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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 8
October through December 1993**

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

**FWDC Project 9-41-3492
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FOSTER WHEELER DEVELOPMENT CORPORATION

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MASTER

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QUARTERLY PROGRESS REPORT 8 (October through December 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 (FWDC) 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 (FWEC)
- General Electric 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

Work is proceeding in accordance with the Revised Project Work Plan issued in May 1993.

Task 3—Preliminary R&D

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

The gas-side environment is an important consideration in the choice of material for the ceramic air heater and the design of the pyrolyzer subsystem. Three candidate materials have been selected for evaluation—sintered alpha-SiC, siliconized-SiC, and SiCp/Al₂O₃ composite. All three of these materials have experienced corrosion under certain test conditions that have been attributed to the effects of alkali interactions [1,2,3].

Figure 1 Simplified Process Block Flow Diagram

With our HIPPS concept, the flue gas going through the ceramic air heater can essentially be made as free of alkalis as required, depending upon the amount the fuel gas is treated to remove particulates and gaseous-phase alkalis. To determine the environment in the ceramic air heater, a reasonable fuel gas cleanup system was designed and then analyzed for gaseous-phase alkali and particulate carryover into the ceramic air heater. This analysis was based on laboratory tests of char/sorbent samples from the FWDC second-generation PFB pyrolyzer, calculations of particulate-removal efficiency, and thermodynamic modeling of the fuel gas. The procedure and the results of this analysis are reported in Quarterly Report 6 [4].

Based on this analysis, there are two regions in the ceramic air heater where corrosion is a concern. One is at the flue gas inlet, where the tube temperature is 2300°F. There the deposits will be molten, and interaction between the alkalis in the ash particles and the ceramic tubes can be a problem. The other region of interest is near the exit of the ceramic air heater, where the temperature is around 1800°F. At this temperature, alkalis will be condensing out of the fuel gas. This situation can lead to increased alkali concentration in the deposits.

Subtask 3.8—Evaluation of Secondary Air Heater Corrosion

Laboratory testing is being done at FWDC to obtain preliminary information on ceramic air heater corrosion. High-temperature electrically heated furnaces are being used to maintain ceramic specimens at operating temperatures. The specimens are sintered alpha-SiC, siliconized-SiC, and SiCp/Al₂O₃ composite. These specimens are flat pieces of material 2 in. long x 1 in. wide. Specimen thicknesses depended on material availability, and they range from 0.125 to 0.375 in. thick. The gaseous atmosphere in the furnaces is a synthesized gas that contains the major components in the flue gas. Char/sorbent samples from FWDC's Second-Generation PFB pilot plant pyrolyzer were used to prepare deposits for the corrosion tests. These samples were ashed in a laboratory furnace and then applied to the ceramic specimens.

The ash was applied in different ways to simulate different conditions in the ceramic air heater. Three general conditions have been simulated so far:

- Light loading at 2300°F, simulating operation with a barrier filter
- Heavy loading at 1800°F with added alkalis, to simulate operation without a barrier filter at a temperature where alkali condensation will occur
- Heavy loading at 2300°F, simulating operation without a barrier filter.

Results of the testing were reported in detail in Quarterly Report 7 [5]. During this quarter, another test run was made with light loading at 2300°F. The initial run under those conditions was with the sintered alpha-SiC only. The current run used all three materials. Analysis of the specimens from this run is not complete yet.

Subtask 3.10—Fuel Characterization Testing

Fuel characterization testing at Brigham Young University (BYU) has been completed. Testing was 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 was to obtain experimental data on high-temperature char reactivity and combustion characteristics in support of combustor analytical modeling and conceptual design activities. The results of this testing are reported in Quarterly Report 7 [6].

Subtask 3.12—Preliminary Design of Topping Combustor

GE gas turbines are not currently designed to have air removed from the machine and then returned to the combustor at a higher temperature. This type of operation, which is necessary in the HIPPS concept, requires some research and development. The R&D is basically in two areas. One is the design of the piping system to remove and return the air (Subtask 3.29). The other R&D area is the determination of the design and operating characteristics of the combustors. The effect of 1800°F air on combustion characteristics and emissions is the primary consideration in this investigation.

The combustor test rig was described in Quarterly Report 7 [7]. Tests have been run with air inlet temperatures up to 1770°F with a diffusion combustor design and up to 1500°F with a premix combustor design. The achievable air inlet temperature with a premix combustor design was limited because of problems with autoignition and flashback.

All the tests were run with a vessel pressure of 7 atm and with a combustor residence time of 12 ms. CO and NO_x were measured at different air inlet temperatures with the exit temperature of the combustor held constant. These tests were repeated for different exit temperatures. The results of the combustor tests cannot be used directly as CO and NO_x levels for the full-scale combustor; however, this information can be used to estimate the levels that will be present in the full-scale combustor.

Figures 2 through 5 show the plots of CO and NO_x with a premix combustor at exit temperatures of 2500, 2600, 2700, and 2800°F. As these graphs show, the NO_x is relatively constant over the range of air inlet temperatures tested. The downward trend of NO_x with inlet air temperature that can be seen in Figure 2 is not a true indication, because the high levels of unburned carbons at the lower temperatures have affected the measurement. Figures 3 through 5 show that the NO_x levels with the premix combustor are relatively constant with air inlet temperature over the range of temperatures tested, and the levels range from 5 to 10 ppm, depending on the combustor outlet temperature.

As seen in all the graphs, the CO decreases sharply with air inlet temperature, and this pollutant should not be a problem at operating conditions. Figure 6 shows all of the CO data from the premix combustor on one graph so the effects of outlet temperature can be seen. The combined results of the NO_x testing are shown in Figure 7.

Figure 2 Emissions Data (Premix) at 2500°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 3 Emissions Data (Premix) at 2600°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 4 Emissions Data (Premix) at 2700°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 5 Emissions Data (Premix) at 2800°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 6 CO as a Function of Inlet Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 7 NO_x as a Function of Inlet Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figures 8 through 13 are plots of CO and NO_x with a diffusion combustor. With this type of a combustor, NO_x levels are higher than with a premix combustor, but operation is possible with air inlet temperatures of 1800°F. Temperatures of 1770°F were achieved in the tests. NO_x levels at 1770°F ranged from 50 ppm with a 2500°F exit temperature to 560 ppm with a 3000°F exit temperature. As seen, the CO decreases to insignificant levels at the normal operating conditions. The CO data for all the combustor exit temperatures are shown in Figure 14. Figure 15 contains all the NO_x data for the diffusion combustor.

Subtask 3.14—Ceramic Air Heater/Furnace Compatibility

Both structural and functional issues had to be addressed in integrating the ceramic air heater and the rest of the HITAF. After exploring many possible arrangements, the arrangement shown in Figure 16 was selected. In this arrangement, the ceramic air heater modules are arranged vertically downstream of a fuel gas-fired furnace. The flue gas leaving the air heaters then enters a passage in the main HITAF, where the flow distribution equalizes before it enters the tube banks.

The main functional consideration is how to orient the fuel gas furnace relative to the air heater modules. It is best to avoid direct radiation from the flame to the first row of air heater tubes. This situation can be easily avoided by making a right-angle turn from the furnace into the ceramic air heater modules. The main problem with this approach is that the turn will cause an uneven distribution of flow entering the air heaters. Research-Cottrell has used a computer model to analyze the flow, and AlliedSignal has done a thermal/structural analysis of the air heater with a skewed inlet flow distribution.

The flow distribution was analyzed using the Phoenix fluid dynamics code. The tube bundle was modeled by assuming slit plates that would yield the same pressure drop as the tube bundle. The geometry is shown in Figure 17, and the resultant velocity distribution is shown in Figure 18. As Figure 18 shows, the inlet velocity imbalance is estimated to be about 3.4:1. This skewed velocity distribution occurs because of centrifugal forces from the turn. AlliedSignal performed a thermal/structural analysis of the air heater using a 3:1 velocity distribution entering the air heater. This analysis is reported in Subtask 3.18.

In addition to the functional considerations, there are structural aspects of the design that had to be addressed. As is typical in boiler designs, consideration must be given to the effects of thermal expansion and the need to limit gas leakage. Ways of supporting the ceramic air heaters from the main HITAF were investigated, but these proved less than satisfactory. The many headers and transfer pipes that are part of the ceramic air heater design were difficult to integrate into a tubewall structure.

We decided to support the ceramic air heater modules separately and use an expansion joint/seal arrangement to connect the modules with the main HITAF and the fuel gas furnace. The four air heater modules are arranged in a vertical stack, as shown in Figure 16, but each module is separately supported on structural steel beams. In this manner, maximum

Figure 8 Emissions Data (Diffusion Flame) at 2500°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 9 Emissions Data (Diffusion Flame) at 2600°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 10 Emissions Data (Diffusion Flame) at 2700°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 11 Emissions Data (Diffusion Flame) at 2800°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 14 CO as a Function of Inlet Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 15 NO_x as a Function of Inlet Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 12 Emissions Data (Diffusion Flame) at 2900°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

Figure 13 Emissions Data (Diffusion Flame) at 3000°F Exit Temperature (Pressure = 7 atm; Residence Time = 12 ms)

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Figure 16 High-Temperature Advanced Furnace – 290-MWe Plant

Staggered PL.
Array
Full Height
for
Mock A.H.
Resistance Simul.

Yields .725 psi
pressure drop

— PLAN VIEW —

1 SQ. = 1'-0

Figure 17 Ceramic Air Heater Tube Bundle Geometry

Figure 18 Velocity Distribution at Horizontal Cut (22.5 ft From Top of Heat Exchanger)

accessibility is maintained, and the design of the ceramic air heater is somewhat decoupled from the rest of the HITAF. Two interfaces then have to be considered—the hot air piping to and from the ceramic air heater modules and the connection of the flue gas passages to the rest of the HITAF.

RM Engineered Products makes expansion joints for the utility industry, and they have done a preliminary design for our system. The main difference between our application and more-conventional applications is the temperature of our flue gas. To limit the temperature of the fabric seal to acceptable levels, the joints are designed to shield and insulate the fabric. Also, the furnace has been designed for negative pressure so any leakage will be into the unit. Figure 19 shows how the expansion joint will be situated around the ceramic air heater modules. A continuous fabric seal will be located along the vertical and horizontal sides of the stacked modules. Figure 20 shows the construction along the vertical sides of the air heater modules. The tubewalls of the HITAF are formed into a corner that offers a pocket for the pillow insulation blocks. The cooled tubewalls provide temperatures at the seal that are typical of other applications. A horizontal seal between the ceramic air heater modules is also needed. This seal is shown in Figure 21. Because there are no tubewalls, extra insulation is needed to lower the temperatures.

Figure 19 Typical Elevation View of Ceramic Air Heater Expansion Joint—Intersection of Vertical Seal With Seal Between Modules

Figure 20 Sectional View of Typical Ceramic Air Heater Expansion Joint—Typical Through Vertical Sides

Figure 21 Sectional View of Typical Ceramic Air Heater Expansion Joint—Typical Between Air Heater Modules

Bechtel has performed stress analyses of the high-temperature air piping, including the following lines:

- Compressor to recuperator
- Primary air heater to ceramic air heater
- Recuperator to primary air heater
- Ceramic air heater to gas turbine

None of the lines presented any unusual stress problems except these from the primary air heater, to the ceramic air heater where, with 1400°F air, several options of piping design are possible:

- Refractory-lined carbon steel pipe at 170°F
- Refractory-lined carbon steel pipe at 230°F
- Unlined stainless steel pipe
- Unlined stainless steel pipe with expansion joints

These different options were analyzed, and the stainless steel pipe with expansion joints was selected as the best option. Even with refractory-lined pipe, the lines from the primary air heater to the ceramic air heater would require expansion loops with approximately 20-ft-long legs. The stainless steel pipe with expansion joints required only a 12-ft horizontal run, and this option should also be lower in cost. Figure 22 shows a possible arrangement of this piping.

Figure 22 Piping Arrangement for Run Between Primary Air Heater and Ceramic Air Heater

Subtask 3.18—Ceramic Air Heater Analysis

One of the key structural concerns for the ceramic air heater is the generation of thermal stresses caused by differential thermal expansion between tubes joined to the same manifold. Tubes at different average temperatures will expand to different lengths, resulting in stress loading at tube-to-manifold junctions. The stresses will be distributed between the tubes and the inlet and outlet manifolds.

Each header/tube module has 3 rows of tubes in the gas flow direction and 20 rows of tubes in the no-flow direction (Figure 23). The normal heat-transfer process results in tubes in the gas flow direction being at different temperatures. Preliminary structural analysis of this situation was presented in Quarterly Report 6 [8].

For a uniform flow distribution in the no-flow direction, the no-flow tubes would all be at the same temperature in a given gas flow row. However, the proposed gas ducting arrangement, shown in Figure 24, will result in some level of flow maldistribution in the no-flow direction because of the relatively small turning radius upstream of the heat exchanger. The flow distribution analysis is discussed in Subtask 3.14.

Instead of the actual flow distribution, a linearly varying flow distribution was imposed in the no-flow direction. The flow velocity was allowed to vary by a factor of three across the heat exchanger face of one header/tube module stack (there are two module stacks across the 15-ft width of the gas duct, shown by the dashed line in Figure 24).

To determine the effects of the flow maldistribution on tubewall temperature and performance, the ASE tubular heat exchanger performance prediction computer code BUNDLE was run over the flow-rate spectrum. The calculations were based on the prior heat exchanger design, with a gas inlet temperature of 3100°F and an average gas flow rate of 821,160 lb/h. Heat exchanger performance is summarized in Table 1.

As indicated in the table, the assumed flow distribution results in a significant variation in air outlet temperature across the heat exchanger face. However, the mixed mean outlet temperature is 1792°F—only a minor degradation in performance from the uniform flow outlet temperature of 1800°F. The gas pressure drop shown in Table 1 represents the pressure drop that must exist to produce the gas flow rate profile.

The tubewall temperatures were predicted using the ASE computer program HO400. This code produces a complete temperature map of the heat exchanger surfaces. It was run for the temperature conditions shown in Table 1. A temperature map of the heat exchanger for the nonuniform flow conditions was derived by combining the outputs of the various HO400 runs.

This temperature map was used as input to the structural analysis. Only the first (hottest) module in the gas flow direction was analyzed. Stresses in the colder modules were assumed to be less severe. The average tube temperature varied from 1782 to 2166°F in the module. To isolate the effects of flow maldistribution, thermal loads alone were considered (no internal

Figure 23 Flow Direction

Figure 24 Plan View of Proposed Gas Duct

Table 1 Ceramic Air Heater Flow Variation

Gas Flow Rate + Average Gas Flow Rate	Outlet Air Temperature, °F	Effectiveness	Gas Pressure Drop, psi
0.5	1637	0.848	0.15
0.7	1709	0.789	0.29
0.9	1772	0.738	0.45
1.0	1800	0.715	0.56
1.1	1827	0.693	0.68
1.3	1876	0.654	0.95
1.5	1921	0.620	1.26

pressure or self-weight loads). The manifold boundary conditions include spring mounting (metallic bellows) and typical values for sliding friction in the supports.

The structural analysis was conducted in two parts. First, a coarse-grid ANSYS model of an entire module was run. This model, discussed in Quarterly Report 6 [8], is shown in Figure 25.

Predicted stresses are shown in Figure 26. These are maximum principal tensile stresses on an element basis. The stresses presented in Quarterly Report 6 [8] were nodal stresses. These nodal stresses are considerably higher than the element stresses because of the point loading of the beam elements used to model the tubes. The coarse-grid model loads are summarized in Figure 27. Tensile loads are positive, and compression loads are negative. The maximum tensile loads are at the open duct end of the inlet manifold region.

The tube loads and displacements resulting from this model were input, along with the temperatures, to a fine-grid ANSYS model of the tube-to-manifold junction region of six tube ends. This model, shown in Figure 28, comprises around 7800 nodes. The model can be used to represent any location along the identically sized inlet or outlet manifolds. The fine grid model temperature distribution is shown in Figure 29.

The predicted stresses are shown in Figure 30. The maximum principal tensile stresses of the element are shown. Maximum principal stresses are generally used for ceramic structural analysis rather than von Mises stresses because ceramics are much stronger under compression than under tension. Element stresses are used by the probabilistic life prediction code. The peak predicted maximum principal stress is around 12.2 ksi. As shown in the expanded view presented in Figure 31, the peak stresses exist at the tube-to-manifold junction. The tube and cruciform fin stresses are shown in Figures 32 and 33 respectively. These stresses are much smaller than the manifold junction stresses.

Typical characteristic strengths for the baseline material, sintered alpha-silicon carbide, are in the 40- to 50-ksi range at operating temperatures. Life predictions for structural ceramics generally require a statistical analysis approach. For reasonable survival probability, the peak stress must be low with respect to the characteristic strength. A favorable situation resulting from the stress fields (see Figures 30 and 31) is the highly localized nature of the peak stress, resulting in a higher probability of survival compared with a broader stress field at the same peak value.

The results of the structural analysis will be used as inputs to determine the probability of survival of the ceramic air heater. The computer code CARES (Ceramics Analysis and Reliability Evaluation of Structures) from NASA-Lewis Research Center will be used. This code uses stress results directly from ANSYS to evaluate component reliability caused by inherent flaws.

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Figure 25 Ceramic Air Heater Module Model

Figure 26 Coarse-Grid Maximum Principal Tensile Stresses (psi)

INPUT TO FINE-GRID MODEL

Tube \ Row	1	2	3
1	416	1372	887
2	-92	889	309
3	-582	523	-214
4	-1127	104	-776
5	-822	394	-486
6	-638	528	-315
7	-560	558	-249
8	-572	511	-273
9	-504	545	-208
10	-511	513	-217
11	-445	552	-180
12	-439	540	-202
13	-382	582	-152
14	-361	600	-139
15	-365	608	-154
16	-389	628	-188
17	-285	462	-103
18	-189	313	-29
19	-89	167	46
20	19		125

Tube 1 is closest to the manifold ducts. The tube cross flow goes from row 1 to row 3.

Figure 27 Coarse-Grid Model Loads (lb)

Figure 28 Fine-Grid Model

Figure 29 Fine-Grid Model Temperatures (°F)

Figure 30 Fine-Grid Maximum Principal Tensile Stresses (psi)

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Figure 31 Manifold Maximum Principal Tensile Stresses (psi)

Figure 32 Maximum Principal Tensile Tube Stresses (psi)

Figure 33 Maximum Principal Tensile Cruciform Fin Stresses (psi)

Subtask 3.21 — Pollution Control Systems

A technology for FGD system sulfur recovery has recently been tested at Lawrence Berkeley Labs under a DOE contract. Dr. S. G. Chang is the principal investigator. The process uses coal gas to reduce the SO_2 produced by a regenerable FGD system to elemental sulfur. This process uses a catalyst, and the development of this catalyst was the object of the DOE-sponsored project.

To use the process with our system, 5 percent of the fuel gas must be used for SO_2 reduction. The process would use up the H_2 and CO but leave the CH_4 . This gas could then be returned to the fuel gas stream before combustion. Some H_2S and COS are added to the fuel gas, but this addition can be handled by the FGD system. The hot water from the sulfur condenser would have to go somewhere also. Figure 34 shows how this would work and gives a mass balance.

The estimates for utility and raw material use were updated to reflect the July 1993 plant heat and material balance and the substitution of the Chang catalyst for a Claus sulfur system. These revised values are given in Figure 35.

The DOE has decided to proceed with the disassembly of the SOXAL pilot unit at Niagara Mohawk's Dunkirk Station. This decision was based upon the facts that the need to test this pilot system for the HITAF program was not demonstrated and that additional costs would be incurred as a result of delaying its disassembly. The component parts of the SOXAL system, such as the soda ash scrubber, remain available to the HITAF program. The Tung system is currently undergoing testing at Dunkirk Station.

The high-temperature filter vendors identified in Table 2 have been contacted and asked to report on the expected performance of their filter media when applied to the fuel gas conditions. To date, three vendors have responded positively in writing and two others have verbally expressed their intent to respond. When all the information is received, the different materials will be compared. Owens Corning, the supplier of the fiberglass media, has indicated that their fiberglass is not appropriate for the fuel gas cleanup application.

Subtask 3.27 — Char Combustor Analytical Modeling

Introduction. Char combustor analytical modeling is being performed during this project to support both the conceptual design of the commercial char combustor and the char combustor test planning being done in Task 5. Preliminary thermodynamic and char oxidation calculations were previously performed to assess the impact of the lower volatile content of the fuel on combustor operating conditions, particle size requirements, and combustor design [9]. Although these calculations were important for determining the feasibility of the proposed approach, more-detailed char combustor calculations are required to support conceptual design and test planning. TRW's Coal Combustor Engineering Program (CCEP) is being utilized for this purpose.

STREAM NO.

- 1 STEAM STRIPPED SO₂ FROM FGD**
- 2 FUEL GAS FROM PYROLYZER**
- 3 MIXTURE OF 1 & 2**
- 4 SO₂ CONVERTED TO S₂ VAPOR**
- 5 CONDENSIBLES REMOVED - RETURN TO FUEL GAS SYSTEM**
- 6 CONDENSATE - SULFUR AND WATER**

Item	Stream Number (Mass Flows in lb/h)					
	1	2	3	4	5	6
Sulfur		0	0	2,997	0	2,997
CH ₄		146	146	146	146	
CO		3,151	3,151	0	0	
H ₂		231	231	0	0	
CO ₂		2,856	2,856	7,793	7,793	
H ₂ O	6,309	1,607	7,916	9,890	550	9,340
N ₂		9,325	9,325	9,325	9,325	
H ₂ S		10	10	200	200	
COS		0	0	19	19	
SO ₂	6,309	0	6,309	126	126	
NH ₃		23	23	23	23	
Temp., °F	200	1,700	875	875	150	150
Press., psia	30	30	30	30	30	30
Total, lb/h	12,618	17,349	29,967	30,519	18,182	12,337

Figure 34 FGD System Sulfur Recovery Based on Chang Catalyst

Box	Kilowatts
1	59
2	338
3	1800
4	450
5	158
6	95
7	95

Arrow	Material	Flow
1	Urea, lb/h	593
2	Soda Ash, lb/h	252
3	Makeup Water, gal/min	135
4	Cooling Water, gal/min	1157
5	LP Steam, lb/h	6309
6	Fuel Gas, lb/h	17665
7	Cooling Water, gal/min	147
8	Limestone, lb/h	315
9	LP Steam, lb/h	5678

Figure 35 Pollution Control System Utilities and Materials

Table 2 High-Temperature Filter Media

Filter Media Type	Material	Temperature, °F	Supplier
Sintered metal fiber	Inconel	1200	Memtec America
Woven ceramic	Alumina silicate	1400	3M
Sintered ceramic granules	Silicon carbide	1800	Pall
Sintered ceramic fibers	Alumina silicate	1400	BWF America
Woven fiberglass	D-fiber glass	> 1000	Owens-Corning
Ceramic honeycomb barrier	Cordierite	1800	CeraMem

The key operating and performance issues related to the char combustor are flame stability, carbon burnout, and NO_x emissions. To support the conceptual design of the char combustor, these issues are being addressed through a combination of empirical correlations, experimental tests, and analytical modeling. Much research has been performed on the combustion and emissions characteristics of a variety of U.S. coals under different operating conditions, and these data are available to support this project. To complement these data, char characterization testing was performed at BYU to provide data on the proposed char. The primary objective of the char characterization tests was to provide data on char oxidation rates, nitrogen and sulfur release, and char morphology. These data, along with applicable char and nitrogen kinetic data from previous studies, are being utilized by the CCEP computer model to support the conceptual design of the char combustor.

Modeling Objectives. The primary objectives of analytical modeling activity for the char combustor are to characterize the baseline performance of the char combustor and to define the design and operating envelope. As discussed earlier, initial char combustor design and operating conditions were determined based on preliminary analysis. Key char combustor operating conditions and internal dimensions are listed in Tables 3 and 4 respectively.

To characterize baseline performance, the following parameters, at a minimum, must be determined:

- Combustor emissions (NO_x, SO₂, particulates)
- Combustor heat fluxes and overall cooling load
- Sectional and overall carbon burnout
- Pressure drop
- Gas temperatures and compositions
- Slag recovery rates.
- Flow velocities

Table 3 Summary of Combustor Operating Conditions

Thermal Input, 10^6 Btu/h	
Coal	116
Char	448
Total	564
Precombustor	
Chamber Stoichiometry	0.8
Exit Stoichiometry	3.83
Exit Temperature, °F	2008
Cooling Load, 10^6 Btu/h	3.5
Char Combustor	
Stoichiometry	0.8
Exit Temperature, °F	3170
Cooling Load, 10^6 Btu/h	92
Total Heat to Steam Cycle, 10^6 Btu/h	96

Table 4 Summary of Char Combustor Dimensions

Precombustor	
Primary Windbox Diameter (in.)	84
Secondary Windbox Diameter (in.)	120
Combustion Chamber Diameter (in.)	60
Overall Precombustor Length (in.)	180
Slagging Stage	
Chamber Diameter (in.)	105
Chamber Length (in.)	185
Number of Injectors	6 to 8
Incline Angle (deg)	15
Slag Recovery Section	
Chamber Diameter (in.)	105
Chamber Length (in.)	185
Exhaust Duct	
Width (in.)	84
Length (in.)	84
Height (in.)	160

Furthermore, it is important not only to characterize the combustor performance at a single design point, but also to characterize operation and performance over the expected operating envelope. Some of the key operating parameters that have been (or are being) varied during parametric calculations include:

- Air preheat temperature and oxygen composition
- Precombustor exit temperature (and coal requirements)
- Combustor stoichiometry
- Char particle size
- Char composition and heating value
- Ash properties.

Finally, analytical model calculations are being used to determine optimum combustor internal dimensions, as well as the allowable design envelope. Some of the key design parameters that have been varied in support of the conceptual design include:

■ Chamber diameter	■ Slag baffle diameter
■ Chamber length	■ Injector diameter and positioning
■ Air inlet positioning	■ Slag tap size
■ Air inlet flow area	■ Slag recovery section and exhaust duct dimensions

Model Description. TRW's CCEP is a proprietary in-house code that models the aerodynamic and combustion processes associated with TRW's family of solid fuel combustors. The model focuses on the slagging stage of the combustor, since this represents the heart of the combustor.

A simple schematic of the slagging stage of the combustor is shown in Figure 36. In the slagging stage, pulverized solid fuel is injected in dry or slurry form in the head-end region into a highly turbulent, confined vortex flow. The solid fuel particles undergo rapid heating, vaporization, devolatilization, and char oxidation. Following combustion, the residual ash particles form molten droplets that are centrifuged to the outer walls of the combustion chamber, forming a self-replenishing, thermal insulating layer. The slag flows under the combination of shear and gravity forces to a slag tap downstream of a slag baffle, where it is

Figure 36 Char Combustor Analytical Model Geometry and Zone Definition

quenched in a water-filled tank. The gaseous products of combustion are exhausted into a steam-cooled radiant furnace, where additional oxidizer is added under controlled conditions to minimize NO_x emissions.

The CCEP computer program models:

■ Slagging-stage aerodynamics	■ Wall combustion
■ Particle trajectories (both char and residual ash particles)	■ Radiant and convective wall heat fluxes
■ Gas recirculation and mixing zones	■ NO_x formation and destruction
■ Particle heating and devolatilization	■ Slag flow
■ In-flight char oxidation	

The model can be described as quasi one-dimensional, with multiple combustion zones. Combustor flow profiles are based on extensive cold flow modeling performed at TRW. Particle trajectories are determined based on the resultant drag and centrifugal forces acting on the particles at various locations within the combustor. The model takes into account the decrease in particle diameter as combustion proceeds. To model particle heating and devolatilization,

convective heat transfer from the gas to the particle is determined. To determine char oxidation rates in oxidizer-rich regions, a model similar to that described by Hurt [10,11] is used. For substoichiometric char oxidation, oxidation is by H_2O and CO_2 and is chiefly limited by convective and radiative heat transfer from the gas to the particle. Wall combustion rates are determined using a two-film model. NO_x formation and destruction are determined in each combustion zone using a global model to track the major species of importance: NO , NH_3 (amines), and HCN . Slag layer thickness is determined based on calculated wall deposition rates, incident heat fluxes, and applied shear and gravity forces.

As indicated in Figure 36, the slagging-stage model is divided into two major zones: the head-end and mixing zones. In the head-end region, fuel particle trajectories are determined based on fuel injector parameters and the combustor flow field. A portion of the total fuel enters the head-end recirculation zone, which typically operates under fuel-lean conditions. The oxidizer flow entering the slagging stage from the precombustor is assumed to be fully reacted, although this assumption can be relaxed. Both in-flight and wall combustion rates are determined. Gas temperatures and compositions are determined across the flow field according to the level of mixing and combustion.

In the mixing region, gas mixing, particle radial drift, and char oxidation are determined as a function of axial distance. As in the head-end zone, both in-flight and wall combustion rates are calculated.

Selected output from the program includes:

■ The amount of devolatilization and char oxidation occurring in each zone	■ Gas temperatures and compositions (including NO , HCN , NH_3)
■ Overall carbon burnout	■ Slag layer thicknesses
■ Wall heat fluxes	■ Combustor pressure drops
■ Wall deposition rates	■ Slag recovery rates

Baseline Performance Characterization. CCEP baseline model calculations were performed for a char combustor firing rate of 282×10^6 Btu/h. Key model assumptions and results are summarized in Table 5. The fuel was assumed to be pyrolyzed char from a Pittsburgh No. 8 coal, with a median particle size of 60 microns. This particle size corresponds to a 60 percent through 200 mesh coal grind. An air preheat temperature of $1130^\circ F$, corresponding to the baseline heat and material balance, was assumed. Pulverized Pittsburgh No. 8 coal is fired in the precombustor to raise the air temperature from $1130^\circ F$ to $2000^\circ F$. The slagging-stage stoichiometry was assumed to be 0.8, also consistent with the baseline heat and material balance. Additional air is added downstream in the furnace to complete combustion of the gaseous products from the char combustor.

Table 5 Baseline Char Combustor Analytical Modeling Results

Key Assumptions	
■ Pittsburgh No. 8 Char	■ Air Preheat Temperature = 1130°F (19% O ₂)
■ Firing Rate = 282 x 10 ⁶ Btu/h	■ Precombustor Exit Temperature = 2000°F
■ Median Particle Size = 60 microns	■ Slagging-Stage Stoichiometry = 0.8
Results	Pittsburgh No. 8 Char
■ Fraction of coal devolatilized in head-end region	0.999
■ Fraction of char consumed on wall in head end	0.254
■ Total fraction of char oxidized in head-end region	0.910
■ Fraction of total fuel consumed in head-end region	0.919
■ Gas temperature at head-end wall	3094°F
■ Gas temperature at head-end exit	2378°F
■ Fraction of total coal consumed in slagging stage	0.9898
■ Gas temperature at baffle	3437°F

Key results from the baseline performance calculations are also summarized in Table 5. For the base case, 99.9 percent of the available volatiles, including the low-Btu carrier gas, is burned within the head-end region of the combustor. In the head-end region, 91 percent of the char is oxidized, with 65 percent of the char oxidized in flight and 25 percent of the char oxidized along the head-end wall. An overall carbon burnout of 99 percent is predicted at the exit of the slagging stage.

Preliminary char combustor model parametric calculations were presented in Quarterly Report 7 [9], including curves which showed the effect of combustor stoichiometry, particle size, and combustor size. In this Quarterly Report, a number of additional parametric cases are

presented, including a comparison of char-fired and coal-fired performance, the effect of increasing the combustor head-end length, the effect of particle size on combustion performance at different scales, and the effect of combustor stoichiometry on NO_x emissions.

Comparison of Char-Fired and Coal-Fired Performance. Figure 37 shows the effect of combustor stoichiometry on carbon burnout for both Pittsburgh No. 8 coal (35 percent ASTM volatile matter) and Pittsburgh No. 8 char produced by the FWDC pyrolyzer (nominally 5 percent ASTM volatile matter). A significant difference in performance is noted at low stoichiometry—the result of a low operating temperature and reduced oxygen availability during char oxidation. However, at a stoichiometry of 0.8, the difference is much smaller because of higher in-flight char oxidation rates in the head-end of the combustor as well as increased char oxidation along the walls of the combustor. At a stoichiometry of 0.8, an overall carbon burnout of 99.3 percent is predicted for Pittsburgh No. 8 coal, while a carbon burnout of 99.0 percent is predicted for the Pittsburgh No. 8 char.

Figure 37 Effect of Combustor Stoichiometry and Volatile Content on Overall Carbon Burnout

Effect of Combustor Head-End Length. Parametric calculations were performed to assess the impact of an increased combustor head-end length on overall combustor performance and carbon burnout. Because of the lower volatile content of the proposed char, a greater portion of char oxidation occurs along the walls of the combustor, relative to a higher-volatile coal. By increasing the available wall surface area within the head-end of the combustor, additional char can be burned in this region, resulting in an increase in overall carbon burnout.

The results of the parametric calculations are shown in Table 6. The table shows the effects of both a decrease and an increase in the combustor head-end length, relative to the baseline case. As the head-end length is increased, the percentage of char oxidized on the head-end wall increases from 19.1 to 30.9 percent. The corresponding overall carbon burnout increases from 98.5 to 99.4 percent.

Selection of Char Particle Size for Subscale Testing. Results presented in Quarterly Report 7 indicated a significant decrease in carbon burnout and a corresponding increase in carbon losses as the combustor is sized down to development scale [9]. This change is primarily the result of a reduction in char particle residence time at the smaller scale. To compensate for this effect during subscale testing, the char particle size can be reduced, shortening the required residence time for burnout.

Figure 38 shows predicted carbon loss for both a 30×10^6 Btu/h subscale char combustor and a 282×10^6 Btu/h full-scale char combustor as a function of median particle diameter. For the full-size char combustor (105 in. chamber diameter), a median particle size of 60 microns or less is required to lower carbon losses below 1 percent. This size corresponds to a particle size distribution in which approximately 60 percent of the material passes through a 200-mesh screen. If the same particle size distribution were used for subscale tests, the corresponding carbon losses would be on the order of 4 to 6 percent. To simulate full-scale combustor performance during the subscale tests, a median particle diameter of 36 microns is required, which would allow approximately 80 percent of the material to pass through a 200-mesh screen.

Effect of Combustor Stoichiometry on Combustor NO_x Emissions. Char combustor analytical model calculations were also performed for the purpose of predicting combustor NO_x emissions. The NO_x submodel has been successfully used to predict NO_x emissions for TRW's 40×10^6 Btu/h combustor for a variety of coals.

The most important combustor design and operating parameter for NO_x emissions is slagging-stage stoichiometry. Based on both theoretical considerations and actual operating experience, there exists an optimum stoichiometry range in which NO_x emissions can be minimized. For Pittsburgh No. 8 char produced by the FWDC pyrolyzer, this optimum range is 0.75 to 0.85, as shown in Figure 39. Within this range, combustor NO_x emissions below $0.25 \text{ lb}/10^6 \text{ Btu}$ are predicted by the model. At higher stoichiometries, increased operating temperatures and oxygen concentration combine to yield high levels of NO. At lower stoichiometries, excessive amounts of NO_x precursors, such as HCN and NH_3 , are produced. These NO_x precursors are readily oxidized to NO when additional air is added within the furnace.

Table 6 Effect of Head-End Length on Carbon Burnout

Key Assumptions			
<ul style="list-style-type: none">■ Pittsburgh No. 8 Char■ Firing Rate = 282×10^6 Btu/h■ Median Particle Size = 60 microns■ Air Preheat Temperature = 1130°F (19% O₂)■ Precombustor Exit Temperature = 2000°F■ Slagging-Stage Stoichiometry = 0.8			
Results	Reduced Head-End Length	Baseline Head-End Length	Increased Head-End Length
■ Head-end length (normalized)	0.65	1.0	1.35
■ Fraction of char burned on head-end wall	0.191	0.255	0.309
■ Fraction of char burned in flight in head end	0.668	0.657	0.633
■ Fraction of char burned in head end	0.859	0.912	0.942
■ Total char burned in slagging stage	0.982	0.988	0.992
■ Total char consumed in slagging stage	0.985	0.990	0.994

Figure 38 Effect of Combustor Size and Char Particle Size on Combustor Carbon Losses

Figure 39 Char Combustor Baseline NO_x Model Prediction

The preferred combustor operating point is slightly to the right of the predicted minimum. This point allows a favorable trade-off between low NO_x emissions and high carbon burnout (greater than 99 percent, as shown in Figure 37).

Subtask 3.29—Preliminary Design of Gas Turbine Piping

GE gas turbines, like most gas turbines, are not designed for the combustion air to be taken off the machine and then returned at a higher temperature. Design modifications to accomplish this type of operation are being developed. The objective is to achieve the required results with as few changes to the gas turbine as possible.

The 7F gas turbine, which is the basis for the 290-MWe plant, has 14 combustors. The design of these combustors is such that the combustion air cools the walls of the combustion chambers. The design of a typical combustion chamber is shown in Figure 40. The combustion air goes through an annulus that surrounds the combustion chamber and cools the wall by convection and transpiration. To minimize changes to the gas turbine, air take-off and return must be designed to achieve this cooling.

In Quarterly Report 7, two possible designs for the gas turbine piping were presented [12]. After further analysis, the toroidal-shaped manifold was selected. This arrangement is shown in Figure 41.

The toroidal arrangement reduces the length of the concentric pipes and makes all the pipes identical. In this design, the concentric pipes continue out axially and slightly canted from the combustion chambers. The compressor discharge air in the annular spaces is collected in the first (cold) toroidal header. The center pipes go through this header and collect in a second (hot) toroidal header. The hot toroidal header is where the 1800°F air from the HITAF is split into the 14 separate pipes.

Task 4—Commercial Generating Plant Design

Subtask 4.9—Plant Performance

The latest heat and material balance is shown in Table 7. This balance includes revisions that were made since the July 1993 balance. The main changes were in the areas of recuperator performance, pressure drops, auxiliary power requirements, and drum modeling.

In the previous heat and material balance, the recuperator had an assumed efficiency of over 90 percent. Although this efficiency is achievable, it is considered impractical because of the large amount of surface area that would be needed. In the current heat and material balance, the recuperator efficiency is approximately 80 percent, which is well within the range of common practice.

Figure 41 Toroidal Manifold Gas Turbine Piping Arrangement

Table 7 NG-HITAF (Based on GE Turbine Balance)

Stream No.		1		2		3		4		5		6		7	
Stream		Coal to Carbonizer		V. Air to Carbonizer		Sorbent to Carbonizer		Char to Carbonizer		Fuel G. to Carbonizer		Fuel Gas to Combust		V. Air to Combust	
		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
Carbon		71.92%	69,379					90.41%	26,538						
Hydrogen		4.69%	4,524					0.38%	167						
Oxygen		6.33%	6,102												
Nitrogen		1.26%	1,212					1.06%	464						
Sulfur		2.99%	2,867					1.00%	440						
Solids lb/hr	Ash	10.32%	9,955			0.95%	90	22.67%	10,045						
	Moisture	2.50%	2,411			2.00%	188								
	CaCO ₃					95.60%	9,006								
	MgCO ₃					1.55%	148								
CaO								2.26%	995						
MgO								0.16%	70						
CaS								11.99%	5,212						
CaSO ₄															
CH ₄										1.32%	4,355	1.32%	4,326		
C ₂ H ₄															
C ₂ H ₆															
C ₃ H ₈															
CO										21.77%	72,096	21.77%	71,616		
Gases lb/hr	H ₂									1.18%	3,918	1.18%	3,892		
	CO ₂			2.57%	6,523					12.28%	40,851	12.28%	40,382	2.57%	14,431
	H ₂ O		15,808	2.88%	7,299					5.22%	17,294	5.22%	17,179	2.88%	16,147
	O ₂			19.07%	48,409									19.07%	107,100
	N ₂			74.21%	188,381					57.07%	188,999	57.07%	187,745	74.21%	416,726
	H ₂ S									0.04%	140	0.04%	139		
COS															
SO ₂															
C ₆ H ₆ +															
Argon				1.27%	3,213					0.97%	3,213	0.97%	3,192	1.27%	7,108
NH ₃										0.16%	516	0.16%	513		
NO ₂															
Total Gas, lb/hr		100.00%	112,075	100.00%	253,804	100.00%	9,431	100.00%	43,930	100.00%	331,171	100.00%	328,974	100.00%	561,513
					8,790						13,454		13,384		19,447
					28.67						24.62		24.62		28.87
Pressure, psia			43.40		32.34		34.40		29.40		29.40		21.40		15.30
Temperature, °F			70.00		350.00		70.00		1,700.00		1,700.00		1,200.00		870.50
Temperature, °C			21.11		176.67		21.11		928.87		928.87		648.89		465.83
Sens. Heat, MM Btu/hr			2.62		19.94		0.02		16.74		175.84		117.60		115.23
Lat. Heat, MM Btu/hr			16.39		7.96						18.16		18.04		16.95
LHV, Btu/lb			12,454.70						9,502.07		1,852.34		1,852.34		
HHV, Btu/lb			12,916.96						9,536.02		2,042.65		2,042.65		
LHV, MM Btu/hr			1,201.47						417.43		613.44		609.37		
HHV, MM Btu/hr			1,245.96						418.92		676.46		671.96		
Total Energy, LHV			1,204.28		19.94		0.02		436.17		789.28		728.97		115.23
MM Btu/hr, HHV			1,265.17		27.90		0.02		437.67		870.48		807.62		132.18

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
Date: February 1994

Table 7 (Cont) NG-HITAF (Based on GE Turbine Balance)

[illegible]

Table 7 (Cont) NG-HITAF (Based on GE Turbine Balance)

Stream No.		16	17		18		19		20		21		22		23		
		Net Gas to GT Comb.		FG to GT Combustor		Gas to Recuperator		Gas to Recuperator		Coal to Precomb.		Char to Char Comb.		Prim. Air to Char C.		Sec. Air to Char C.	
Stream		%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr
	Carbon									71.92%	6,482	57.53%	28,538				
	Hydrogen									4.89%	423	0.36%	187				
	Oxygen									6.33%	570						
	Nitrogen									1.26%	113	1.01%	464				
	Sulfur									2.99%	270	0.95%	440				
Solids	Ash									10.32%	930	21.78%	10,045				
Btu	Moisture									2.50%	225						
	CaCO3																
	MgCO3																
	CaO											2.16%	995				
	MgO											0.15%	70				
	CaS											11.30%	5,212				
	CaSO4																
	CH4	100.00%	30,701									0.06%	29				
	C2H4																
	C2H6																
	C3H8																
	CO											1.04%	478				
Gases	H2											0.06%	28				
Btu	CO2			3.32%	85,427	2.57%	75,347	2.57%	75,347			0.58%	270	2.57%	10,440	2.57%	5,220
	H2O			3.48%	88,788	2.88%	84,309	2.88%	84,309			0.25%	115	2.88%	11,882	2.88%	5,841
	O2			17.93%	481,804	19.07%	558,182	19.07%	558,182					19.07%	77,481	19.07%	38,741
	N2			74.01%	1,906,978	74.21%	2,175,814	74.21%	2,175,814			2.72%	1,254	74.21%	301,480	74.21%	150,740
	H2S											0.00%	1				
	COS																
	SO2																
	C6H6+																
	Argon			1.26%	32,528	1.27%	37,114	1.27%	37,114			0.05%	21	1.27%	5,142	1.27%	2,571
	NH3											0.01%	3				
	NO2																
	Total Gas, Btu	100.00%	30,701	100.00%	2,578,801	100.00%	2,831,778	100.00%	2,831,778	100.00%	9,013	100.00%	48,127	100.00%	408,225	100.00%	203,113
			1,814		88,433		101,538		101,538						14,088		7,035
			18.04		28.81		28.87		28.87						28.87		28.87
	Pressure, psia		250.00		189.70		18.00		15.30		16.00				16.00		
	Temperature, °F		200.00		2,590.70		1,137.70		870.50		60.00		1,700.00		1,137.70		870.50
	Temperature, °C		93.33		1,421.50		614.28		485.83		15.56		928.87		614.28		485.83
	Sens. Heat, MM Btu/hr		2.38		1,817.13		812.82		801.83		0.00		24.88		112.84		41.88
	Lat. Heat, MM Btu/hr				84.25		88.52		88.52						12.27		6.13
	LHV, Btu/lb		21,502.00								12,454.70		9,137.78				
	HV, Btu/lb		23,881.00								12,915.98		9,179.19				
	LHV, MM Btu/hr		680.13								112.28		421.50				
	HV, MM Btu/hr		732.58								118.41		423.41				
	Total Energy, LHV		682.82		1,817.13		812.82		801.83		112.28		448.48		112.84		41.88
	Total Energy, HV		734.94		1,911.38		901.45		890.15		118.42		448.39		124.90		47.81

FOSTER WHEELER DEVELOPMENT CORPORATION

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Table 7 (Cont) NG-HITAF (Based on GE Turbine Balance)

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
Date: February 1994

Stream No.		24		25		26		26 A		27		28		29		30	
		FG to DSH #1-A		Sing In Char Comb.		FG to SH #3		FG to Air Hr.		Tot Gas to Air Hr.		F. Gas to Air Hr.		Dirty FG to FGD		Clean FG to LP Econ	
Stream		%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr	%wt	Btu/hr
Solids	Carbon																
	Hydrogen																
	Oxygen			3.40%	577												
	Nitrogen																
	Sulfur																
	Ash			64.62%	10,975												
	Molture																
	CaCO ₃																
	MgCO ₃																
	CaO			23.21%	3,942												
Gases	MgO			0.41%	70												
	CaS			8.36%	1,421												
	CaSO ₄																
	CH ₄																
Gases	C ₂ H ₄																
	C ₂ H ₆																
	C ₃ H ₈																
	CO																
	H ₂																
	CO ₂	21.28%	137,751			21.28%	137,751	21.28%	137,751	20.61%	316,956	20.61%	316,956	20.61%	316,956	2.57%	55,886
	H ₂ O	3.38%	21,843			3.38%	21,843	3.38%	21,843	6.55%	100,654	6.55%	100,654	6.55%	100,654	2.88%	82,321
	O ₂	3.34%	21,629			3.34%	21,629	3.34%	21,629	2.46%	37,783	2.46%	37,783	2.46%	37,783	19.07%	413,351
	N ₂	70.08%	453,473			70.08%	453,473	70.08%	453,473	68.80%	1,057,944	68.80%	1,057,944	68.80%	1,057,944	74.21%	1,808,348
	H ₂ S																
Gases	CO ₂																
	SO ₂	0.74%	4,786			0.74%	4,786	0.74%	4,786	0.33%	5,048	0.33%	5,048	0.33%	5,048		
	C ₂ H ₆ +																
	Argon	1.18%	7,714			1.18%	7,714	1.18%	7,714	1.17%	18,014	1.17%	18,014	1.17%	18,014	1.27%	27,434
	NH ₃																
	NO ₂	0.00%	0			0.00%	0	0.00%	0	0.00%	1,385	0.00%	1,385	0.00%	1,385		
	Total Gas, Btu	100.00%	647,305	100.00%	16,985	100.00%	647,305	100.00%	647,305	100.00%	1,537,802	100.00%	1,537,802	100.00%	1,537,802	100.00%	2,167,151
			21,287				21,287		21,287		51,845		51,845		51,845		75,068
			30.41				30.41		30.41		29.66		29.66		29.66		29.67
Gases	Pressure, psia		14.50		14.50		14.50		13.90		13.90		13.90		13.90		15.00
	Temperature, °F		3,234.90		2,400.00		2,715.00		1,888.00		1,903.00		1,311.00		208.90		130.00
	Temperature, °C		1,779.33		1,315.56		1,480.56		1,030.00		1,039.44		710.56		98.83		54.44
	Sens. Heat, MM Btu/hr		584.67		17.99		467.95		322.52		797.70		621.25		57.91		37.61
	Lat. Heat, MM Btu/hr		23.04				23.04		23.04		105.88		105.88		105.88		65.44
	LHV, Btu/lb																
	HHV, Btu/lb																
	LHV, MM Btu/hr																
	HHV, MM Btu/hr																
	Total Energy, LHV		584.67		17.99		467.95		322.52		797.70		621.25		57.91		37.61
Gases	HHV, MM Btu/hr		617.71		17.99		510.99		345.56		903.38		626.93		163.69		103.05

As the plant design has become more complete, work has been done to further refine the plant pressure drops and auxiliary power requirements. The data from this work have been included in the current heat and material balance.

The drum system is somewhat involved because of the distribution of evaporator surface among a few components of the system. The overall thermodynamics of the initial modeling in this area were correct, but some of the temperatures around the drum system were inaccurate. The model was improved to better represent drum system operation.

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