture, and ash)
- Ultimate analysis (C,H,N,S, and O by difference)
- Ti tracer analysis (by ICP atomic adsorption spectroscopy)
- Apparent density (tap density technique)
- Internal surface area (N₂ B.E.T.)

Summary of Results.

Flow Conditions in the Flat Flame Burner. Actual measured flow conditions in the FFB were compared with theoretical gas compositions and temperatures calculated using a version of the NASA-Lewis thermochemical equilibrium code. The actual test conditions, listed in Table 11, were determined using an on-line oxygen analyzer and a thermocouple just above the methane flame. Inlet gas flows were measured using standard rotameters.

Results indicate that the flow rates reported give close to the measured values of the mole fraction in each condition (within 1 percent). Complicating factors that may be affecting the measurement include:

- Use of natural gas instead of pure CH_4
- Calibration errors in the rotameters for the facility
- Incomplete combustion of natural gas.

Table 12 summarizes equilibrium calculations performed with the NASA-Lewis code. In general, good agreement was obtained with the theoretical excess O_2 calculations summarized in Table 11. The adiabatic flame temperatures are roughly 200 K higher than measured, because of heat losses to the burner surface.

Preliminary Char Burnout Results. A set of sampling experiments were performed in the flat flame burner for the 330 char (Pittsburgh No. 8—cyclone char) at the 1800 K, 5-percent post-flame oxygen condition. Preliminary analyses of these partially-reacted char samples are shown in Table 13. Analyses are continuing in parallel with additional sampling experiments at other gas temperatures and oxygen concentrations. The elemental inorganic data reported in Table 13 are being repeated, since the analysis for a large number of elements for each sample introduced some machine drift. The ash analyses for these samples show a decrease in the ash content at longer residence times, indicating that all the ash from the char is not collected in the cyclone, and probably that small fly ash particles travel completely through the cyclone system.

The extent of char burnout is calculated using both titanium and aluminum as tracers, and corrected for ash loss from the sample using the ash content of the partially reacted char. A more formal investigation of the percent ash loss from the sample is underway, which includes a slightly different way to calculate the burnout from the tracer concentrations. The preliminary values of the percent burnout based on these two tracers on a dry, ash-free basis is shown in bold type in Table 13. These values of burnout will eventually be used to calculate reaction rate coefficients, especially when combined with additional data from other gas conditions in the FFB.

Table 11 Summary of Conditions in Flat Flame Burner

Gas Temperature, °F	2000	1800	2000	1800
O ₂ (mol%)	5	5	0	0
Methane (cc/s)	71.4	55.3	68.5	53.9
Air (cc/s)	623.9	632.9	690	486.6
O ₂ (cc/s)	41.7	11.3	0	0
N ₂ (cc/s)	0	0	0	85.8
Net O ₂ (cc/s)	172.719	144.209	144.9	102.186
Net N ₂ (cc/s)	492.881	499.991	545.1	470.214
Equivalent Ratio	0.8268	0.7669	0.9455	1.0549
CH ₄ (mole fraction)	0.0969	0.0791	0.0903	0.0861
Air (mole fraction)	0.8465	0.9048	0.9097	0.7769
O ₂ (mole fraction)	0.0566	0.0162		
N ₂ (mole fraction)				0.1370
CO ₂ (cc/s, complete combustion)	71.4	55.3	68.5	53.9
H ₂ O (cc/s, complete combustion)	142.8	110.6	137	107.8
O ₂ (cc/s, complete combustion)	29.919	33.609	7.9	-5.614
N ₂ (cc/s, complete combustion)	492.881	499.991	545.1	470.214
Sum (cc/s, complete combustion)	737	699.5	758.5	626.3
CO ₂ (mole fraction, complete combustion)	0.0969	0.0791	0.0903	0.0861
H ₂ O (mole fraction, complete combustion)	0.1938	0.1581	0.1806	0.1721
O ₂ (mole fraction, complete combustion)	0.0406	0.0480	0.0104	-0.0090

Table 12 Summary of Equilibrium Calculations

Gas Temperature, °F	2000	1800	2000	1800
O ₂ (mol%)	5	5	0	0
Equivalence Ratio	0.8268	0.7670	0.9455	1.0549
CO ₂ (mole fraction)	0.0919	0.0784	0.0856	0.0728
H ₂ O (mole fraction)	0.1879	0.1568	0.1766	0.1642
O ₂ (mole fraction)	0.0386	0.0459	0.0112	0.0001
Temperature (K, adiabatic)	2272	2021	2185	2047

Table 13 Analyses of Partially Reacted 330 Char in the 1800 K/5-Percent O₂ Condition

Constituents	Parent 330 Char	Sampling Height			
		2 in.	4 in.	6 in.	8 in.
Ash (dry)	35.4	36.3	20.5	32.2	32.7
C (wt% dry)	62.45	62.57	---	---	---
H	0.56	0.52	---	---	---
N	0.89	0.92	---	---	---
Fe (wt% dry)	3.67	2.33	1.76	2.33	2.30
Si	2.29	2.25	1.76	2.33	2.30
Mg	3.59	2.39	1.56	3.87	3.58
Ti	0.096	0.106	0.102	0.122	0.122
(% burnout)	0.0	0.8	9.2	18.6	24.3
Ca	5.54	3.93	2.65	6.25	5.76
Al	1.46	1.60	1.56	1.96	1.84
(% burnout)	0.0	1.3	5.4	17.3	26.1
Na	0.14	0.20	0.21	0.26	0.17

Separation of Char from Spent Sorbent. A simple fluidized bed apparatus was developed to separate the 331 char (bed drain) from the sorbent (see Figure 11). The 331 char/sorbent mixture was received in crushed form (≈ 1 - to 5-mm diameter). Separation of the char from the sorbent was needed to measure char reactivity in the FFB. Separation attempts on pulverized samples of the 331 char/sorbent mixture in fluidized beds proved unsuccessful, probably because of the porosity of the pulverized char. However, separation of the initial crushed mixture without grinding it first proved successful. The apparatus was about 1 in. in diameter and 12 in. high. A vibrator also assisted in the fluidization. The separated 331 char rose to the top of the fluidized bed and was carefully decanted, leaving most of the sorbent in the bottom of the fluidizing cylinder. The ash analyses of the 331 char/sorbent mixture and the separated 331 char are given in Table 14 show approximately a 50-percent decrease in the ash content of the separated sample. The ash content of the separated 331 char is comparable to the ash content of the 330 char (see Table 13).

Figure 11 Schematic of Fluidized Bed Apparatus for Separating 331 Char (Bed Drain) From Sorbent

Table 14 Ash Contents of 331 Char Samples

331 Char/Sorbent		Separated 331 Char	
Top	74.1 (wt% dry) 74.0	Sample 1	32.1
Middle	78.6 78.4	Sample 2	32.7
Bottom	87.5 81.1		
Average	78.9	Average	32.4

Char Combustion Predictions. During the previous quarter (Quarterly Report 4), char combustion was calculated to approximate the range of burnout expected in the FFB in 5-percent post-flame oxygen. A linear gas temperature profile in these predictions approximated actual measured gas temperatures vs. residence time for the two flame conditions. Kinetic parameters for two coal chars were taken from related research at Sandia National Laboratories [6,7].

During the current reporting period, two more char combustion calculations were performed to approximate the range of burnout expected in 5-percent oxygen. Conditions for the predictions more closely correspond to the conditions expected in the slagging combustor:

- Initial particle temperatures of 1200 K and wall temperatures of 1200 K, with gas temperature decaying from 2050 to 1550 K
- Same conditions except that the gas temperature was held constant at 2000 K.

Kinetic parameters for the coal char were assumed to be those of a Pocahontas low-volatile bituminous coal char [6,7].

Predictions of char burnout for the two cases are shown in Figures 12 and 13. The initial diameter for these calculations was 72 microns. The burnout expected for the char in 5-percent oxygen when the gas temperature is held constant at 2000 K is 96.7 percent (dry, ash-free basis) after 95 ms. With the decaying gas temperature shown in Figure 13, the predicted burnout is 73.5 percent. These predictions were made assuming a constant amount of O₂ throughout the computational region. The implication of these calculations is: to achieve high carbon burnout within a short residence time (100 to 200 ms) with a low-reactivity char, the char combustor must be designed and operated to maintain a relatively high temperature throughout the combustion zone.

Figure 12 Predicted Burnout for a Pocahontas Low-Reactivity Char in 5 Percent Oxygen for Gas Temperatures Shown in Figure 13

Figure 13 Prediction of Particle and Gas Temperatures for Pocahontas Char With 1200 K Wall Temperatures

Subtask 3.13—Preliminary Design of Secondary Air Heater

AlliedSignal Aerospace redesigned the ceramic air heater based on the December 1992 plant heat and material balances. The design conditions are presented in Table 15. The ceramic air heater was sized using the AlliedSignal computer program BUNDLE. This program is a tubular heat exchanger performance code. The design restrictions were that there be an even number of air heater modules and that the modules could be stacked.

Table 15 Ceramic Air Heater Design Conditions

Parameter	Air Side	Gas Side
Inlet Temperature, °F	1400	3100
Outlet Temperature, °F	1800	---
Inlet Pressure, psia	197.6	15.6
Pressure Drop, psi	4.9	---
Flow Rate, lb/h	2,959,456	821,003
Composition, wt%		
CO ₂	2.0	18.6
H ₂ O	2.4	7.6
N ₂	75.5	71.3
O ₂	20.1	2.5

The basic tube/header module structure, previously developed, was retained. This arrangement is shown in Figure 14. Each tube/header module has 59 tubes. The headers have a 7.5-in. I.D. and are approximately 5 ft long. The active length of the tubes is 6.7 ft. The tube/header modules are arranged in air heater modules as shown in Figure 15. A 290-MWe plant requires four of these modules operating in parallel. The air heater modules are stacked and connected with manifolds. There are 80 tube/header modules in a 290-MWe plant, yielding a total of 4720 tubes. Major design information is summarized in Table 16.

The air heater walls and dividers can be fabricated out of a high-alumina brick such as HW-33 (Harbison-Walker Refractories). This material has a 3300°F operating temperature limit, which is comfortably above the maximum flue gas temperature.

Figure 16 shows the way the air heater modules can be stacked. A two module stack is shown; however, more units can be stacked with the proper support structure and transfer pipe design.

Figure 14 Ceramic Air Heater Module

Figure 15 Ceramic Air Heater

Table 16 Ceramic Air Heater Design

Tube Material	Sintered Alpha = Silicon Carbide
Total Tubes	4720
Tubes per Module	59
Modules per Stack	10
Modules	80
Active Tube Length, ft	6.7
Gas Flow Length, ft	6.8
No-Flow Length, ft (4 units)	39.4
Tube Weight, lb	56,730
Core Volume, ft ³	1795
Tube O.D./I.D., in. *	2.0/1.7
Tube Spacing, in.	3.0 (equilateral triangles)
Minimum Tube Clearance, in.	1.0
* Internal cruciform fins; fin thickness equal to wall thickness.

Figure 16 Two-Unit Stackup (Front View)

The air heater performance is summarized in Table 17. This performance is based on the December 1992 plant heat and material balance.

Table 17 Ceramic Air Heater Performance

Parameter	Value
Gas Outlet Temperature	1885°F
Heat Exchanger Effectiveness	0.715
Gas Side Pressure Drop	0.6 psi
Maximum Tube Wall Temperature	≈ 2300°F
Thermal Conductance Ratio (air-to-gas)	3.6:1
Capacity Rate Ratio (air-to-gas)	3.0:1

Subtask 3.21 — Pollution Control Systems

Work in the first quarter of 1993 focussed on updating the emissions inventories to reflect more accurate systems mass balances, investigating fuel gas cleanup options, and equipment and operating cost estimating.

Emissions Inventories. SO₂, NO_x, and particulate inventories were calculated based upon the simplified flow diagrams given in Figures 17 and 18 (Stream numbers are identified in Tables 18 and 19). These diagrams only show sources and sinks for SO₂, NO_x and particulate for the NG-HITAF and FG-HITAF systems. Using the Bechtel mass balances from February 17, 1993, Tables 18 and 19 were generated for the NG-HITAF and FG-HITAF systems. The inputs are the Bechtel mass flows, coal characteristics, pollution control equipment efficiencies, and NO_x production rates at the various NO_x sources. Most uncertainty centers around these NO_x rates. The SO₂, NO_x, and particulate emissions rates are within the acceptable levels of 0.15 and 0.0075 lb/10⁶ Btu respectively for the NG-HITAF case, but the SO₂ and NO_x emissions rates exceed these limits for the FG-HITAF case. The most significant uncertainty is that of the degree of conversion from NH₃ to NO_x in the combustion of the fuel gas.

Figure 19 shows how the overall FG-HITAF plant NO_x emissions are affected by this conversion. As the figure shows, 0.15 lb/10⁶ Btu is exceeded when the NH₃-to-NO_x conversion is greater than 40 percent—even when an 80 percent deNO_x system is employed and when all NO_x contained in the vitiated air is assumed to be destroyed upon its use as a combustion oxidizer. Figure 20 shows the same calculation for the indirect-fired case. Since much lower

Figure 17 NG-HITAF Flow System

Figure 18 FG-HITAF Flow System

Table 18 NG-HITAF Emissions Inventory

Initial Conditions		System Emissions Rates	
Coal, % Ash	10	SO ₂ , lb/10 ⁶ Btu	0.1388
Coal, % S	3	NO _x , lb/10 ⁶ Btu	0.1424
Ca/S to Pyrolyzer	2.5	Ash, lb/10 ⁶ Btu	0.0070
Solids to Fuel Gas, %	7	10 ⁶ Btu/h	2187
S to H ₂ S, %	5	MW at 48% Efficiency	308
Ash Capture, %	80		
Combustion, % S Capture	20		
Barrier Filter, %	0		
Particle Control, %	99.8		
DeSO _x , %	95		
DeNO _x 1, %	0		
DeNO _x 2, %	0		
% NH ₃ in Fuel Gas	0.12		
NH ₃ to NO Conversion	0		
FB Combustion, lb/10 ⁶ Btu	0.08		
Precombustor, lb/10 ⁶ Btu	0.5		
Char Combustor, lb/10 ⁶ Btu	0.25		
GT Combustor, lb/10 ⁶ Btu	0.2		
Vit. Air Combustor, NO _x Reducing %	50		

Stream		HITAF Flow Conditions						
No.	Name	Flow, 10 ³ lb/h	Press., psia	Temp., °F	S, lb/h	NO, lb/h	Part., lb/h	HHV, Btu/lb
1	Coal	109.9	50	70	3297.0	0.0	36747.8	12916
2	Fuel Gas	411	30	1700	164.9	0.0	130.1	2112
3	Flue Gas	1232	15	1800	164.9	69.6	130.1	
4	Natural Gas	28	15	70	0.0	0.0	0.0	21800
5	Air	2959	150	1800	0.0	0.0	0.0	
6	Vit Air	3493	30	851	0.0	122.1	0.0	
7	Vit Air	1635	30	851	0.0	57.1	0.0	
8	Vit Air	1858	30	851	0.0	64.9	0.0	
9	Vit Air	1858	14	851	0.0	64.9	0.0	
10	Char	37.9	45	1700	3132.2	69.5	36617.8	7333
11	Coal	12.2	15	70	366.0	78.8	1220.0	12916
12	Flue Gas	1762	15	300	3036.6	217.9	7697.6	
13	Flue Gas	1762	15	300	3036.6	217.9	7697.6	
14	Flue Gas	1762	15	300	3036.6	217.9	15.4	
15	Flue Gas	1762	15	100	151.8	217.9	15.4	
16	Stack	3620	15	100	151.8	311.4	15.4

Table 19 FG-HITAF Emissions Inventory

Initial Conditions		System Emissions Rates	
Coal, % Ash	10	SO ₂ , lb/10 ⁶ Btu	0.4069
Coal, % S	3	NO _x , lb/10 ⁶ Btu	0.3689
Ca/S to Pyrolyzer	2.5	Ash, lb/10 ⁶ Btu	0.0070
Solids to Fuel Gas, %	10	10 ⁶ Btu/h	2143
S to H ₂ S, %	10	MW at 48% Efficiency	301
Combustion, % S Capture	80		
Combustion, % S Capture	20		
Barrier Filter, %	99.9		
Particle Control, %	99.9		
DeSO _x %	97		
DeNO _x 1 %	0		
DeNO _x 2 %	0		
NH ₃ to NO Conversion	50		
% NH ₃ in Fuel Gas	0.12		
Precombustor, lb/10 ⁶ Btu	0.5		
Char Combustor, lb/10 ⁶ Btu	0.25		
GT Combustor, lb/10 ⁶ Btu	0.50		
Vit. Air Combustor, NO _x Reducing %	50		

Stream Number		HITAF Flow Conditions						
No.	Name	Flow, 10 ³ lb/h	Press., psia	Temp., °F	S, lb/h	NO, lb/h	Part., lb/h	HHV, Btu/lb
1	Coal	147.1	226	60	4413.0	0.0	49186.6	12916
2	Fuel Gas	616	206	1700	441.3	0.0	9247.7	2112
3	Air	434	226	1100	0.0	0.0	0.0	
4	Fuel Gas	616	206	68	441.3	652.2	9.2	2112
5	Air	2477	205	1800	0.0	0.0	0.0	
6	Vit Air	3644	205	700	441.3	652.2	9.2	
7	Vit Air	1001	205	700	121.2	179.2	2.5	
8	Vit Air	2643	205	100	320.1	473.1	6.7	
9	Vit Air	2643	205	100	320.1	473.1	6.7	
10	Char	58	15	1700	3971.7	106.3	39938.9	7333
11	Coal	18.9	15	68	564.0	121.4	1880.0	12916
12	Flue Gas	1052	15	300	3862.6	227.7	8363.8	
13	Flue Gas	1052	15	300	3862.6	227.7	8.4	
14	Flue Gas	1052	15	300	3862.6	227.7	8.4	
15	Flue Gas	1052	15	100	115.9	227.7	8.4	
16	Stack	3695	15	100	436.0	790.4	15.1

Figure 19 FG-HITAF—Effect of Gas Turbine Combustor NO_x Production on Overall System NO_x Emissions (System goal shown by heavy horizontal line.)

Figure 20 NG-HITAF—Effect of Gas Turbine Combustor NO_x Production on Overall System NO_x Emissions (System goal shown by heavy horizontal line.)

NH_3 -to- NO_x conversions are expected for the air heater fuel gas burner, the x-axis range is limited to 20 percent, and NO_x emissions remain below $0.15 \text{ lb}/10^6 \text{ Btu}$ —provided NH_3 -to- NO_x conversion is less than 10 percent.

Figure 21 shows SO_2 emissions as a function of the efficiency of the FGD system downstream of the char combustor only. The emissions level of $0.15 \text{ lb}/10^6 \text{ Btu}$ can be achieved by the NG-HITAF with a 94-percent efficient FGD system, but the specified emission limit cannot be achieved by the FG-HITAF, even when 5 percent of the coal sulfur converted to fuel gas H_2S is assumed.

Figure 22 shows how particulate emissions are affected by the efficiency of the electrostatic precipitator. The limit of $0.0075 \text{ lb}/10^6 \text{ Btu}$ can be met by both the NG-HITAF and the FG-HITAF, provided that the precipitator is 99.9-percent efficient.

There are very few commercial applications of high-temperature filters, and much of the reported experimental work has not proved the capability of long-term operation. Seven suppliers of high-temperature filter media have been asked to supply the characteristics and cost of their product:

■ Memtec America - metal fiber	■ Schumacher GmbH - ceramic candle
■ Bekaert Corporation - metal fiber	■ 3M - woven ceramic
■ BWF America - ceramic mat	■ Ceramem - extended-surface area ceramic
■ Foseco International - ceramic mat	

Experimental operation of high-temperature barrier filters show the wide range face velocities and pressure drops typically utilized. This range is shown in Figure 23, which gives the face velocity and associated pressure drop of three candle filter experiments and three cross-flow filter experiments. A data point is added to show typical cloth filter-bag operation. As expected, face velocity can be increased at the cost of higher pressure drop. The advantage of high face velocity is that the barrier filter becomes smaller and less costly, which can be especially important when the housing for the barrier filter is a pressure vessel. Considering that the fuel gas system is pressurized, it would seem that high face velocity/high pressure drop operation is the best specification for the barrier filter.

For the NG-HITAF system, we determined that a pressure drop across the filter of up to several psi would be acceptable. Therefore a filter face velocity of $10 \text{ ft}/\text{min}$, which yields a pressure drop of 1.5 psi, would be acceptable. A 3.5-in.-diam x 6.5-ft-long metal fiber filter element was assumed, and 2433 elements are needed to filter the $145,970 \text{ aft}^3/\text{min}$ fuel gas flow rate at a $10 \text{ ft}/\text{min}$ face velocity. These elements can be housed in four 12-ft-diam pressure vessels at a total cost of \$1,684,700. These specifications are summarized in Table 20.

Figure 21 Sensitivity of SO₂ Emissions to SO₂ Absorber Efficiency

Figure 22 Sensitivity of Particulate Emissions to Particle Collector Efficiency
(System goal shown by heavy, horizontal line)

Figure 23 Pressure Drop vs. Face Velocity for Various Type Filters

Table 20 NG-HITAF Barrier Filter Specifications

Item	Value
Flow Rate	145,970 aft^3/min
Filter Element Size	3.5 in. diam $\times$ 6.5 ft long
Filter Element Area	6 ft^2
Gas Face Velocity	10 ft/min
Pressure Drop	1.5 psi
Elements	2433
Vessel Size	12 ft diam.
Elements/Vessel	608
Vessels	4
Cost per Element	\$446
Cost per Vessel	\$150,000
Total Cost	\$1,684,700

Economics. A determination of the utilities and materials consumption of the pollution control systems was based upon the use of a precipitator followed by a regenerable SO₂ scrubber. The scrubber system was assumed to be a Tung design, producing elemental sulfur. A diagram of the system is shown in Figure 24. The rates of utility and raw material consumption were obtained from Research-Cottrell specifications, from Tung specifications, and from the general literature. These rates and the corresponding consumptions are shown in Table 21. for the NG-HITAF.

Cost calculations for the NG-HITAF pollution control equipment were made based upon the Bechtel's February 17, 1993, mass balances; they are given in Table 22 and are based upon the utility and raw material consumption rates given in Table 21. The equipment considered includes SO₂ removal, particulate control, and the associated ductwork and fans. The plant output in MW and the percentage thermal efficiency correspond to conventional plants producing flue gas rates equivalent to those that char combustion would produce for a 290-MW HITAF plant; they must be given in this manner so that existing software can be utilized.

The calculations show a capital cost of \$84 million and a yearly operating cost of \$9.9 million for the NG-HITAF case. This translates to capital costs of \$290/kW and operating costs of \$0.0056/kWh and \$0.0039/kWh.

Task 4—Commercial Generating Plant Design

Subtask 4.19—Plant Cost and Economics

One of the goals of the HITAF program is to provide power at a cost that is 10 percent lower than a conventional pulverized coal fired (PCF) boiler with fuel gas desulfurization. Although too early to do an analysis of the capital requirements for our system, Bechtel was asked to estimate the approximate allowable capital cost based on estimated fixed and variable costs available from current heat and material balances and experience with similar advanced power systems.

Using EPRI's TAGTM [10] and available in-house data, Bechtel estimated the approximate cost of electricity (COE) for a PCF plant to be about 51 mills/kW. Of this, about 13 mills is attributable to the cost of fuel. Thus, even with a 30-percent reduction in the cost of fuel resulting from higher efficiency, the savings will amount to only about 4 mills/kW.

Limestone is another significant cost factor. A conventional PCF plant will use about 3 lb limestone/lb sulfur captured. In the December NG-HITAF balance, over 18 lb of dolomite entered the system for each pound of sulfur in the coal. A graph was prepared (see Figure 25) to highlight the effect of limestone consumption on the estimated allowable capital, consistent with achieving a 10-percent reduction in COE.

Figure 24 Pollution Control System Utility and Materials Input

Table 21 Pollution Control System Utilities and Materials

NG-HITAF	493,600 aft ³ /min	2790 lb SO ₂ /h
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Box*	Consumption	NG-HITAF
1	0.7 kW/1000 ft ³ /min	346
2	4 kW/1000 ft ³ /min	1974
3	1 kW/1000 ft ³ /min	494
4	0.025 kWh/lb SO ₂	70
5	0.015 kWh/lb SO ₂	42
6	0.015 kWh/lb SO ₂	42
Total Power, kW		2967

Arrow			NG-HITAF
1	Soda Ash	0.04 lb/lb SO ₂	112 lb/h
2	Make-Up Water	0.03 gal/1000 ft ³	148 gal/min
3	Cooling Water	11 gal/lb SO ₂	512 gal/min
4	LP Steam	1 lb/lb SO ₂	2790 lb/h
5	Methane	0.125 lb/lb SO ₂	349 lb/h
6	LP Steam	-0.3 lb/lb SO ₂	-837 lb/h
7	Limestone	0.05 lb/lb SO ₂	140 lb/h
8	LP Steam	0.09 lb/lb SO ₂	2511 lb/h
Total LP Steam, lb/h			4464

*See Figure 24.

Table 22 Comparative Economics NG-HITAF/TUNG

Plant Output, MW	180	lb SO ₂ /10 ⁶ Btu In	3.00
Thermal Efficiency, %	33	NO _x In, ppm	300
Coal Heat Value, Btu/lb	12,000	SO ₂ Removal, %	95
Hours per Year	6000	NO _x Removal, %	0
Annual Interest, %	5	lb SO ₂ /10 ⁶ Btu Out	0.15
Plant Life, yr	30	lb NO ₂ /10 ⁶ Btu Out	0.43
Coal Sulfur Content, %	1.80	Capital Cost	8.4E + 07
Coal Ash Content, %	10.00	Yearly Operating Cost	4.4E + 06
10 ⁶ Btu/h	1.9E + 03	Yearly Cost	9.9E + 06
sft ³ /10 ⁶ Btu	12,527	\$/kW	467
sft ³ /min	3.9E + 05	\$/ton (SO ₂ + NO _x)	621

No. Units	Unit	Capital Costs	
		\$/sft ³ /min	\$/kW
1	Reagent Feed System	3.2	7
1	SO ₂ Removal System	31.6	68
1	Regeneration System	31.6	68
1	By-Product System	22.4	48
1	Flue Gas Handling	16.1	35
1	Precipitator	16.1	35
1	Waste Handling	6.3	14
	Total Process Capital	127.1	274.5
% Capital	Other	\$/sft ³ /min	\$/kW
20.0	General Facilities	25.4	54.9
20.0	Engineering and Home Office Fees	25.4	54.4
10.0	Project Contingency	12.7	27.4
10.0	Process Contingency	12.7	27.4
10.0	Preproduction Costs	12.7	27.4
	Total Capital Investment	216.0	466.6

Table 22 (Cont) Comparative Economics NG-HITAF/TUNG

Reagent Mole Ratio			\$ / yr / sft ³ / min	
SO ₂	NO _x	Consumables	SO ₂	NO _x
0	0	Lime	0.0	
0	0	Hydrate	0.0	
0	0	Limestone	0.0	
0	0	Soda Ash	0.7	
0	0	Bicarb	0.0	
0	0	Ammonia	0.0	
1	0	Methane	0.8	
0	0	Carbon	0.0	
Byproduct (1 or 0)				
1	0	Sulfur	1.8	
0	0	Sulfuric Acid	0.0	
0	0	Gypsum	0.0	
0	0	Ammonium Bisulfite	0.0	
0	0	Potassium Sulfate	0.0	

Cost Category	\$ / yr / sft ³ / min
Operating Costs	
Operating	2.2
Maintenance	6.5
Power Usage	2.0
Disposal	0.3
Steam	0.5
Raw Water	0.07
Cool Water	0.19
First-Year Costs	
Operating	11.8
Reagents	1.5
Byproduct Sales	-1.8
Total	11.4
Capital Recovery	14.1
Total Including Capital Recovery	25.4

* Based on values in December 15, material balance

Figure 25 Projected Allowable Capital as Function of Limestone Used (COE 10% less than PC w/FGD)

Based on these data and other considerations, the dolomite was changed to limestone, the limestone to the pyrolyzer was reduced by about a third, and the limestone to the char combustor was eliminated altogether. Current balances have lowered the limestone requirements to about 2.4 lb/lb of sulfur entering the system.

The economic determinations assumed a cost for fuel of \$1.33/10⁶ Btu. This relatively low cost was based on work for EPRI using Illinois No. 6 coal. As the coal price rises, the impact of higher efficiency plays a greater role. The base-case fuel for HITAF is Pittsburgh seam coal, which is valued closer to \$1.80/10⁶ Btu. The use of this coal would increase the allowable capital by about \$50 million.

REFERENCES

1. Y. H. Song, A. F. Sarofim, and J. M. Beér, "Reduction of Nitric Oxide by Coal Char at Temperatures of 1250-1750 K," *Combustion Science and Technology*, Vol. 25, pp. 237-340, 1981.
2. Y. H. Song, A. F. Sarofim, and J. M. Beér, "Kinetics of the NO-Carbon Reaction at Fluidized Bed Combustor Conditions," *Combustion and Flame*, Vol. 52, pp. 37-45, 1983.
3. N. A. Burdett and J. W. Pye, "The Effect of Coal Composition on NO_x During Combustion Under Controlled Conditions," *Proceedings of International Conference on Coal Science*, Elsevier Science Publications, Amsterdam, p. 845.
4. J. W. Glass and J. O. L. Wendt, "Fuel Nitrogen Conversion During Fuel Rich Combustion of Pulverized Coal and Char," Topical Report 1, DOE Report DOE/ET/15184-1152, 1981.
5. Y. H. Song, et al., "Nitric Oxide Formation During Pulverized Coal Combustion," *Combustion Science Technology*, Vol. 28, pp. 31-39, 1982.
6. R. H. Hurt and R. E. Mitchell, "Unified High-Temperature Char Combustion Kinetics for a Suite of Coals of Various Rank," 24th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Pennsylvania, 1992.
7. R. H. Hurt, et al., "Char Combustion Kinetics of U.S. Coals: A Comprehensive Data Base for Industry," *Proceedings of the Ninth Annual Pittsburgh Coal Conference*, Pittsburgh, Pennsylvania, pp. 634-639, 1992.
8. S. J. Bossart, et al., "Gas Stream Cleanup," DOE/METC-91/0273, August 1990.
9. G. N. Krishnan, et al., "Study of Ammonia Removal in Coal Gasification Processes," DOE/MC/23087-2667, September 1988.
10. TAG™ - Technical Assessment Guide, Palo Alto, California, Electric Power Research Institute, EPRI P-4463-SR, December 1986.
11. T. Knowlton, Correspondence to J. Shenker, November 16, 1993.

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