1 of 2

M-1
2
MAR 22 1994

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

RECEIVED
MAY 02 1994
OSTI

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DE-AC22-91PC91154

**Quarterly Progress Report 7
July through September 1993**

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

**FWDC Project 9-41-3492
November 1993**

FOSTER WHEELER DEVELOPMENT CORPORATION

12 Peach Tree Hill Road, Livingston, New Jersey 07039

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Contents

	<u>Page</u>
INTRODUCTION	1
PROJECT WORK	2
Task 1—Project	2
Task 2—Concept Definition and Analysis	2
Subtask 2.7—Define Cycle Analysis Model	2
Task 3—Preliminary R&D	4
Subtask 3.1—Analytical Determination of Pyrolyzer Yields	4
Subtask 3.2—Characterization of Ceramic Air Heater Gas-Side Environment	4
Subtask 3.8—Evaluation of Secondary Air Heater Corrosion	4
Subtask 3.10—Fuel Characterization Testing	23
Subtask 3.12—Preliminary Design of Topping Combustor	35
Subtask 3.21—Pollution Control System	35
Subtask 3.27—Char Combustor Analytical Modeling	42
Subtask 3.29—Preliminary Design of Gas Turbine Piping	63
Subtask 4.9—Plant Performance	69
Subtask 4.10—Pyrolyzer Subsystem Arrangement and Operation	73
Subtask 4.12—High-Temperature Furnace Design and Cost Estimate	86
Subtask 4.13—Char Combustor Design and Cost Estimate	88
Subtask 4.16—Power Island and Balance of Plant Cost Estimate	94
Subtask 4.17—Plant Arrangement	94
REFERENCES	101

Figures

<u>Number</u>		<u>Page</u>
1	Simplified Process Block Flow Diagram	3
2	Polished Cross Section of SA-SiC Sample After Ash Exposure (100 μ m)—Test Run 1	8
3	Specimens Coated With Pittsburgh No. 8 Ash Doped With Alkalies and Exposed at 1800°F in a Simulated Combustion Atmosphere for 500 hours	10
4	Specimens From Figure 3 With Ash Layer Coating Scraped Off	11
5	SA-SiC and SiC _p /Al ₂ O ₃ Specimens Exposed at 1800°F	13
6	Siliconized-SiC Mounted and Polished Specimens Exposed at 1800°F	14
7	Surfaces of SA-SiC Specimen Coated With High-Alkali Ash	15
8	Surfaces of Siliconized-SiC Specimen Coated With High-Alkali Ash	16
9	Cross-Section of SiC _p /Al ₂ O ₃ Specimen Coated With High-Alkali Ash, Along With an Unexposed Specimen	17
10	Specimens Coated With One of Three Ashes (Pittsburgh No. 8, Eagle Butte, or Illinois No. 6) and Exposed at 2300°F in a Simulated Combustion Atmosphere for 500 hours	18
11	Exposed Specimens Illustrated in Figure 10, After Scraping Off Any Friable Ash	19
12	Cross-Sectional Views of Mounted and Polished SA-SiC Specimens	20
13	Cross-Sectional Views of Mounted and Polished Siliconized-SiC Specimens	21
14	Cross-Sections of SiC _p /Al ₂ O ₃ Specimens Exposed at 2300°F	22
15	Schematic of Flat-Flame Burner System	25

Figures (Cont)

<u>Number</u>		<u>Page</u>
16	Schematic of the Flat-Flame Burner Assembly	26
17	Char Burnout vs. Distance in FFB for 330 Char and Parent Pittsburgh No. 8 Coal in 1800 K/5 mol% O ₂ Environment	29
18	N ₂ and CO ₂ Internal Surface Areas of the Parent Pittsburgh No. 8 Project Coal Compared With Literature Values for Other Coals	31
19	N ₂ and CO ₂ Internal Surface Areas of Project Chars Compared With Literature Values for Other Chars Immediately After Devolatilization	32
20	Apparent Densities of Coal and Char Samples From FFB Experiments	34
21	Topping Combustor Laboratory Testing	36
22	CO in Exit Gas vs. Exit Gas Temperature—Preliminary Data	37
23	NO _x in Exit Gas vs. Exit Gas Temperature—Preliminary Data	38
24	SO _x Emission vs. FGD System Efficiency	41
25	Resistivity of Char Ash	45
26	Pollution Control Flow System	46
27	Char Combustor Analytical Model Geometry and Zone Definition	52
28	Carbon Burnout as a Function of Combustor Length for Subscale and Commercial-Scale Char Combustors	56
29	Temperature Profile for Commercial-Scale Char Combustor	57
30	Temperature Profile for Subscale Developmental Char Combustor	58
31	Effect of Stoichiometry on Char Combustor Carbon Burnout	60

Figures (Cont)

<u>Number</u>		<u>Page</u>
32	Effect of Stoichiometry on Char Combustor Core Temperature Profile— Full Combustor Length	61
33	Effect of Stoichiometry on Char Combustor Core Temperature Profile— Head-End Region Only	62
34	Effect of Particle Size on Carbon Burnout in Commercial-Scale Char Combustor	65
35	Straight Manifold Gas Turbine Piping Arrangement	66
36	Toroidal Manifold Gas Turbine Piping Arrangement	67
37	Concentric Pipe Design	68
38	Pressures in High-Pressure Systems	71
39	Pressures in Low-Pressure Systems	72
40	Fuel-Gas Generation System	74
41	Pyrolyzer Riser Vessel	76
42	Pyrolyzer Primary Cyclone	78
43	Pyrolyzer Secondary Cyclone	79
44	Fuel Gas Cooler	80
45	Precombustor Coal Pulverizer System	83
46	Pyrolyzer Sorbent Pulverizer System	84
47	Pyrolyzer Coal Pulverizer System	85
48	High-Temperature Advanced Furnace	87
49	Sectional Side View of HITAF	89

Figures (Cont)

<u>Number</u>		<u>Page</u>
50	Proposed Char Combustor Configuration	92
51	Precombustor Flow Conditions	93
52	Slagging-Stage Flow Conditions	95
53	Effect of Adding Mill Air on Precombustor Exit Temperature and Coal Flow Requirements	96
54	Plant Layout—Gas Furnace Parallel to Char Furnace	98
55	Plant Layout—Ceramic Air Heaters Closely Coupled to Fuel Gas and Char Furnace	99
56	Plant Layout—Gas Turbine at 90-deg Angle to Fuel Gas Furnace	100

Tables

<u>Number</u>		<u>Page</u>
1	Flue Gas Composition for Ceramic Corrosion Tests	6
2	Ash Composition of Char/Sorbent Mixtures	6
3	Ceramic Corrosion Test Conditions	7
4	Maximum Thickness Loss—Test Runs 2A and 2B	12
5	Maximum Thickness Loss—Test Run 3	23
6	Char Burnout Results	28
7	Coal and Char Surface Areas From Other Experiments	30
8	Hydrogen, Nitrogen, and Sulfur Release Rates	34
9	Ash Resistivity Calculation	43
10	HITAF Emissions	47
11	HITAF Flow Conditions	48
12	Summary of Combustor Operating Conditions	50
13	Summary of Char Combustor Dimensions	50
14	Baseline Char Combustor Analytical Modeling Results	55
15	Effect of Char Particle Size	64
16	Fuel Gas Composition	81
17	High-Temperature Filter Media	82

QUARTERLY PROGRESS REPORT 7 (July through September 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 is proceeding in accordance with the Revised Project Work Plan issued in May 1993.

Task 2—Concept Definition and Analysis

Subtask 2.7—Define Cycle Analysis Model

The plant heat and material balance reported in Quarterly Report 6 defines the HIPPS cycle [1]. It is the product of several iterations of preliminary component design and plant cycle analysis. This heat and material balance is being further refined for the commercial plant design. This work is being done in Subtask 4.7.

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
Date: November 1993

Figure 1 Simplified Process Block Flow Diagram

Task 3—Preliminary R&D

Subtask 3.1—Analytical Determination of Pyrolyzer Yields

Expected pyrolyzer heat and material balances have been previously reported [2]. These balances were developed using a combination of analytical models and data from the FWDC second-generation PFB pilot plant carbonizer. The Institute of Gas Technology (IGT) is currently organizing this information into one program and writing a report that will provide backup information on the correlations used in the code. This report should be issued in the next Quarter.

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. These materials are sintered alpha-SiC, siliconized-SiC, and SiC_p/Al₂O₃ composite. All three of these materials have experienced corrosion under certain test conditions that have been attributed to effects of alkali interactions [3-5].

With our HIPPS concept, the flue gas going through the ceramic air heater can essentially be made as free of alkalis as required. It is a matter of how much 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 [6].

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. Here 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

As discussed in Subtask 3.7, the most-severe conditions for ceramic corrosion are expected to be at temperatures of around 2300 and 1800°F. In our HIPPS concept, the fuel gas stream can be cleaned of alkalis and particulate to whatever extent is required, but we need to know what level of alkali is acceptable. Also, we need to know the relative corrosion resistance of candidate materials, because this will be a factor in the selection process.

Laboratory testing is being done at FWDC to obtain preliminary information on the 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 SiC_p/Al₂O₃ (an SiC particulate-reinforced Al₂O₃ composite). These specimens are flat pieces of material 2-in. long by 1-in. wide. The specimen thicknesses depended on material availability; 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. The gas composition is listed in Table 1. Char/sorbent samples from FWDC's Second-Generation PFB pilot plant pyrolyzer were used to prepare deposits for the corrosion tests. The char/sorbent samples were ashed in a laboratory furnace. The chemical compositions of the three ashes, determined by atomic absorption and x-ray diffraction, are listed in Table 2.

The ash was applied in different manners 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.

In each of the test runs, ash was added to the specimens every 100 hours, and the tests were run for a total of 500 hours. The conditions in the three test runs are summarized in Table 3. Test Run 1 simulated 2300°F operation with an ash deposition rate that would occur if a barrier filter is used to clean particulates from the fuel gas stream. Based on laboratory testing and analysis of the system, we determined that approximately 23 mg/in² would be deposited on the tubes in 100 hours [6]. Every 100 hours, the tubes were taken from the furnaces and scraped to remove any loose material. They were then loaded with 23 mg/in² of fresh char/sorbent ash and put back in the furnace for another 100 hours. Ashes derived from pyrolyzer runs with Pittsburgh No. 8, Illinois No. 6, and Eagle Butte coals were used.

This initial screening test to evaluate the corrosivity of the three ashes was only done with the sintered alpha-SiC. Under the conditions of this test run, we did not see any corrosion. Figure 2, a typical photomicrograph from this test run, illustrates the formation of a glassy phase on the SiC surface. Surface microcracks are attributed to specimen preparation. An uncoated area of this specimen is shown for comparison. There were some microcracks at the surface, which we attribute to the preparation of the specimens; but no corrosion of the material was evident with any of the ashes.

The next test run was done at 1800°F. At this temperature, increased alkali concentration resulting from condensation of gaseous-phase alkalis is a concern. This type of corrosion can be avoided in the HIPPS plant by removing alkalis from the fuel gas before it is burned in the fuel gas furnace. They can be removed either by using alkali getters or

Table 1 Flue Gas Composition for Ceramic Corrosion Tests

Component	wt%
CO ₂	18.54
H ₂ O	7.61
O ₂	2.54
N ₂	71.11
SO ₂	0.0268

Table 2 Ash Composition of Char/Sorbent Mixtures (wt%)

Component	Pittsburgh No. 8	Illinois No. 6	Eagle Butte
SiO ₂	20.1	40.5	0.4
Al ₂ O ₃	10.4	17.7	0.4
TiO ₂	0.4	0.9	Nil
Fe ₂ O ₃	12.1	15.1	0.3
CaO	31.8	13.1	91.1
MgO	9.7	1.2	4.8
Na ₂ O	0.4	0.8	1.3
K ₂ O	0.8	1.9	Nil
SO ₃	12.1	7.1	3.4
P ₂ O ₅	0.1	0.1	Nil

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
Date: November 1993

Table 3 Ceramic Corrosion Test Conditions

Test Run	Temperature, °F	Specimens	Char/Sorbent *	Deposit Loading [†] , mg/in ²	Deposit Composition, § wt%			Test Duration, h
					Ash	Na ₂ SO ₄	K ₂ SO ₄	
1	2300	SA-SiC	Pittsburgh No. 8/Plum Run Dolomite Illinois No. 6/Longview Limestone Eagle Butte/Longview Limestone	23	100	0	0	500
2A	1800	SA-SiC SiC _p /Al ₂ O ₃ Siliconized-SiC	Pittsburgh No. 8/Plum Run Dolomite	600	56	42	2	500
2B	1800	SA-SiC SiC _p /Al ₂ O ₃ Siliconized-SiC	Pittsburgh No. 8/Plum Run Dolomite	600	93	6.6	0.4	500
3	2300	SA-SiC SiC _p /Al ₂ O ₃ Siliconized-SiC	Pittsburgh No. 8/Plum Run Dolomite Illinois No. 6/Longview Limestone Eagle Butte/Longview Limestone	600	100	0	0	500
*All combinations of ceramic type and deposit type are tested. †Applied every 100 hours. §Sodium and potassium additions to ash.								

Figure 2 Polished Cross Section of SA-SiC Sample After Ash Exposure (100 μ m) — Test Run 1

cooling the fuel gas to a level where most of the alkalies will condense out of the gaseous phase.

For the purposes of this test, an attempt was made to quantify the alkali enhancement that would result if no gaseous-phase alkalies were removed from the fuel gas. This estimate was based on thermodynamic modeling of the combustion products at 1800°F and estimates of particulate carryover. We assumed that, as the fuel gas cooled, alkalies would condense on the particles and then deposit on the tubes. SOLGAS MIX was the thermodynamic equilibrium program that was used, and particle carryover was estimated using an FWEC circulating bed computer model [7].

The levels of sodium sulfate and potassium sulfate from this analysis are shown as Test Run 2A data in Table 3. Only char/sorbent ash from the Pittsburgh No. 8 was used for these tests. The estimation of alkali enhancement from condensation is admittedly very uncertain; however, the testing will provide us with information on the general severity of the problem and the relative corrosion resistance of the candidate ceramics. For this reason, specimens with the lower levels of alkali in Test Run 2B were tested at the same time. The deposit loading for Test Runs 2A and 2B was increased significantly from the Test Run 1 loading to increase the potential for corrosion and so that differences could be seen between the candidate materials.

Two specimens of each candidate material (six specimens total) were exposed at 1800°F while coated with the alkali-doped char/sorbent ash from the Pittsburgh No. 8 pyrolyzer run. The as-exposed specimens are shown in Figure 3. Patterns of melted or sintered ash on the sintered alpha-SiC and siliconized-SiC specimens correlate with the locations of greatest corrosion, as displayed in Figure 4. The high-alkali ash puddled in the middle of the specimens, producing a dished surface. The low-alkali ash sintered but did not melt, creating a uniform corrosion morphology over the surface of the specimens.

Neither $\text{SiC}_p/\text{Al}_2\text{O}_3$ specimen displayed any significant corrosion. The specimen coated with high-alkali ash had minor surface blemishes, while the specimen covered with low-alkali ash was untouched (the two horizontal marks on the low-alkali $\text{SiC}_p/\text{Al}_2\text{O}_3$ specimen were produced during the manufacturing process). The ashes covering $\text{SiC}_p/\text{Al}_2\text{O}_3$ specimens did not melt—the high-alkali ash was slightly sintered, while the low-alkali ash was completely unchanged. (Note: The white flecks in Figure 3 are chips that spalled from the furnace tube during cooling.)

Table 4 lists the maximum thickness losses for specimens from Test Runs 2A and 2B, as measured by a point micrometer. Loss rates correlate with the observed wastage discussed previously. (Note: "High-Alkali Ash" and "Low-Alkali Ash" refer to the ash compositions listed in Table 3 for Test Runs 2A and 2B respectively. Both ashes have been doped with additional sodium sulfate and potassium sulfate.)

After Exposure

Figure 3 Specimens Coated With Pittsburgh No. 8 Ash Doped With Alkalies and Exposed at 1800°F in a Simulated Combustion Atmosphere for 500 hours (Test Run 2A listed in Table 3) [Note the melted high-alkali ash covering both the SA-SiC and Siliconized-SiC specimens.]

1-1/2X (Reduced for Publication)

Figure 4 Specimens From Figure 3 With Ash Layer Coating Scraped Off
1-1/2X (Reduced for Publication)

Table 4 Maximum Thickness Loss—Test Runs 2A and 2B

Specimens	Thickness Loss (mils)
SA-SiC, Low-Alkali Ash	2
SA-SiC, High-Alkali Ash	47
SiC _p /Al ₂ O ₃ , Low-Alkali Ash	0
SiC _p /Al ₂ O ₃ , High-Alkali Ash	0
Siliconized-SiC, Low-Alkali Ash	1
Siliconized-SiC, High-Alkali Ash	84

Photomicrographs of transverse cross sections of these specimens are presented in Figures 5 and 6 (cracks in the specimens were formed during the mounting process). Significant wastage is visible on the sintered alpha-SiC and siliconized-SiC specimens coated with high-alkali ash. The attack morphology on both specimens consists of broad, shallow pits, generating a scalloped cross-sectional profile.

Photomicrographs of the sintered alpha-SiC and siliconized-SiC specimens coated with high-alkali ash are displayed in Figures 7 and 8. Voids in both specimens are scattered randomly throughout, suggesting that they were created either during manufacture or as an artifact of specimen preparation. No evidence of subsurface penetration or preferential attack was evident in either specimen.

Views of the SiC_p/Al₂O₃ composite specimen coated with high-alkali ash and an unexposed specimen are presented in Figure 9. Both specimens contain a layer of modified material, 3 to 5 mils (75 to 125 microns) thick, adjacent to the surface. This layer was purposely created during the manufacturing process [8]. It is not a result of the exposure.

Figure 10 illustrates specimens exposed at 2300°F under a loading of 600 mg/in² of char/sorbent ash from Pittsburgh No. 8, Illinois No. 6, or Eagle Butte pyrolyzer runs. This was Test Run 3 (see Table 2). The total exposure time was 500 hours. All specimens were coated with a glassy layer of melted ash. The coatings on the sintered alpha-SiC and siliconized-SiC specimens formed a light, brittle froth, which could be easily scraped away from the specimens. The SiC_p/Al₂O₃ composite specimens were covered with a much denser coating, which was quite difficult to remove. Specimens scraped free of the outer layer of coating are displayed in Figure 11. A thin layer of glassy material was left on the sintered alpha-SiC and siliconized-SiC specimens. Coatings on the SiC_p/Al₂O₃ composite specimens were much more tenacious and could not be scraped off. Cross-sectional views of the specimens are presented in Figures 12 through 14; cracks in the specimens occurred

SA-SiC
High and Low

Mounted and Polished

$\text{SiC}_p/\text{Al}_2\text{O}_3$
High

Mounted and Polished

$\text{SiC}_p/\text{Al}_2\text{O}_3$
Low

Mounted and Polished

Figure 5 SA-SiC and $\text{SiC}_p/\text{Al}_2\text{O}_3$ Specimens Exposed at 1800°F (Test Runs 2A and 2B in Table 3) [Coated surface of each specimen faces upward and small chip in each mount marks coated face of specimen. Significant corrosion is evident on the SA-SiC specimen coated with Ash Mixture 1 listed in Table 5 (an ash containing 44-percent alkalis).]

3X (Reduced for Publication)

High

Low

Figure 6 Siliconized-SiC Mounted and Polished Specimens Exposed at 1800°F (Test Runs 2A and 2B in Table 3) [Coated surface of each specimen faces upward and small chip in each mount marks coated face (wastage visible on both specimens)]

3X (Reduced for Publication)

Top Surface

Bottom Surface

Figure 2. Surfaces of SA Sil. Specimen Coated With High Alkali Ash - 100X

Top Surface

Bottom Surface

Figure 8 Surfaces of Siliconized-SiC Specimen Coated With High-Alkali Ash — 100X

Figure 1

Figure 2. The same area as in Figure 1, but with a more pronounced horizontal band of darker, silty material.

Figure 1 shows the results of a field survey conducted in the summer of 1998. The area shown is a large, flat, and highly textured surface, likely a dry lake bed or salt flat. The surface is covered in a dense, granular material. In the background, there are dark, silty mounds or hills under a bright sky.

SA-SiC

SiC_p/Al₂O₃

Siliconized-SiC

Pittsburgh No. 8

Eagle Butte

Illinois No. 6

Figure 10 Specimens Coated With One of Three Ashes (Pittsburgh No. 8, Eagle Butte, or Illinois No. 6) and Exposed at 2300°F in a Simulated Combustion Atmosphere for 500 Hours (Test 3 Listed in Table 3)

1-1/2X (Reduced for Publication)

Figure 11 Exposed Specimens Illustrated in Figure 10, After Scraping Off Any Friable Ash
1-1/2X (Reduced for Publication)

Pittsburgh No. 8

Illinois No. 6

Eagle Butte

Figure 12 Cross-Sectional Views of Mounted and Polished SA-SiC Specimens (Test Run 3 listed in Table 3) [Coated surface of each specimen faces upward and small chip in each mount marks coated face specimen.]

3X (Reduced for Publication)

Pittsburgh No. 8

Illinois No. 6

Eagle Butte

Figure 13 Cross-Sectional Views of Mounted and Polished Siliconized-SiC Specimens (Test Run 3 in Table 3) [Coated surface of each specimen faces upward.]

Pittsburgh No. 8

Illinois No. 6

Eagle Butte

Figure 14 Cross-Sectional of $\text{SiC}_p/\text{Al}_2\text{O}_3$ Specimens Exposed at 2300°F (Test Run 3 in Table 3) [Coated surface of each specimen faces upward.]

during the mounting process. Thickness losses, as measured by examination of the transverse cross section, are presented in Table 5.

Table 5 Maximum Thickness Loss—Test Run 3

Specimens	Thickness Loss (mils)
SA-SiC, Pittsburgh No. 8	28
SA-SiC, Illinois No. 6	22
SA-SiC, Eagle Butte	31
SiC _p /Al ₂ O ₃ , Pittsburgh No. 8	20
SiC _p /Al ₂ O ₃ , Illinois No. 6	2
SiC _p /Al ₂ O ₃ , Eagle Butte	19
Siliconized-SiC, Pittsburgh No. 8	36
Siliconized-SiC, Illinois No. 6	22
Siliconized-SiC, Eagle Butte	37

Photomicrographs of the specimens from Test Run 3 have been prepared and are in the process of being analyzed. A test run with the same conditions as those in Test Run 1 (2300°F with light ash loading) is also in process. This test is being done with all three candidate materials. The first run under these conditions used all three ashes, but only with sintered alpha-SiC specimens. When these analyses and tests are completed, we will assess the corrosion aspects of the ceramic air heater design and operation.

Subtask 3.10—Fuel Characterization Testing

During the last quarter, fuel characterization testing at Brigham Young University (BYU) was 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.

Preliminary analysis of the char produced from FWDC's second-generation PFB combustion project indicated 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 were performed at BYU to provide information on:

- Expected volatile yields at high heating rates
- Char reaction rates as a function of particle residence time, gas temperature, and gas composition
- Nitrogen and sulfur release rates (preliminary values) during char oxidation.

Description of Experiments. The rates of char combustion, sulfur release and nitrogen release were determined in a flat-flame burner (FFB) experiment as a function of flame temperature, gas composition, and particle residence time. Both the parent coal and char samples were characterized. Gas temperatures and compositions were selected to be similar to the actual slagging-stage combustor environment (approximately 2000 K/3000°F). Conditions simulated both an oxygen-rich and a fuel-rich high-temperature environment.

A schematic of the FFB test configuration is shown in Figure 15. Air and methane are transported separately through a monolithic structure, as shown in Figure 16. A steady, flat flame is produced at the top of the structure. Coal or char is fed pneumatically upward through the middle of the FFB. Above the FFB, an adjustable collection probe with a nitrogen quench collects and extinguishes the burner char particles. The char is then collected by either a cyclone or filter for subsequent post-test analysis.

The post-flame gases in the FFB experiment can be adjusted to contain 0 to 20 mole-percent oxygen by changing the stoichiometry of the flame. These post-flame gases generally contain 13 mole-percent steam and 6 mole-percent carbon dioxide. To determine kinetic rates, char samples were collected in the FFB at different residence times. Particle velocities and thus particle residence times in the FFB were determined by streak photography. Maximum particle residence time in the FFB was approximately 100 ms.

The particle residence time in the flame was controlled by varying the distance of the collection probe above the burner. The relationship between distance and particle residence time is given below:

Distance, in.	Residence Time, ms
0	0
2	20
4	40
6	60
8	80

Figure 15 Schematic of Flat-Flame Burner System

Figure 16 Schematic of Flat-Flame Burner Assembly

The gas temperature was measured at various distances above the burner using Type B thermocouples inserted in the gas stream. The thermocouple reading was corrected for radiation losses through the transparent tower, assuming the radiation losses balance the convective heat transfer to the thermocouple bead.

A series of modifications was made to the sampling system during the course of the project. The original cyclone system was found to be inadequate for the proposed char, apparently because of the particle size tested. A glass fiber filter also proved inadequate because of retention of fines in the filter. The final sampling system for this project consisted of a 2.5-in. polycarbonate Nuclepore filter (1 micron pores) without the cyclone.

Post-test fuel analyses were performed on collected char and compared with pretest analyses to determine carbon, sulfur, and nitrogen losses. Results were compared with those obtained with the parent coal. Analyses that were 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; O by difference)
- Titanium and aluminum tracer analysis (by ICP atomic adsorption spectroscopy)
- Apparent density (tap density technique)
- Internal surface area (N_2 and CO_2).

Summary of Results.

Char Reactivity. Results include data on char reactivity, char surface area, apparent density, and chemical composition during burnout. For each case, char results are compared with those obtained with the parent coal.

Results of the coal and char reactivity and characterization tests for the baseline gas environment (1800 K/5-percent oxygen) are shown in Table 6. Burnout for individual samples was determined by an average of the values calculated from the titanium and aluminum tracers, using ICP atomic adsorption spectroscopy. Burnout results are reported on a dry-ash-free (DAF) basis.

To compare the post-volatile char burnout rates for both the parent coal and char, the coal data were corrected to account for devolatilization. The corrected coal burnout data are also listed in Table 6. The value of the coal burnout at the first sampling position (2 in.) is taken as the volatile yield for the coal. This is approximately the location in which the intensity of the individual burning coal particles was observed to decrease significantly, indicating a transition between devolatilization and char oxidation.

Table 6 Char Burnout Results (1800 K/5% O₂)

Pittsburgh No. 8	Sampling Distance, in.	Average Burnout (% DAF)		Average Apparent Density, g/cc	Surface Area	
		Volatiles Included	Char Only		N ₂ , m ² /g	CO ₂ , m ² /g
Coal	2	50.4	0	0.38	77	241
Coal	4	58.6	14.1	0.37	44	241
Coal	6	60.5	29.6	0.42	37	188
Coal	8	63.5	30.3	0.42	33	134
Char	2	N/A	10.6	0.70	31	146
Char	4	N/A	20.4	0.65	28	149
Char	6	N/A	29.2	0.67	33	135
Char	8	N/A	34.7	0.68	31	101

Char burnout for both the coal and char as a function of sampling distance above the FFB is compared in Figure 17. In addition, the burnout for the 63 to 75-mm size fraction of a Pittsburgh No. 8 coal from the DOE/PETC data base [9] is shown for the 1800 K/5 mole-percent oxygen condition. Burnouts are the averages of the values calculated from the titanium and aluminum tracers. Important conclusions from the data are:

- The char burnout for the Pittsburgh No. 8 char, which was obtained from FWDC, occurs at a slightly greater rate than the char burnout of the parent coal, after accounting for devolatilization.
- The char burnout for the Sandia Pittsburgh No. 8 coal, normalized for volatile yield, is slightly lower in the 1800 K/5-percent oxygen environment than the burnout for the TRW Pittsburgh No. 8 coal or 330 char.

Char Properties. Physical properties of the respective coal chars were measured to better compare char reactivities with known data. Apparent densities and internal surface areas were measured and compared with char property data from other experiments. Table 6 summarizes results from this project. The surface areas of coals and chars from other projects are listed in Table 7, and compared with chars from this project in Figures 18 and 19. Figure 18 shows that the parent coal exhibits properties similar to those reported for other coals of similar rank (percentage of oxygen in the DAF coal is used as a

Figure 17 Char Burnout vs. Distance in FFB for 330 Char and Parent Pittsburgh No. 8 Coal in 1800 K/5 mol% O₂ Environment

Table 7 Coal and Char Surface Areas From Other Experiments

Description	Coal	Coal N ₂ , m ² /g	Char N ₂ , m ² /g	Coal CO ₂ , m ² /g	Char CO ₂ , m ² /g	%C Coal (DAF)	%O Coal (DAF)
Cope (1992)	Dietz (subb)		229		337	72.9	17.3
	Zap (lignite)		65 190		543	72.9 76.0	17.3 20.3
Hyde (1990)	Pittsburgh No. 8 (hvab)		85		214	83.3	6.8
	Dietz (subb)		217		301	72.9	17.3
	Zap (lignite)		140		301	76.0	20.3
White (1989)	Zap (lignite)	0.5			476	76.0	20.3
		1				76.0	20.3
		1.9		242		76.0	20.3
				268		76.0	20.3
	Wyodak (subb)	5		238		75.0	18.0
		2.6		115		75.0	18.0
		1.3		207		83.2	8.8
	Pittsburgh No. 8 (hvab)	1	93	308	252	83.2	8.8
		1		118		91.1	2.5
	Poc (lv)	1		141		91.1	2.5
		2.8		231		72.3	20.1
	Wilcox (lignite)		47 124		252	72.3	20.1
Hurt, et al. (1992)	Hiawatha (hvcb)	1	135 120	140	325 410	79.6 79.6	13.3 13.3
			5		400	88.2	3.5
	Lower Kit (lvb)	1	60	110	280	88.2	3.5
TRW (this project)	Pittsburgh No. 8 Coal	1.3	77	138	241	79.0	10.5
	330 Char	103	74	279	220	79.0	10.5

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
Date: November 1993

Figure 18 N₂ and CO₂ Internal Surface Areas of Parent Pittsburgh No. 8 Project Coal Compared With Literature Values for Other Coals [Logarithmic scale shows N₂ and CO₂ surface areas on the same graph.]

Figure 19 N₂ and CO₂ Internal Surface Areas of Project Chars Compared With Literature Values for Other Chars Immediately After Devolatilization [Logarithmic scale shows N₂ and CO₂ surface areas on the same graph.]

rank indicator). Figure 19 shows that the surface areas of the parent 330 char and of the partially reacted chars from both the coal and the 330 char are similar to surface areas of other chars prepared in FFBs.

The apparent densities of the coal and char during burnout are also given in Table 6 and are shown in Figure 20. These values represent averages from several experiments. A packing factor of 0.6 (cc solid/cc tube) was used to derive the values of the apparent density, which allows the parent coal to have an apparent density of 1.3 g/cc. As the coal devolatilizes, the char reaches a density of about 0.4 g/cc and then slightly increases to about 0.47 g/cc during char combustion. The 330 char increases in apparent density during devolatilization from 0.5 g/cc to approximately 0.7 g/cc, and then remains at 0.65 to 0.70 g/cc during char oxidation. As a comparison, the Pittsburgh No. 8 char studied at Sandia had an initial apparent density of 0.4 g/cc, and the apparent densities of chars of other coals ranged from 0.26 to 0.68 g/cc [10]. The slight densification of the 330 char during high-temperature devolatilization is not uncommon, especially when the char is generated at low to moderate temperatures [11].

Nitrogen and Sulfur Release. Data concerning the release rates of hydrogen, nitrogen, and sulfur are summarized in Table 8 for both the coal and char samples in the 1800 K/5-percent oxygen flame environment. Results are compared after 80 ms of exposure in the high-temperature FFB environment. The results have also been normalized to the rates of carbon consumption.

The coal data indicate that nitrogen and sulfur are released into the gas phase at a rate slightly higher than the rate of carbon release. For the char, which includes spent sorbent primarily in the form of CaS, the sulfur release rate is still greater than the rate of carbon consumption, indicating that most of the sulfur contained within either the coal or spent sorbent is likely to be released during char oxidation at high temperatures. The nitrogen release rate is slightly lower than the carbon release rate.

Conclusions From Fuel Characterization Testing. The char burnout rates for Pittsburgh No. 8 coal and FWDC char under high-temperature oxygen-rich conditions are comparable. Hence, in addition to the information obtained during BYU testing, kinetic rate data obtained from other studies of Pittsburgh No. 8 coal can be used for analytical modeling of post-devolatilization char burnout. These data include the comprehensive set of apparent reactivities for high-temperature char oxidation recently published [9].

- Measured char surface area and apparent densities at various stages of burnout are within the range of values measured in other kinetic studies. This agreement further validates the approach of using previously determined kinetic parameters for modeling FWDC char burnout.

Figure 20 Apparent Densities of Coal and Char Samples From FFB Experiments

Table 8 Hydrogen, Nitrogen, and Sulfur Release Rates

Fuel	Pittsburgh No. 8 Coal	Pittsburgh No. 8 Char
Flame Temperature, K	1800	1800
Oxygen Concentration, %	5	5
Residence Time, ms	80	80
Burnout, DAF	63.5	34.7
%C Release	59.0	34.7
%N Release	68.7	30.0
%S Release	69.3	46.2
N Release/Burnout	1.1	0.9
S Release/Burnout	1.1	1.3
N Release/C Release	1.2	0.9
S Release/C Release	1.2	1.6

- The sulfur contained within the char and spent sorbent mix was determined to be released at a rate as great or greater than the observed char burnout rate under high-temperature conditions. Hence most, if not all, of the sulfur introduced into a high-temperature flame zone will probably be gasified during char oxidation. Therefore, the sulfur emissions goal will have to be achieved in the back-end system, possibly by removing some spent sorbent before the char combustor.

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 R&D—basically in two areas. One is the design of the piping system to remove and return the air (Subtask 3.29). The other is the determination of the design and operating characteristics of the combustors. The effect of 1800°F inlet air on combustion characteristics and emissions is the primary consideration in this investigation.

Figure 21 shows the combustor test rig. This rig has been used in other test programs, but it had to be modified to provide operation with 1800°F air. The inside of the rig is a quartz tube approximately 2 in. in diameter and 4 ft long. A quartz window in the side of the rig allows for visual monitoring. The preheater was originally electric, but it had to be changed to a natural-gas-fired preburner to get an 1800°F inlet temperature. Both premixed and diffusion combustion operation can be tested in this rig. The flame can be observed, and measurements of temperature, pressure, and exit gas composition can be made. The amount of CO, CO₂, O₂, and NO_x in the exit gas is measured.

Testing has begun, and baseline data have been obtained at combustion air temperatures of 725 and 1025°F. These tests have been run with natural gas and a premixed flame. Preliminary emissions data with 725 and 1025°F air are plotted in Figures 22 and 23. Figure 22 shows the CO concentration vs. exit gas temperature, and Figure 23 plots NO_x vs. the gas exit temperature. As the figures show, an increase in temperature from 725 to 1025°F has very little effect on the CO and NO_x levels. The combustor exit temperature is expected to be in the range of 2500 to 2700°F in commercial applications. Testing is now proceeding with higher-temperature inlet air.

Subtask 3.21—Pollution Control Systems

Oxides of Nitrogen Emissions. NO_x is generated in three areas of the HIPPS plant—the char combustor, the fuel gas burners, and the topping combustor. The total NO_x generated in the system depends on the quantities of fuel to each of these combustors and the rate of NO_x generation in each. Throughout the project, NO_x emissions estimates have been revised as the plant heat and material balances have changed and as better estimates of NO_x generation in components have been obtained.

Figure 21 Topping Combustor Laboratory Test Rig

Figure 22 CO In Exit Gas vs. Exit Gas Temperature—Preliminary Data

NO_x, ppm dry at 15% O₂ Figure 23 NO_x in Exit Gas vs. Exit Gas Temperature—Preliminary Data

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-ACC22-91PC91154
Date: November 1993

During this quarter, the gas turbine NO_x production estimate was reexamined. The current NSPS for gas turbines is 75 lb/min at 15 percent O_2 . At a level of 15 percent exit O_2 , gas combustion produces 28.5 ft³ flue gas for each cubic foot of methane burned. If a heating value of 1000 Btu/ft³ methane is assumed, then 75 lb/min of NO_x translates to 0.16 lb/10⁶ Btu. It has been reported that levels of 30 lb/min, or 0.06 lb/10⁶ Btu, are possible [12]. The use of 1800°F combustion air would likely increase NO_x levels significantly. Tests are being run by GE to quantify this effect, but until these tests are completed, the assumed value of 0.2 lb/10⁶ Btu does not appear to be out of line.

The NO_x production of the fuel gas burners was estimated to be 260 lb/min, based on tests performed with natural gas burners using high-temperature combustion air [13]. This estimate corresponds to 0.35 lb/10⁶ Btu and 25-percent conversion of NH_3 to NO_x . To increase our confidence in the estimate of fuel gas NO_x , burner manufacturers will be solicited for proposals for testing. The current estimated NO_x production levels are:

Gas Turbine Combustor	0.2 lb/10 ⁶ Btu
Fuel Gas Combustor	0.34 lb/10 ⁶ Btu
Char Combustor	0.25 lb/10 ⁶ Btu

The latest design of the HITAF furnace and convection passes was examined for compatibility with SNCR de NO_x . This design is discussed in Subtask 4.12. A difference between this design and previous designs is a large tube-free pass that the flue gas from the ceramic air heaters travels through before mixing with the flue gas from char combustion. The feasibility of using this area for reagent injection was examined.

A urea or ammonia injection system requires 0.5 to 1 seconds of residence time at 1700 to 2000°F to achieve better than 50-percent NO_x reduction. Detailed flow and chemical kinetic modeling of the furnace and convection sections is required for the proper placement of urea injectors and for NO_x removal prediction, but a brief examination of the system and temperatures can determine whether an SNCR system can be employed. In the new configuration, the flue gas from the ceramic air heater mixes with the flue gas from the char-fired furnace at about 2000°F. The combined stream then enters the platen air heater. The mixing zone provides about 0.5 seconds of residence time at a constant 2000°F, and the platen air heater provides about 1 second of residence time between 2000 and 1400°F. SNCR can therefore be successfully applied to this configuration, with the location of the urea injectors in the ceramic air heater exit plane.

When a 50-percent NO_x reduction is assumed by means of SNCR applied at the platen air heater zone, then plant-wide NO_x emissions are 0.135 lb/10⁶ Btu. It should be pointed out that if the conversion of ammonia to NO_x at the fuel gas combustor is reduced to 8 percent (a value initially proposed) and if the gas turbine NO_x production rate can be lowered to 0.1 lb/10⁶ Btu, the 0.15 lb/10⁶ Btu system limit can be achieved without the need for an SNCR.

The use of fuel gas as a reburn fuel in the furnace has been investigated. Studies have shown that many types of gases (including coal-derived fuel gas) are equally effective for NO_x reburning [14]. A 50-percent NO_x reduction requires that at least 20 percent of the combustion heat input be supplied by the reburning gas. Since the heat inputs of the fuel gas and the char plus precombustor coal are about equal, about 20 percent of the fuel gas would have to be used for reburning. Ammonia contained in the fuel gas would also likely become NO_x. These considerations probably preclude the use of the fuel gas for reburning.

Sulfur Dioxide Emissions. We had been assuming that 20 percent of the sulfur contained in the char will leave the system in the slag. We now estimate that there will be no sulfur removal by the slagging combustor. The effect of this change on the overall system SO₂ emissions is small, as shown in Figure 24. This figure shows SO₂ emissions as a function of control system efficiency and combustor SO₂ removal. If SO₂ emissions are 0.15 lb/10⁶ Btu at 20-percent combustor capture, they increase to 0.18 lb/10⁶ Btu at 0-percent capture, but can be lowered to 0.15 lb/10⁶ Btu if the FGD efficiency is raised from 94 to 95 percent.

Four SO₂ control technologies have been candidates for selection for the HITAF system. These technologies were identified because they are all regenerable and they all have some measure of full-scale demonstration. The Tung and SOXAL technologies apply energy-efficient modifications to the regeneration step of the proven Wellman-Lord process. The CANSOLV and Dow processes utilize an organic amine as the SO₂ scrubbing solution. These processes are already in commercial use for natural gas H₂S scrubbing and have been pilot-scale tested on flue gas SO₂ scrubbing.

Cancellation of the commercial-scale installations of the Dow and CANSOLV systems for flue gas applications have recently been announced. Both organizations cite cost and lack of supplementary funding as reasons for the cancellations.

The Tung and SOXAL processes are both being pilot-scale tested at Niagara Mohawk's Dunkirk Station. SOXAL testing has been successfully completed, and Tung testing is under way. Niagara Mohawk Power has been formally requested to delay the disassembly of the Tung and SOXAL pilot plants at their Dunkirk Station until a decision can be made on our part regarding additional testing for the Combustion 2000 Program. Dr. Peter Strangway of Niagara Mohawk has taken this request under consideration. He feels that one unit can be left intact, but he would need assurances that resources will be available to disassemble the unit at the conclusion of the testing.

The Research-Cottrell Process Design Group has been given the task of the specification and placement of the major components of a generic Wellman-Lord/Tung/SOXAL FGD system. This task should be completed in October; it will result in a scaled general arrangement drawing of the system.

Figure 24 SO₂ Emission vs. FGD System Efficiency

Particulate Control Emissions. To verify the operation of an electrostatic precipitator, the electrical resistivity of the HITAF particulate was calculated. An analysis of the char ash produced by the pyrolyzer and Pittsburgh No. 8 coal (dated 7/92) was used as input to the SoRI resistivity program. This program utilizes empirical correlations between ash chemistry and electrical resistivity to calculate resistivity. Aside from particle size, particle layer electrical resistivity has the largest influence on the collection efficiency of an electrostatic precipitator. When the resistivity is high ($> 10^{11}$ ohm-cm), the phenomenon of back-corona causes charge neutralization and premature sparking. When the resistivity is low ($< 10^9$ ohm-cm), the collected particulate is reentrained into the flow field. A resistivity of 10^{10} ohm-cm is optimum for high-efficiency particulate collection. Often, as a result of furnace sorbent injection, an ash with a high CaO content has a high resistivity.

The Foster Wheeler ash mineral analyses for the bed drain and cyclone catch were combined (54:46 parts respectively). The output of the SoRI program is shown in Table 9. After listing the input ash characteristics, the program gives resistivity as a function of temperature and gaseous SO_3 concentration. The resistivity is dominated by volume conductivity at high temperature and by surface conductivity at low temperature. Surface conductivity is principally determined by SO_3 concentration. High ash concentrations of CaO and MgO lead to low gaseous SO_3 concentration. We can thus assume that the SO_3 concentration for the HITAF system will be less than 1 lb/min. When the data in Table 9 are plotted, Figure 25 results. The figure clearly shows the importance of temperature and SO_3 concentration. We can assume that the resistivity curve for HITAF will lie somewhere between the solid and dashed lines. Thus at the 220°F operating point, the resistivity will be between 10^9 and 10^{11} ohm-cm. This result indicates that the precipitator should operate satisfactorily.

Updated Mass Balance. The mass balance for SO_2 , NO_x , and particulates, corresponding to Figure 26, is given in Tables 10 and 11. This balance incorporates the July 1, 1993, Bechtel values as well as the NO_x and SO_2 values discussed. An input for pyrolyzer sorbent was added as 1A in Figure 26. Previously, the sorbent was included as part of the coal input. The balance reveals that program objectives with respect to emissions can be met with a 96-percent SO_2 control, a 50-percent NO_x control, and a 99.8-percent particulate control—all applied to the flue gas produced by the fuel gas and char combustors only.

Subtask 3.27—Char Combustor Analytical Modeling

Char combustor analytical modeling under this project supports both the conceptual design of the char combustor and char combustor test planning for Phase 2 of the HIPPS program. Earlier in the project, preliminary thermodynamic and char oxidation calculations were performed to assess the impact of a lower fuel volatile content on combustor operating conditions, particle size requirements, and combustor design [15]. 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

Table 9 Ash Resistivity Calculation (Pyrolyzer Char: $H_2O = 6.6$, $SO_2 = 3300$)

Description	Ash Analysis	Corrected Ash Analysis	Atomic Concentration
Li_2O	0.00	0.00	0.000
Na_2O	0.30	0.31	0.208
K_2O	0.70	0.72	0.320
MgO	10.70	10.94	8.573
CaO	34.90	35.68	20.101
Fe_2O_3	7.60	7.77	1.230
Al_2O_3	8.70	8.90	2.205
SiO_2	19.20	19.63	6.879
TiO_2	0.30	0.31	0.081
P_2O_5	0.10	0.10	0.013
SO_3	15.30	15.64	3.086
Total	97.80	100.00	42.696
Sum of lithium and sodium atomic concentrations			0.21
Sum of magnesium and calcium atomic concentrations			28.70
Iron atomic concentration			1.20

Table 9 (Cont) Ash Resistivity Calculation

1000/ T(K)	K	°C	°F	RHO(VS)	RHO (VSA) 3.3 ppm	RHO (VSA) 1.0 ppm	RHO (VSA) 4.0 ppm	RHO (VSA) 10.0 ppm
1.40	714	441	826	1.9E+10	1.9E+10	1.9E+10	1.9E+10	1.9E+10
1.50	667	394	740	5.0E+10	5.0E+10	5.0E+10	5.0E+10	5.0E+10
1.60	625	352	665	1.3E+11	1.3E+11	1.3E+11	1.3E+11	1.3E+11
1.70	588	315	599	2.8E+11	2.8E+11	2.8E+11	2.8E+11	2.8E+11
1.80	556	282	540	4.8E+11	4.8E+11	4.8E+11	4.8E+11	4.7E+11
1.90	526	253	488	6.5E+11	5.9E+11	6.2E+11	5.8E+11	5.3E+11
2.00	500	227	440	6.8E+11	4.5E+11	5.9E+11	4.1E+11	2.7E+11
2.05	488	215	418	6.7E+11	3.1E+11	5.0E+11	2.6E+11	1.4E+11
2.10	476	203	397	6.4E+11	1.8E+11	3.8E+11	1.4E+11	6.3E+10
2.15	465	192	378	6.0E+11	9.0E+10	2.5E+11	6.9E+10	2.6E+10
2.20	455	181	359	5.6E+11	4.2E+10	1.5E+11	3.1E+10	1.1E+10
2.25	444	171	340	5.1E+11	1.9E+10	7.9E+10	1.4E+10	4.3E+09
2.30	435	162	323	4.6E+11	8.1E+09	4.0E+10	6.0E+09	1.7E+09
2.35	426	152	306	4.1E+11	3.5E+09	2.0E+10	2.6E+09	6.7E+08
2.40	417	144	290	3.6E+11	1.5E+09	9.4E+09	1.1E+09	2.7E+08
2.45	408	135	275	3.1E+11	6.4E+08	4.5E+09	4.8E+08	1.1E+08
2.46	407	133	272	3.0E+11				8.6E+07 *
2.50	400	127	260	2.6E+11	2.7E+08	2.1E+09	2.0E+08	
2.52	397	124	255	2.4E+11			1.5E+08 *	
2.53	395	122	252	2.3E+11	1.7E+08 *			
2.55	392	119	246	2.1E+11		9.9E+08		
2.60	385	111	233	1.8E+11		4.6E+08 *		
2.70	370	97	207	1.0E+11				
2.80	357	84	183	5.6E+10				

*Resistivity at acid dew point.

Figure 25 Resistivity of Char Ash (Pittsburgh No. 8 Coal, Dolomite Sorbent)

Figure 26 Pollution Control Flow System (Numbers in smaller type are identified in Bechtel's flow diagram presented in Quarterly Report 6)

Table 10 HITAF Emissions

Initial Conditions		System Emissions Rates	
Coal Ash, %	10.32	SO ₂ , lb/10 ⁶ Btu	0.1204
Coal Sulfur, %	2.99		
Solids to Fuel Gas, %	7		
S to H ₂ S, %	5		
Combustible Ash Captured, %	80	NO _x , lb/10 ⁶ Btu	0.1343
Combustible Sulfur Captured, %	0		
Barrier Filter, %	0		
Particulate Control, %	99.8		
DeSO _x , %	96	Ash, lb/10 ⁶ Btu	0.0065
DeNO _{x1} , %	50		
DeNO _{x2} , %	0		
NH ₃ in Fuel Gas, %	0.16		
NH ₃ to NO Conversion	25	10 ⁶ Btu/h	2095
Fuel Gas Combustion, lb/10 ⁶ Btu	0.35		
Precombustor, lb/10 ⁶ Btu	0.25		
Char Combustor, lb/10 ⁶ Btu	0.25	MW at 48% Efficiency	295
Gas Turbine Combustor, lb/10 ⁶ Btu	0.2		
Vitiated Air Combustor NO _x (Red), %	50

Table 11 HITAF Flow Conditions

No.	Stream Number	Flow, 10 ³ lb/h	Pressure, psia	Temperature, °F	S, lb/h	NO, lb/h	Particulate, lb/h
1	Coal	96.5	50	70	2885.4	0.0	9958.8
1A	Sorbent	9.4	35	70	0.0	0.0	9400.0
2	Fuel gas	331.2	30	1700	144.3	0.0	3073.0
3	Flue gas	890.5	15	2936	144.3	233.8	3073.0
4	Nat gas	30.7	250	200	0.0	0.0	0.0
5	Air	2546	209	1800	0.0	0.0	0.0
6	Vit Air	3337	16	1100	0.0	146.5	0.0
7	Vit Air	1425	16	1000	0.0	62.6	0.0
8	Vit Air	1912	16	350	0.0	83.9	0.0
9	Vit Air	1912	16	350	0.0	83.9	0.0
10	Char	43.9	45	1700	2741.1	100.7	18003.7
11	Coal	9	17	60	269.1	29.1	928.8
12	Flue gas	1538	15	300	3154.5	394.9	6859.5
13	Flue gas	1538	15	300	3154.5	394.9	6859.5
14	Flue gas	1538	15	300	3154.5	394.9	13.7
15	Flue gas	1538	15	100	126.2	197.4	13.7
16	Stack	3450	15	100	126.2	281.4	13.7

purpose. A description of the capabilities of the CCEP computer model is included in this discussion.

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. First, a large amount of research has been conducted on the combustion and emissions characteristics of a variety of U.S. coals under different operating conditions, and is available to support this project. To complement these data, char characterization testing was performed at Brigham Young University to provide data specific to the proposed char (see Subtask 3.10). 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 Coal Combustor Engineering Program (CCEP) computer model to support char combustor conceptual design.

Modeling Objectives. The primary objectives of the char combustor analytical modeling activity are to characterize the baseline performance of the char combustor and to define the design and operating envelope. As previously discussed, 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 12 and 13.

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

- Sectional and overall carbon burnout
- Gas temperatures and compositions
- Flow velocities
- Combustor emissions (NO_x , SO_2 , particulates)
- Combustor heat fluxes and overall cooling load
- Pressure drop
- Slag recovery rates.

Table 12 Summary of Combustor Operating Conditions

Thermal Input	
Coal, 10 ⁶ Btu/h	116
Char, 10 ⁶ Btu/h	448
Total, 10 ⁶ Btu/h	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 13 Summary of Char Combustor Dimensions

Precombustor, in. (m)		
Primary Windbox Diameter	84	(2.13)
Secondary Windbox Diameter	120	(3.05)
Combustion Chamber Diameter	60	(1.52)
Overall Precombustor Length	180	(4.57)
Slagging Stage		
Chamber Diameter, in. (m)	105	(2.67)
Chamber Length, in. (m)	185	(4.70)
Number of Injectors	6 to 8	
Incline Angle, deg	15	
Slag Recovery Section, in. (m)		
Chamber Diameter	105	(2.67)
Chamber Length	135	(3.43)
Exhaust Duct, in. (m)		
Width	84	(2.13)
Length	84	(2.13)
Height	160	(4.06)

Furthermore, it is not only important 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 already (or to be) varied in support of the conceptual design include:

■ Chamber diameter	■ Air inlet positioning
■ Chamber length	■ Air inlet flow area
■ Slag baffle diameter	■ Slag tap size
■ Injector diameter and positioning	■ Slag recovery section exhaust 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 stage represents the heart of the combustor.

A simple schematic of the slagging stage of the combustor is shown in Figure 27. 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,

Figure 27 Char Combustor Analytical Model Geometry and Zone Definition

under the combination of shear and gravity forces to a slag tap downstream of a slag baffle, where it is 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
- Particle trajectories (both char and residual ash particles)
- Gas recirculation and mixing zones
- Particle heating and devolatilization
- Slag flow
- In-flight char oxidation
- Wall combustion
- NO_x formation and destruction
- Radiant and convective wall heat fluxes

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 [9] 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 27, the slagging-stage model is divided into two major zones—the head end and the 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 functions 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	■ Wall heat fluxes
■ Overall carbon burnout	■ Wall deposition rates
■ Gas temperatures and compositions (including NO , HCN , NH_3)	■ Slag layer thicknesses
■ Slag recovery rates	■ Combustor pressure drops

Baseline Performance Characterization. CCEP model calculations were performed for char combustor firing rates of 30 and 300×10^6 Btu/h, which correspond to the expected firing rates for combustor development testing and a full-scale commercial plant (290 MWe).

Key model assumptions and results are summarized in Table 14. The fuel was assumed to be pyrolyzed char from a Pittsburgh No. 8 coal, with a median particle size of 60 microns, corresponding to a 60- through 200-percent mesh coal grind. An air preheat temperature of 1130°F was assumed, which corresponds to the baseline heat and material balance. Pulverized Pittsburgh No. 8 coal is fired in the precombustor to increase the air temperature from 1130°F to 2000°F. This precombustor exit temperature will be varied in future calculations. 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.

Key results from the baseline performance calculations are also summarized in Table 14. For both combustor sizes, 100 percent of the available volatiles, including the low-Btu carrier gas, are burned within the head-end region of the combustor. The fractions of char consumed/oxidized in the head-end region are 0.759 and 0.869 for the 30- and 300 x 10⁶ Btu/h combustors respectively. A larger percentage of the total char is deposited and oxidized on the walls of the combustor in the head-end region for the smaller combustor, because of the shorter distance from the injector to the wall and the relatively higher centrifugal forces acting on particles in smaller combustors. Overall carbon burnout is calculated to be 0.979 for the smaller combustor and 0.996 for the larger combustor. This burnout should be compared with the actual performance of TRW's 34-in. combustor (30 to 40 x 10⁶ Btu/h), which nominally achieves carbon burnout of 0.995 or better when firing medium- to high-volatile coals.

A plot of carbon burnout as a function of combustor axial distance is presented in Figure 28 for the two cases discussed. For convenience, the axial distance, Z , has been normalized to the overall length of the slagging stage, L . For each combustor, the head-end zone extends from $Z/L = 0$ to 0.4. The mixing zone extends from this point to the baffle, or $Z/L = 1.0$. The slight bump in the curves at $Z/L = 0.4$ indicates the transition from the head-end zone to the mixing zone. Note that the initial carbon burnout for the smaller combustor is higher than for the larger combustor. This difference is because a larger proportion of the total char is deposited on the walls of the smaller combustor; hence more wall oxidation takes place in the head-end recirculation zone before the char enters the head-end core region. The overall burnout along the length of the combustor is lower for the 30 x 10⁶ Btu/h combustor, however, because of the lower residence time available (axial flow velocities are approximately the same for the two combustors).

The temperature profiles are also calculated to be different for the two combustors as a result of the different combustion profiles. For the larger combustor, the peak temperature zone in the head end of the combustor is relatively narrow compared with the smaller combustor, as indicated in Figures 29 and 30. Again, this difference is because of the shorter available distance and residence time in the smaller combustor. The rapid increase in temperature near the head-end wall ($Z/L = 0$) indicates exothermic oxidation of volatiles and small char particles, while the slow decay in temperature indicates endothermic reactions. Note that a short delay is evident near $Z/L = 0$ because of particle heating. In the mixing zone, the average temperature increases, as additional oxidizer from the precombustor raises

Table 14 Baseline Char Combustor Analytical Modeling Results

Key Assumptions		
Feedstock	=	Pittsburgh No. 8 Char
Median Particle Size	=	60 microns
Air Preheat Temperature	=	1130°F (19% O ₂)
Precombustor Exit Temperature	=	2000°F
Slagging Stage Stoichiometry	=	0.8
Results	Char Combustor	
	30 x 10 ⁶ Btu/h	300 x 10 ⁶ Btu/h
Fraction of coal devolatilized in head-end region	1.0	1.0
Fraction of char consumed on wall in head end	0.355	0.200
Total fraction of char oxidized in head-end region	0.759	0.869
Fraction of total fuel consumed in head-end region	0.830	0.909
Gas temperature at head-end wall, °F (K)	3440 (2167)	2834 (1830)
Gas temperature at head-end exit, °F (K)	2780 (1800)	2546 (1670)
Fraction of total coal consumed in slagging stage	0.979	0.996
Gas temperature at baffle, °F (K)	3554 (2230)	3526 (2214)

Figure 28 Carbon Burnout as a Function of Combustor Length for Subscale and Commercial-Scale Char Combustors

Figure 29 Temperature Profile for Commercial-Scale Char Combustor

58

Figure 30 Temperature Profile for Subscale Developmental Char Combustor

the effective stoichiometry from approximately 0.5 at the head-end exit to 0.8 at the baffle exit. The core temperature remains lower, however, because of the lower effective stoichiometry in this region.

Overall, these baseline performance calculations indicate that carbon burnout is expected to be above 99 percent at the exit of slagging stage for a commercial-scale char combustor. Carbon losses are expected to be higher for the subscale combustor, if the same particle grind and injector positioning is used. The subscale combustor performance can be improved, however, by reducing the particle size or by modifying the injector configuration.

To evaluate combustor emissions performance, the baseline calculations presented here are currently being updated to include the results of the NO_x submodel.

Effect of Slagging-Stage Stoichiometry. Parametric model calculations were performed to assess the impact of slagging-stage stoichiometry on combustor performance. Both experimentally and analytically, slagging-stage stoichiometry has been shown to have a strong effect on carbon burnout and NO_x emissions. The initial results described here focus on carbon burnout. NO_x emissions calculations will be presented in the next quarterly report.

Figure 31 shows carbon burnout for the 300×10^6 Btu/h char combustor for different slagging-stage stoichiometries. The baseline stoichiometry, 0.8, is indicated by the solid line. An increase in stoichiometry leads to an increase in carbon burnout, all other things being equal. This parallel is primarily because the average temperature is lower for the lower stoichiometry cases, as well as because a greater proportion of char oxidation occurs through endothermic reactions, which are generally slower than exothermic reactions. These results are consistent with TRW's development experience with substoichiometric coal combustors. In general, larger combustors are less sensitive to stoichiometry levels because of the longer residence times available. Carbon losses range from 1.2 percent for a stoichiometry of 0.6 to less than 0.2 percent for a stoichiometry of 0.9.

Core temperature profiles are plotted in Figures 32 and 33 for the different stoichiometry cases. As discussed, the overall temperature levels are lower for the lower stoichiometry cases, according to thermochemical equilibrium considerations. For all cases, the fraction of char oxidized in the head-end recirculation zone is approximately 0.15 to 0.20. Since less oxygen is available at lower stoichiometry, exothermic reactions in the head-end region are limited, and most of the char oxidation must proceed by endothermic reactions. This phenomenon is indicated more clearly in Figure 33, which expands the head-end region of the combustor.

The main requirement driving the selection of the slagging-stage stoichiometry is the allowable NO_x emissions. At high stoichiometry, excessive amounts of NO are formed

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
Date: November 1993

Figure 31 Effect of Stoichiometry on Char Combustor Carbon Burnout

Figure 32 Effect of Stoichiometry on Char Combustor Core Temperature Profile—Full Combustor Length

62

Figure 33 Effect of Stoichiometry on Char Combustor Core Temperature Profile—Head-End Region Only

within the slagging stage. At low stoichiometry, excessive amounts of NO_x precursors (HCN , NH_3) are formed, which are oxidized to NO during secondary combustion. Intermediate values of stoichiometry (0.7 to 0.8) have been shown to minimize overall NO_x emissions while achieving high levels of carbon burnout. NO_x submodel calculations are currently being performed to identify the optimum stoichiometric range for a char combustor. Results will be reported in the next quarterly report.

Effect of Char Particle Size. Char particle size is another important variable that affects both combustion characteristics and, potentially, NO_x emissions. Table 15 summarizes a comparison between the baseline char particle size distribution (median particle diameter = 60 microns) and a coarser particle size distribution (median particle diameter = 120 microns). The comparison is made for a commercial-scale char combustor (300×10^6 Btu/h) with an air preheat of 1130°F , a precombustor exit temperature of 2000°F , and a slagging-stage stoichiometry of 0.8.

Carbon burnout is plotted for the two particle size cases in Figure 34. As expected, both head-end and overall carbon burnout are somewhat lower for the coarser particle size case. A larger portion of the char is oxidized on the walls of the head end of the combustor for the coarser particle size case, as a greater percentage of the particles contacts the walls before burnout. Carbon losses at the slagging-stage exit amount to 3.1 percent, in comparison to 0.4 percent for the baseline case. The effect of particle size on slag recovery and NO_x emissions will be presented in the next quarterly report.

Subtask 3.29—Preliminary Design of Gas Turbine Piping

GE gas turbines, like most gas turbines, are not designed for the compressor air to be taken from 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-MW plant, has 14 combustors. The design of these combustors is such that the compressor air cools the walls of the combustion chambers. 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.

Two designs are being considered (Figures 35 and 36). In both, the concentric piping arrangement of the combustion chamber is extended out to manifolds. A typical concentric pipe is illustrated in Figure 37. This piping has the 1800°F air from the ceramic air heater on the inside and the 735°F air from the compressor in the annulus. The inner pipe is lined with a ceramic wool insulation, held in place with a perforated metal shield. The manifold collects the compressor discharge air from the individual combustion chambers and splits the heated air going to the combustion chambers. It also provides the transition from the concentric piping required by the gas turbine to the separate pipes that connect to the

Table 15 Effect of Char Particle Size

Key Assumptions		
Feed Stock	=	Pittsburgh No. 8 Char
Particle Size	=	Median
Air Preheat Temperature	=	1130°F (19% O ₂)
Precombustor Exit Temperature	=	2000°F
Slagging Stage Stoichiometry	=	0.8
300 x 10 ⁶ Btu/h Combustor (105-in. Chamber Diameter)		
Results	Particle Size	
	60 Microns	120 Microns
Fraction of coal devolatilized in head-end region	1.0	0.993
Fraction of char consumed on wall in head end	0.200	0.305
Total fraction of char oxidized in head-end region	0.869	0.816
Fraction of total fuel consumed in head-end region	0.909	0.866
Gas temperature at head-end wall, °F (K)	2834 (1830)	3286 (2081)
Gas temperature at head-end exit, °F (K)	2546 (1670)	2672 (1740)
Fraction of total coal consumed in slagging stage	0.996	0.969
Gas temperature at baffle, °F (K)	3526 (2214)	3567 (2237)

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
Date: November 1993

Figure 34 Effect of Particle Size on Carbon Burnout in Commercial-Scale Char Combustor

Figure 35 Straight Manifold Gas Turbine Piping Arrangement

Figure 36 Toroidal Manifold Gas Turbine Piping Arrangement

Ref.: DE-AC22-91PC91154
Date: November 1993

Figure 37 Concentric Pipe Design (Typical)

recuperator and the air heater. The difference between the two designs is basically in the shape of the manifolds.

The first design investigated, where two straight manifolds are used, is shown in Figure 35. This approach simplifies the design of the manifold, but the interconnecting piping between the manifold and the gas turbine is long. Pipe lengths are uneven, which complicates the thermal expansion and support aspects of the design. The uneven pipe lengths also increase cost because there are more parts that are different.

The design shown in Figure 36 uses a toroidal-shaped manifold. This 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 turbine axis. The compressor discharge air in the annular spaces will be collected in the first (cold) toroidal header. The center pipes will 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. The toroidal design appears to have the advantages of lower pressure drops and consistent piping runs, but further investigation is needed before a decision is made.

Subtask 4.9—Plant Performance

The plant heat and material balance and plant performance data (July 7, 1993) are being used for the initial equipment design work. This analysis still requires some revision, but it is sufficiently accurate to serve as the basis for starting the design effort. A revised plant heat and material balance and performance analysis will be issued in November. Work done during this Quarter was primarily in the area of more accurately determining in-plant power consumption and system pressure drops.

In-Plant Power Consumption . The heat and material balance, as well as the performance estimates issued on July 7, 1993, used an assumed level of in-plant or auxiliary power consumption that was based on experience gained from similar systems. During the past quarter, Bechtel identified those balance-of-plant (BOP) and power island components and systems where experience indicates that power demands are large. Power requirements were developed for each of these systems.

Two methods were used. Where possible, the piece of equipment was included as an integral part of the GATE performance analysis, and the power demands were estimated by the program. Equipment such as the vitiated air booster compressor, induced-draft (ID) fan upstream of the emissions control unit, boiler feedwater (BFW) pumps, and condensate pump were accounted for in this manner.

For the cooling water tower, coal- and sorbent-handling facilities, and other supporting systems, estimates were made by extrapolating load demand calculated for similar systems developed for other jobs. Once the approximate power demands were estimated for

the base conditions, the percentage allocated within GATE for miscellaneous auxiliary power demands was adjusted to account for this additional load requirement.

In the July 7 balance, about 2.6 percent of the gross power production was used for in-plant power consumption. This value was based on Pressurized Fluidized Bed Combustion (PFBC) systems recently evaluated by Bechtel. Originally, since both systems use a combination of gas turbine and steam turbine to generate power, the in-plant power requirements were assumed to be similar. This assumption turned out to be somewhat optimistic, mainly because of relatively large power consumption in three areas:

- ID fan capacity to operate the fuel gas furnace at atmospheric pressure
- Compression of vitiated air for the pyrolyzer
- Power demands of the flue gas desulfurization (FGD) system.

Without these systems auxiliary power demands are actually only about 2.2 percent of the gross power production. However, the vitiated air compressor and ID fan together add another 2 percent, and the FGD system is estimated to require an additional 1 percent, which brings the total in-plant power requirements to 5.2 percent. This power requirement is about twice the original estimate. Fortunately, the evaluation of pressure losses through the system (discussed in the next section) provided a lower expected discharge pressure at the exit of the turbine. This decrease in gas turbine discharge pressure increased the turbine power production, offsetting a portion of the increased auxiliary power demand.

System Pressure Drops. With the development of preliminary plant layout drawings (see Subtask 4.17), estimates could be made for pressure losses through the system. The pressure losses in three systems were examined:

- The system between the compressor outlet and turbine inlet
- The dirty gas system between the combustors and the FGD system
- The clean gas system between the turbine outlet and the stack.

Figures 38 and 39 show the pressure relationship. Figure 38 is the high-pressure system; Figure 39 is the low-pressure system, which combines both the clean and dirty gas systems. Setpoints around which the pressure calculations were made consist of:

- Discharge pressure of 218 psia from the air compressor, as set by GE
- Pressure of 0 psig in the fuel gas combustor, as set by FWDC
- Pressure at the stack of 0 psig.

Figure 38 Pressures in High-Pressure Systems

Figure 39 Pressures in Low-Pressure Systems

As Figure 39 shows, the back pressure on the turbine outlet is now estimated to be about 16.0 psia (36 in. H₂O)—down from the 16.8-psia estimated earlier and the 44 in. H₂O given to GE in our meeting in February. This change, combined with other factors and changes in pressure drops throughout the systems, increased the gross power by 4.3 MWe—or about 1.4 percent. The revised pressure levels around the gas turbine have been submitted to GE for confirmation of turbine performance.

Subtask 4.10—Pyrolyzer Subsystem Arrangement and Operation

During this Quarter, the pyrolyzer, cyclones, fuel gas cooler, and coal and sorbent feed systems were designed in sufficient detail to obtain cost estimates. Figure 40 shows the general arrangement of the pyrolyzer subsystem. The pyrolyzer is a circulating fluidized bed, where the bed temperature is maintained at about 1700°F under substoichiometric conditions. With this type of operation, a low-Btu fuel gas and char are produced. The riser section and cyclone are designed so that a large amount of material is recirculated through the bed. This material provides thermal inertia, which maintains even bed temperatures and rapidly brings the feed coal up to the bed temperature.

The fuel gas and char exiting the top of the primary cyclone are the fuel streams for the HITAF. The design and operation of the pyrolyzer and the primary cyclone provide the proper flow rate and char size distribution. The secondary cyclone will remove approximately 80 percent of the char destined to go to the HITAF. The fuel gas and the char particles not removed by the secondary cyclone then go through a fuel gas cooler. In the fuel gas cooler, heat is transferred to superheated steam, and the fuel gas temperature is lowered from 1700°F to 1200°F.

The fuel gas is cooled to remove alkalis. As it is cooled, alkalis condense onto the char particles. These particles are then removed from the fuel gas stream in the barrier filter. The temperature to which the fuel gas is cooled is based on laboratory analysis of soluble alkalis in the char/sorbent mixture and thermodynamic analysis of the fuel gas. The procedure and results have been presented in previous Quarterly Reports [6,16]. The cooled fuel gas enters two, parallel, barrier filter vessels. These filters remove the remaining char from the fuel gas.

The pyrolyzer is designed for full-load operation at 30 psia and at a 13 ft/s superficial gas velocity. Partial-load operation can be accomplished by lowering the pyrolyzer pressure while maintaining a relatively constant superficial gas velocity. In this manner, the fluid dynamics, which are primarily determined by the superficial gas velocity, can be maintained while the airflow rate is reduced. This type of operation is required with the pyrolyzer because the air-to-coal ratio is fixed. In atmospheric fluidized bed combustors, the excess air is generally increased to achieve the same result.

The char collected in the secondary cyclone and barrier filter needs to be reduced in pressure, metered, and transported to the char combustor. This char first enters the surge

Figure 40 Fuel-Gas Generation System

hopper, where it is stored so that char flow to the combustor will not be affected by short-term fluctuations in char flow from the pyrolyzer. Storage also ensures that there will always be a head of material between the cyclone and the restrictive pipe discharge (RPD) hopper.

A small amount of fuel gas flows downward in the pipe between the surge hopper and the RPD hopper and then out through a vent in the RPD hopper. The pressure drop of fuel gas in the packed bed lowers the pressure in the RPD hopper. Pressure is controlled with a valve that meters the flow through the fuel gas vent. With a constant pressure difference between the RPD hopper and the pneumatic transport line, a slide valve at the RPD hopper exit can be used to control char flow.

Because the char collected in the barrier filter will be finer and cooler than the char from the secondary cyclone, a different system is used to depressure and meter this solids flow. In this system, a lock-hopper arrangement reduces the pressure, and a rotary valve meters the flow to the pneumatic transport line.

Pyrolyzer and Cyclones. A drawing of the pyrolyzer vessel is shown in Figure 41. Coal and sorbent are pneumatically injected into this vessel through four nozzles (No. 1) around its circumference. Air is injected through air distribution nozzles just below the coal/sorbent injection nozzles and also through nozzles near the bottom of the vessel. These air distribution nozzles are connected to air plenum chambers.

The riser section of the circulating fluidized bed is from the J-valve inlet nozzle (No. 4) up to the cyclone inlet (No. 9). In this section of the pyrolyzer, char and sorbent are elutriated from the bed, and those particles that are captured by the primary cyclone are re-injected into the bed. This type of operation provides good mixing of the solids and gaseous components. Solids recirculation also tends to maintain even temperatures in the bed and rapidly raises the temperature of the incoming coal. The rapid increase in coal temperature is of benefit to prevent agglomeration.

Below the riser section of the pyrolyzer, there is a constriction of the inside diameter. This constriction separates the riser section from the oxidizer section of the pyrolyzer. The oxidizer section of the pyrolyzer is maintained at a lower superficial gas velocity than the riser section; however, superficial gas velocity in the oxidizer section increases where the internal diameter of the bed is reduced. The effect of this geometry and operation is to preferentially remove the larger and heavier particles from the bottom of the pyrolyzer vessel.

In an ideal situation, the coal and sorbent particles would be sized so that, after conversion and attrition, the proper size and flow rate of particles would leave the bed through the primary cyclone gas outlet. With this type of operation, no material would have to be removed from the bottom of the bed. It is not possible to control the many variables close enough to always ensure that no material will need to be removed from the bottom of the pyrolyzer. Some agglomeration could occur, and particles too large to be elutriated

Y ANCHOR 9" CTR
- 140.9 (3103.5)
Y 3" DIA
Y 9" STAGGERED CTR
Y ANCHORS
- 80275 (3103.5)
TO PROVIDE PLASTIC
TIGHT TIGHT DURING
F REFRACTORY

ELEVATION

NOZZLE CHART			
SIZE	ANGL	SERVICE	NO
1/2"	140.9	3103.5	1
1"	140.9	3103.5	2
2"	140.9	3103.5	3
3"	140.9	3103.5	4
4"	140.9	3103.5	5
6"	140.9	3103.5	6
8"	140.9	3103.5	7
10"	140.9	3103.5	8
12"	140.9	3103.5	9
14"	140.9	3103.5	10
16"	140.9	3103.5	11
18"	140.9	3103.5	12
20"	140.9	3103.5	13
22"	140.9	3103.5	14
24"	140.9	3103.5	15
26"	140.9	3103.5	16
28"	140.9	3103.5	17
30"	140.9	3103.5	18
32"	140.9	3103.5	19
34"	140.9	3103.5	20
36"	140.9	3103.5	21
38"	140.9	3103.5	22
40"	140.9	3103.5	23
42"	140.9	3103.5	24
44"	140.9	3103.5	25
46"	140.9	3103.5	26
48"	140.9	3103.5	27
50"	140.9	3103.5	28
52"	140.9	3103.5	29
54"	140.9	3103.5	30
56"	140.9	3103.5	31
58"	140.9	3103.5	32
60"	140.9	3103.5	33
62"	140.9	3103.5	34
64"	140.9	3103.5	35
66"	140.9	3103.5	36
68"	140.9	3103.5	37
70"	140.9	3103.5	38
72"	140.9	3103.5	39
74"	140.9	3103.5	40
76"	140.9	3103.5	41
78"	140.9	3103.5	42
80"	140.9	3103.5	43
82"	140.9	3103.5	44
84"	140.9	3103.5	45
86"	140.9	3103.5	46
88"	140.9	3103.5	47
90"	140.9	3103.5	48
92"	140.9	3103.5	49
94"	140.9	3103.5	50
96"	140.9	3103.5	51
98"	140.9	3103.5	52
100"	140.9	3103.5	53
102"	140.9	3103.5	54
104"	140.9	3103.5	55
106"	140.9	3103.5	56
108"	140.9	3103.5	57
110"	140.9	3103.5	58
112"	140.9	3103.5	59
114"	140.9	3103.5	60
116"	140.9	3103.5	61
118"	140.9	3103.5	62
120"	140.9	3103.5	63
122"	140.9	3103.5	64
124"	140.9	3103.5	65
126"	140.9	3103.5	66
128"	140.9	3103.5	67
130"	140.9	3103.5	68
132"	140.9	3103.5	69
134"	140.9	3103.5	70
136"	140.9	3103.5	71
138"	140.9	3103.5	72
140"	140.9	3103.5	73
142"	140.9	3103.5	74
144"	140.9	3103.5	75
146"	140.9	3103.5	76
148"	140.9	3103.5	77
150"	140.9	3103.5	78
152"	140.9	3103.5	79
154"	140.9	3103.5	80
156"	140.9	3103.5	81
158"	140.9	3103.5	82
160"	140.9	3103.5	83
162"	140.9	3103.5	84
164"	140.9	3103.5	85
166"	140.9	3103.5	86
168"	140.9	3103.5	87
170"	140.9	3103.5	88
172"	140.9	3103.5	89
174"	140.9	3103.5	90
176"	140.9	3103.5	91
178"	140.9	3103.5	92
180"	140.9	3103.5	93
182"	140.9	3103.5	94
184"	140.9	3103.5	95
186"	140.9	3103.5	96
188"	140.9	3103.5	97
190"	140.9	3103.5	98
192"	140.9	3103.5	99
194"	140.9	3103.5	100

VESSEL DATA			
1	INTERIOR SURF. AREA	17	PSIG
2	INTERIOR SURF. AREA	18	PSIG
3	INTERIOR SURF. AREA	19	PSIG
4	INTERIOR SURF. AREA	20	PSIG
5	INTERIOR SURF. AREA	21	PSIG
6	INTERIOR SURF. AREA	22	PSIG
7	INTERIOR SURF. AREA	23	PSIG
8	INTERIOR SURF. AREA	24	PSIG
9	INTERIOR SURF. AREA	25	PSIG
10	INTERIOR SURF. AREA	26	PSIG
11	INTERIOR SURF. AREA	27	PSIG
12	INTERIOR SURF. AREA	28	PSIG
13	INTERIOR SURF. AREA	29	PSIG
14	INTERIOR SURF. AREA	30	PSIG
15	INTERIOR SURF. AREA	31	PSIG
16	INTERIOR SURF. AREA	32	PSIG
17	INTERIOR SURF. AREA	33	PSIG
18	INTERIOR SURF. AREA	34	PSIG
19	INTERIOR SURF. AREA	35	PSIG
20	INTERIOR SURF. AREA	36	PSIG
21	INTERIOR SURF. AREA	37	PSIG
22	INTERIOR SURF. AREA	38	PSIG
23	INTERIOR SURF. AREA	39	PSIG
24	INTERIOR SURF. AREA	40	PSIG
25	INTERIOR SURF. AREA	41	PSIG
26	INTERIOR SURF. AREA	42	PSIG
27	INTERIOR SURF. AREA	43	PSIG
28	INTERIOR SURF. AREA	44	PSIG
29	INTERIOR SURF. AREA	45	PSIG
30	INTERIOR SURF. AREA	46	PSIG
31	INTERIOR SURF. AREA	47	PSIG
32	INTERIOR SURF. AREA	48	PSIG
33	INTERIOR SURF. AREA	49	PSIG
34	INTERIOR SURF. AREA	50	PSIG
35	INTERIOR SURF. AREA	51	PSIG
36	INTERIOR SURF. AREA	52	PSIG
37	INTERIOR SURF. AREA	53	PSIG
38	INTERIOR SURF. AREA	54	PSIG
39	INTERIOR SURF. AREA	55	PSIG
40	INTERIOR SURF. AREA	56	PSIG
41	INTERIOR SURF. AREA	57	PSIG
42	INTERIOR SURF. AREA	58	PSIG
43	INTERIOR SURF. AREA	59	PSIG
44	INTERIOR SURF. AREA	60	PSIG
45	INTERIOR SURF. AREA	61	PSIG
46	INTERIOR SURF. AREA	62	PSIG
47	INTERIOR SURF. AREA	63	PSIG
48	INTERIOR SURF. AREA	64	PSIG
49	INTERIOR SURF. AREA	65	PSIG
50	INTERIOR SURF. AREA	66	PSIG
51	INTERIOR SURF. AREA	67	PSIG
52	INTERIOR SURF. AREA	68	PSIG
53	INTERIOR SURF. AREA	69	PSIG
54	INTERIOR SURF. AREA	70	PSIG
55	INTERIOR SURF. AREA	71	PSIG
56	INTERIOR SURF. AREA	72	PSIG
57	INTERIOR SURF. AREA	73	PSIG
58	INTERIOR SURF. AREA	74	PSIG
59	INTERIOR SURF. AREA	75	PSIG
60	INTERIOR SURF. AREA	76	PSIG
61	INTERIOR SURF. AREA	77	PSIG
62	INTERIOR SURF. AREA	78	PSIG
63	INTERIOR SURF. AREA	79	PSIG
64	INTERIOR SURF. AREA	80	PSIG
65	INTERIOR SURF. AREA	81	PSIG
66	INTERIOR SURF. AREA	82	PSIG
67	INTERIOR SURF. AREA	83	PSIG
68	INTERIOR SURF. AREA	84	PSIG
69	INTERIOR SURF. AREA	85	PSIG
70	INTERIOR SURF. AREA	86	PSIG
71	INTERIOR SURF. AREA	87	PSIG
72	INTERIOR SURF. AREA	88	PSIG
73	INTERIOR SURF. AREA	89	PSIG
74	INTERIOR SURF. AREA	90	PSIG
75	INTERIOR SURF. AREA	91	PSIG
76	INTERIOR SURF. AREA	92	PSIG
77	INTERIOR SURF. AREA	93	PSIG
78	INTERIOR SURF. AREA	94	PSIG
79	INTERIOR SURF. AREA	95	PSIG
80	INTERIOR SURF. AREA	96	PSIG
81	INTERIOR SURF. AREA	97	PSIG
82	INTERIOR SURF. AREA	98	PSIG
83	INTERIOR SURF. AREA	99	PSIG
84	INTERIOR SURF. AREA	100	PSIG

Figure 41 Pyrolyzer Riser Vessel

would build up in the bed. The oxidizer section of the bed is designed allow the removal from the bottom of the bed while minimizing the unburned carbon and calcium sulfide in this material. By using larger sorbent particles than coal particles, it may be possible to remove sulfur from the system at this point. This type of operation will be investigated in Phase 2 testing.

The vessel has a 13 ft-6 in. O.D. and is 104 ft high. It is constructed of carbon steel and is internally lined with refractory (6 in. of HW-22 lightweight castable refractory for insulation and a 3-in. layer of Resco RS-17E hard face refractory on the I.D. to prevent erosion). The refractory is held to the shell with stainless steel anchors. The air distribution nozzles are the same design as those used in commercial CFB units.

The primary and secondary cyclones are lined with the same refractory as the pyrolyzer. The primary cyclone (Figure 42) is designed for an inlet velocity of 50 ft/s and the secondary cyclone (Figure 43) for an inlet velocity of 90 ft/s.

Fuel Gas Cooler. The fuel gas cooler is shown in Figure 44. Here heat is transferred from the fuel gas to superheated steam. The steam is superheated from 750 to 805°F, and the fuel gas temperature is lowered from 1700°F to 1200°F. Using superheated steam for this heat exchanger simplifies the design. The construction is the common method of supporting serpentine tube elements from a tubewall enclosure.

Fuel Gas Filter. To minimize particulate carryover to the ceramic air heaters, a barrier filter will be used for final fuel gas cleanup. The gaseous and particulate environment that will confront the fuel gas filter is given in Table 16. The filters itemized in Table 17 essentially represent the full scope of available media types. A vendor for each filter medium has been identified, and these vendors are also listed in the table. Each vendor has been contacted and asked to consider and report on the expected performance of his filter medium when applied to the conditions given in Table 17. It may be possible to eliminate one or more of the filter media candidates based on evaluation of the existing data. The most-promising candidates will be tested in Phase 2 under actual operating conditions.

Coal and Sorbent Feed System. Flow diagrams of the coal and sorbent pulverizing systems are shown in Figures 45, 46, and 47. These are basically commercial systems that have been designed by Williams Patent Crusher and Pulverizer Corporation, Inc. (Williams) for our requirements. The coal pulverizer in Figure 45 feeds coal to the char precombustors. This is a simple direct-fired arrangement, and one pulverizer will feed both precombustors. If this pulverizer requires maintenance, natural gas will be used to fire the precombustor.

There will be one sorbent pulverizer system and one coal pulverizer system for each pyrolyzer. Some of our initial designs used one pulverizer to grind both the coal and the sorbent. That type of operation has been successful, but then there is no separate control of the coal size and sorbent sizes [17]. If we use a sorbent that is larger than the coal, it may be possible to remove some spent sorbent from the pyrolyzer and thereby reduce the efficiency requirement of the back-end sulfur-removal system.

FOSTER WHEELER DEVELOPMENT CORPORATION

TYPE NOZZLE DETAIL
FOR FIELD WELD

DETAIL "A"
TYP. REFRACTORY DETAIL
(DUAL-LAYER)

VESSEL DATA		
1	ITEM NO	NO REQ'D 2ND
2	SERVICE PRIMARY CYCLONE	
3		
4	OPER PRESSURE ABOVE 1 NORM	7 PSIG
5	LIQUID LEVEL MAX	19 PSIG
6	DESIGN PRESSURE INT	30 PSIG
7	EXT	PSIG
8	OPER LIQUID HOLD 1 PRESS	PSIG
9	OPER PRESS DROP THRU VESSEL	3 PSIG
10	MAX RELIEVING PRESS AT TOP HD	4 PSIG
11	MAX OPER TEMPERATURE	100° F INT/321° F
12	DESIGN TEMPERATURE	120° F
13	SPECIFIC GRAVITY PROCESS FLUID	0.6 (WAT)
14	MIN DESIGN METAL TEMP	3° F
15	WIND DATA ASCE 7-88	70 MPH EXPOS
16	EARTHQUAKE DATA ASCE 7-88	ZONE 4
17	CODE ASME DIV 1	STAMPED YES
18	WMT FOR CODE	OR PROCESS NO
19	RADIATION PROTECT	92% METAL BD YES
20	JOINT EFFICIENCY	85%
21	CORROSION ALLOW	1/8"
22	WALL SHELL	SA-516-70
23	WALL HEADS	SA-516-70
24	WALL SUPPORTS	SA-516-70
25	WALL FLANGES	SA-105
26	WALL NOZZLES	SA-106-B/SA-236-WPB
27	EXTERNAL BOLTING	SA-193-B7/SA-193-2H
28	WALL COILS	SA-516-70
29	GASKETS SPIRAL WOUND	316 SS/GRAPOL
30	TYPE OF HEADS	ELLIPITICAL
31		
32		
33	INSULATION TYPE	NONE
34	NT	300 PSF 1" AN
35	PAINT	PRIMER ONLY 70-35/P-101
36	TEMPERATURE	ONE PIECE
37	VOLUME	4445 GRT
38	EMPTY WGT METAL ONLY	47,500 LB
39	WATER ONLY WGT	343,500 LB
40	REMOVABLE TRAY WGT	LB
41	PACKING CATALYST WGT	LB
42	INSULATION WGT	LB
43	ROOF TRUCK	37,400 LB
44	OPER LIQUID WGT	LB

NOZZLE CHART				
NO. No.	SIZE	AN# DATE	SERVICE	NO. REQ. LINE
1	3" 8' 6"	WYB 2-7	INLET	1
2	7' 0"	---	OUTLET	1
3	5' 0"	---	DRAIN	1
4	3' 0"	Q150	MANWAY & JAVIF	1
5	3"	Q6300	FEED	1
6	3"	---	TEMP	1
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
22				
23				
24				
25				
26				
27				
28				
29				
30				
31				
32				
33				
34				
35				
36				
37				
38				
39				
40				
41				
42				
43				
44				
45				
46				
47				
48				
49				
50				

Figure 42 Pyrolyzer Primary Cyclone

FOSTER WHEELER DEVELOPMENT CORPORATION

270°

270°

270°

270°

TYP. NOZZLE DETAIL
FOR FIELD WELD

DETAIL "A"
TYP. REFRACTORY DETAIL
(DUAL LAYER)

GENERAL DATA			
1	ITEM NO	NO REQD	026
2	HAYES: SUGGESTARY CYCLONE		
3			
4	OPER PRESSURE ABOVE	NORM.	7
5	LIQUID LEVEL	MAX	14
6	DESIGN PRESSURE	INT	50
7		EXT	
8	OPER LIQUID HOLD. UP PRESS		051G
9	OPER PRESS DROP THRU VESSEL		051G
10	MAX RELIEVING PRESS AT TOP MO		3
11	MAX OPER TEMPERATURE		19 PS G
12	DESIGN TEMPERATURE		1700 (INTERNAL)
13	SPECIFIC GRAVITY PROCESS FLUID		50°F
14	MMB DESIGN METAL TEMP.		0.6 (DUST)
15	WIND DATA: ASCE 7-88		91°
16	EARTHQUAKE DATA		70 MPH EX P.C.
17	CRSE. ASME DIV. 1 FLANGE		ASCE 7-88 ZONE 1
18	P.W.T FOR CODE NO		Y32
19	RADIATION		NO
20	JOINT EFFICIENCY		50% FOR P.C.
21	STRESSER ALLOW		Y42
22	MAT'L SHELL		1/2"
23	MAT'L HEAD		SA-516-70
24	MAT'L SUPPORT		SA-516-70
25	MAT'L FLANGE		SA-516-70
26	MAT'L NOZZLES		SA-106-B/SA-236-WPB
27	EXTERNAL COATING		1A-199-B/1A-199-2H
28	MAT'L COMB.		SA-516-70
29	GASKETS		SPRINGS
30	TYPE OF HEAD		ELLIPITICAL
31			
32			
33	INSULATION: TEXT		WOM
34	INT		50% D.T. A"
35	PAINT		PRIMER ONLY
36	STRUCT		ONE PICES
37	VOLUME		1470
38	EMPTY WT		METAL ONLY
39	WATER ONLY WT		147.300
40	REMOVABLE TRAY WGT		147.300
41	PACKING CATALYST ET. WGT		
42	INSULATION WGT		
43	REFRACTORY:		
44	OPER LIQUID WGT		51.700

[illegible]

Figure 43 Pyrolyzer Secondary Cyclone

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-AC22-91PC91154
 Date: November 1993

Figure 44 Fuel Gas Cooler

Table 16 Fuel Gas Composition (2 atm/1200°F)

Gas			
Constituent	Mol wt	wt%	vol%
CO	28.00	21.77	18.97
CO ₂	44.00	12.52	6.94
H ₂	2.00	1.18	14.39
H ₂ O	18.00	5.22	7.07
CH ₄	16.00	1.32	2.01
NH ₃	17.00	0.16	0.23
H ₂ S	34.00	0.04	0.03
O ₂	32.00	0.00	0.00
N ₂	28.00	57.79	50.35
Mol wt = 24.40			
Solids			
Constituent	wt%		
Carbon	64.67		
SiO ₂	8.02		
Al ₂ O ₃	4.15		
TiO ₂	0.16		
Fe ₂ O ₃	4.83		
CaS	12.40		
CaO	3.56		
MgO	0.17		
Na ₂ SO ₄	0.36		
K ₂ SO ₄	0.60		
SO ₃	1.05		
P ₂ O ₅	0.04

Table 17 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

Figure 45 Precombustor Coal Pulverizer System (Williams)

FEED RATE= 6,000
EVAP LBS/HR= 61
PROD LBS/HR= 5,939
DRY SOLIDS= 5,880
INITIAL H₂O= 2.0
FINAL H₂O= 59- 1.0%
HARDGROVE= 37.3

VENT TEMP= 120 48.9C
DEM POINT= 62
EXHAUST ACFM= 1,455

Figure 46 Pyrolyzer Sorbent Pulverizer System (Williams)

2 of 2

FEED RATE= 67,000
EVAP LBS/HR= 3,384
PROD LBS/HR= 63,616
DRY SOLIDS= 62,980
INITIAL H₂O= 6.0
FINAL H₂O= 636- 1.0%
HARDGROVE= 57.0

VENT TEMP= 180 82.2C
DEN POINT= 153
EXHAUST ACFM= 6,412

Figure 47 Pyrolyzer Coal Pulverizer System (Williams)

Flow diagrams of the pyrolyzer sorbent and coal pulverizing systems are shown in Figures 46 and 47. These systems are bin systems. They have also been designed by Williams. Bin systems are used commercially when coal or another pulverized product cannot be used directly from the pulverizer. In our case, the pressure in the pyrolyzer prohibits direct coal firing and sorbent injection. There are no existing pulverizers that can operate at 2 atm pressure. In the bin systems, the pulverizer operates in the conventional manner, with a gaseous medium blowing through the pulverizer to entrain the pulverized product. After leaving the pulverizer, however, the solids are removed from the gas by a cyclone and a baghouse. The solids are then collected in a hopper and fed to a pneumatic transport line with a solids pump. The gas that goes through the pulverizer is recycled, for the most part; however, a portion of this gas needs to be removed from the system through the baghouse.

The coal system differs from the sorbent system in that a natural gas-fired dryer is used. This dryer has two purposes. It provides air at 900°F to dry the coal in the mill. It also provides an inert gas (the products of combustion) to prevent explosions in the bin system.

Firth pumps are being proposed to inject the solids into the pneumatic transport line. These pumps are under development, but successful tests have been run at pressures of up to 27 psig [18]. These pumps will be tested as part of the Phase 2 R&D.

Subtask 4.12—High-Temperature Furnace Design and Cost Estimate

The HITAF design has been determined to a great extent by the requirements of the ceramic air heater. Because of design restrictions imposed by available ceramic materials, we were not able to integrate the air heaters into the tubewall furnaces. Instead, the ceramic air heaters were kept as separate modules that are supported independently from the rest of the HITAF. Expansion joint seals are used to connect the ceramic air heaters to other parts of the HITAF.

Figure 48 depicts the HITAF arrangement. Four ceramic air heater modules are stacked vertically. The design of these modules has been discussed in previous Quarterly Reports [19,20]. Each of the modules is separately supported from structural steel. The remainder of the HITAF enclosure is of tubewall construction, supported at the top in the typical manner.

Fuel gas is fired in the fuel gas furnace, and the products of combustion go through the ceramic air heater modules. The fuel gas furnace walls are MONOWALL® panels with 1.5-in. O.D. tubes. The inside surface of the enclosure is studded and lined with 1 in. of low-conductivity plastic refractory. The refractory is used to limit the furnace heat absorption and thereby provide high-temperature gas entering the ceramic air heaters. The temperature entering the air heater is 2935°F. The furnace walls are forced-circulation evaporator surface.

Figure 48 High-Temperature Advanced Furnace

Some earlier HITAF arrangements had the fuel gas furnace parallel to the char furnace with a 90-deg turn into the ceramic air heaters. This arrangement prevents the ceramic air heater from being exposed to direct radiation from the fuel gas burners. A preliminary analysis was done by Research-Cottrell to estimate the gas distribution entering the air heaters with this arrangement. This analysis was done with the Phoenix fluid-flow model. Although the flow model needs to be revised to represent our conditions more accurately, initial results indicate that the distribution could be quite uneven. The current approach is to have the flue gas flow directly into the ceramic air heaters, but to design the initial rows for direct flame radiation.

The flue gas leaving the ceramic air heater modules flows downward in an open passage and then upward in a passage that spans the width of the main HITAF enclosure. This arrangement can best be seen in Figure 49. The unsymmetrical arrangement of the fuel gas furnace and the char furnace was necessitated by the structural constraints of the ceramic air heaters. The arrangement is certainly not ideal from the standpoint of distribution of flue gas entering the main HITAF. The problem was overcome by providing a relatively large open passage where flue gas from the ceramic air heaters is distributed across the unit before it is mixed with the flue gas from the char-fired furnace. This chamber also turns out to be a good place to inject ammonia or urea for an SNCR system (see Subtask 3.21).

Subtask 4.13—Char Combustor Design and Cost Estimate

The primary objective of the char combustor conceptual design task is to develop a conceptual design and cost estimate for the char combustor subsystem in support of the evaluation of overall plant technical and economic feasibility. Char combustor operating requirements have been derived in an iterative fashion as the overall plant heat and material balance has been developed. Combustor design criteria have also been developed based on previous TRW slagging combustor development experience, experimental results obtained during char characterization testing at BYU, and combustor analytical modeling activities.

The char combustor design is based primarily on TRW's slagging coal combustor technology. Recently, TRW's 40×10^6 Btu/h combustor (34-in. chamber diameter) has been scaled up to 350×10^6 Btu/h (105-in. chamber diameter) as part of the Healy Clean Coal Project cofunded by the Department of Energy [21]. The proposed char combustor for this project has similar size requirements similar to those for the Healy coal combustor.

Preliminary char combustor dimensions have been established based on the design requirements, design criteria, and preliminary analytical model calculations. Parametric analytical model calculations are now being performed to determine final combustor dimensions, as well as to identify the combustor operating envelope. Initial results from these calculations are presented in Subtask 3.27. Separate thermal and mechanical analyses are also being conducted to select combustor materials and methods of construction. Once the combustor dimensions, operating conditions, materials, and method of construction are

Figure 49 Sectional Side View of HITAF

selected, preliminary combustor costs will be estimated. This cost estimate will be based primarily on the cost data developed at part of the Healy project.

Char Combustor Operating Conditions. The char combustor operating conditions were summarized earlier in Table 12. This summary is based on the July 1, 1993, heat and material balance performed by Bechtel. The overall char firing rate is 448×10^6 Btu/h, which includes the heating value of the fuel gas that transports the char to the combustor. Pulverized coal is fired in the precombustor to raise the air temperature from 1130°F to $\approx 2000^\circ\text{F}$. This temperature level is necessary at the inlet to the combustor slagging stage to prevent fouling and to ensure rapid combustion of char within the head-end of the combustor. Parametric combustor analytical model calculations are being performed to determine the sensitivity of overall combustor performance to precombustor exit temperature.

The baseline slagging-stage stoichiometry has been selected at 0.8 (fuel rich). The selection of slagging-stage stoichiometry represents a trade-off among carbon burnout, NO_x emissions, and combustor cooling load. More-detailed char combustor analytical model calculations are being performed to verify this selection as well as to determine the performance of the char combustor as a function of stoichiometry.

The combustor cooling load, (92×10^6 Btu/h), represents 17 percent of the char combustor fuel thermal input. This value was determined through analytical model calculations, which agree well with 34-in. slagging combustor test results. An additional cooling load of 3.5×10^6 Btu/h is obtained from the precombustor, representing 3 percent of the precombustor fuel thermal input. This value is based on Healy precombustor testing performed in 1992 at TRW's Capistrano Test Site (CTS).

Selection of the Number of Char Combustors. One of the key combustor design decisions is the determination of the number of char combustors for the baseline 290-MWe power generation system. Important considerations affecting this decision include maximum turndown for each combustor, maximum combustor size, number of pyrolyzers, complexity, and cost.

The required char combustor turndown is 3:1. Based on past development experience, TRW slagging combustors can operate effectively down to approximately 50 percent of the nominal firing rate, or a turndown of 2:1 for each combustor. In the Healy project, twin combustors are fired into a single furnace.

The operating envelope of a char-fired combustor (relative to coal) is being determined initially through analytical modeling. Assuming that the maximum turndown for an individual char combustor is no greater than 2:1, then at least two char combustors are required to achieve a total char combustor turndown of 3:1. This 3:1 turndown can be achieved by operating only one of the two char combustors at approximately 67-percent load.

The largest TRW slagging combustor designed to date is the Healy combustor [22], with a maximum continuous firing rate of 350×10^6 Btu/h and a chamber diameter of 105 in. Cyclone combustors have been designed with chamber diameters of up to 12 ft. Two char combustors firing at 280×10^6 Btu/h each (560×10^6 Btu/h total) would require approximately the same chamber diameter as the Healy combustor. This diameter is needed because the lower fuel firing rate for the char combustor is offset by a higher required airflow rate for the char when utilizing vitiated air from the gas turbine exhaust.

The selection of two char combustors will also match the proposed number of pyrolyzers. Thus each char combustor can be dedicated to a specific pyrolyzer, eliminating the need for temporary char storage and fuel splitting at the outlet of the pyrolyzers.

Finally, from the viewpoint of complexity and cost, it is desirable to keep the number of char combustors to a minimum. Each additional char combustor will add to the complexity and overall cost of the system. Based on these considerations, the baseline HIPPS configuration selected was two char combustors.

Char Combustor Preliminary Sizing. A three-dimensional view of the proposed char combustor configuration is shown in Figure 50. The char combustor system consists of a coal-fired precombustor, a char-fired slagging stage, a slag-recovery section, a slag tank, and an exhaust duct. The geometry of the exhaust duct can be modified if necessary according to furnace interface requirements. This basic configuration follows the design of the Healy combustors. The key char combustor internal dimensions were summarized earlier in Table 13.

Parametric char combustor analytical model calculations are being performed to determine the effect of key combustor geometric dimensions on combustor performance. These calculations will be used to help make the final selection of combustor dimensions for the conceptual design. Important combustor design parameters to be varied include chamber diameter, chamber length, head-end volume, and injector configuration.

Char Combustor Flow Parameters. Figure 51, a schematic of the coal-fired precombustor, indicates flow rates, pressures, and temperatures at various locations. These flow rates assume that two char combustors are utilized in the baseline 290-MWe plant. An oil or natural-gas pilot burner is provided at the center of the precombustor coal burner to assist during start-up, shutdown, or load changes, if required. Pulverized coal is transported to the precombustor by mill air at a ratio of approximately 1.8 lb air/lb coal. The coal and air mixture is introduced tangentially into the precombustor burner, creating a swirling flow. Primary air is also introduced into the precombustor burner to achieve a precombustor chamber stoichiometry of approximately 0.8. Secondary air is introduced separately downstream of the combustion chamber and mixed with the primary combustion products from the precombustor burner. The temperature at the exit of the precombustor is 2000°F, at an overall stoichiometry of 3.85. These values translate into an oxygen content of 12.5 vol%. Flow dampers at the transition between the precombustor and slagging stage control the slagging-stage inlet tangential velocity.

FOSTER WHEELER DEVELOPMENT CORPORATION

Ref.: DE-ACC22-91PC91154
Date: November 1993

Figure 50 Proposed Char Combustor Configuration

COAL-FIRED
PRECOMBUSTOR

CHAR-FIRED
SLAGGING STAGE

SLAG RECOVERY SECTION

SLAG TANK

EXHAUST
DUCT

Figure 51 Precombustor Flow Conditions

A schematic of the char-fired slagging stage is shown in Figure 52. Again, flow rates were determined assuming two char combustors for the baseline 290-MWe plant. The precombustor exhaust gases enter the slagging stage at velocities between 200 and 400 ft/s. Hot char is injected into the head end of the combustor through multiple injectors. The char is transported by a fraction of the fuel gas that is generated in the pyrolyzer. The ratio of char to fuel gas is approximately 20:1. Molten slag is rejected from the combustor and quenched in a water tank, forming a granular, vitrified product that is amenable to either disposal in a landfill or reuse as a construction material. The combustor exhaust gases are directed upward and are injected either vertically or horizontally into the furnace, where a final stage of air is added to complete combustion while minimizing NO_x formation.

Effect of Mill Air Temperature. The plant heat and material balance prepared on July 1, 1993, assumed that all char combustor air is available at 1132°F. However, a portion of the total combustion air is the mill sweep air, which also transports the coal to the precombustor. This air stream is expected to be at approximately 130°F, with an oxygen content of 19 wt% (same as the primary and secondary combustion air). The addition of the mill air lowers the effective air preheat temperature to 1093°F. Precombustor combustion calculations were performed to assess the impact of this temperature decrease on precombustor exit temperature and precombustor coal requirements.

A plot of precombustor exit temperature as a function of precombustor coal flow rate is shown in Figure 53. Calculations were performed at inlet air temperatures of 750, 1093, and 1132°F. As indicated in the figure, the decrease in the effective air temperature from 1132°F to 1093°F because of the addition of mill air has a very small effect on the precombustor exit temperature, decreasing the temperature from 2000°F to 1964°F at the nominal coal flow of 9000 lb/h (total of two precombustors). The temperature can be returned to 2000°F by increasing the total precombustor coal flow by 300 lb/h, to a rate of 9300 lb/h.

Subtask 4.16—Power Island and Balance of Plant Cost Estimate

Conceptual design work was initiated for the BOP water systems, including the BFW system, the cooling water system, the raw water intake and treatment system, effluent treatment system, and potable water system. The raw water analysis is based on a Lake Michigan water analysis used in several recent EPRI studies. Once each system was sufficiently defined, a request for performance details and budgetary price quotations was sent to one or more manufacturers. These data will be used to confirm design estimates and to provide information on catalyst and chemical demands for each system.

Subtask 4.17—Plant Arrangement

Bechtel continued to work with FWDC and FWEC to develop a workable and practical layout for the major power island components. The critical systems include the char furnace, ceramic air heaters, fuel gas furnace, and gas turbine. The location of the other systems such as the pyrolyzers, steam turbine, recuperator, and heat-recovery steam

Figure 52 Slagging-Stage Flow Conditions

Figure 53 Effect of Adding Mill Air on Precombustor Exit Temperature and Coal Flow Requirements

generators (HRSGs) were also considered, but the location of these systems is not as critical.

The major decision to be made for the plant layout is the relative locations of the char furnace, fuel gas furnace, and ceramic air heaters. Three basic configurations were considered (Figures 54, 55, and 56). In all three, the ceramic air heater is closely coupled to the fuel gas furnace, eliminating the very-high-temperature ducting that would be required between the two pieces of equipment.

The arrangement shown in Figure 54 has the fuel gas furnace located parallel to the char furnace. This arrangement has the advantage of providing a fairly compact system. It minimizes the distance from the ceramic air heater to the gas turbine, which is a benefit. There is, however, a major drawback to this arrangement. It requires a long duct with a 90-deg bend to transfer the gas from the ceramic air heater to the char furnace. This duct will be expensive and may be difficult to build.

An alternative arrangement is shown in Figure 55. In this arrangement the ceramic air heaters are closely coupled to both the fuel gas furnace and the char furnace. Passages in the HITAF collect the flue gas streams from the ceramic air heaters and mix them with the flue gas from the char furnace. In this arrangement, the in-line placement of the gas turbine, ceramic air heater, and fuel gas furnace system was maintained, but the gas turbine ended up farther away from the other equipment. This situation lengthened the large hot air lines taking gas to and over the turbine. The arrangement was an improvement over configuration shown in Figure 54, but further improvement was thought possible.

Figure 56 shows the compromise between the arrangements shown in Figures 54 and 55 that is currently being examined in more detail. In this configuration, the close coupling of the fuel gas furnace, ceramic air heaters, and char furnace is maintained, but the gas turbine is located at a 90-deg angle to the fuel gas furnace in the approximate location shown in Figure 56. To minimize the difference in line lengths and therefore pressure drops, the lines to and from the ceramic air heater are crossed.

A quick analysis was performed by Bechtel's piping stress group to determine whether any one of these arrangements offered significant advantages or disadvantages over the other two. Although no strong advantage was found, the configuration shown in Figure 56 appeared to be as good or better than the other two. This confirmation, coupled with the other advantages already mentioned, led us to choose this arrangement for the conceptual plant design. Elevation drawings are now being developed to help evaluate this configuration in more detail.

An examination of the piping stresses for the large, high-temperature air lines is now under way. The purpose of the examination is to reveal fatal flaws (if any) not detected in the first analysis and to come up with recommendations for materials, layouts, and supports required for these interconnecting pipes. The effort is now concentrating on the interface to and from the ceramic air heater.

FOSTER WHEELER DEVELOPMENT CORPORATION

Figure 54 Plant Layout—Gas Furnace
Parallel to Char Furnace
(Grade Level)

FOSTER WHEELER DEVELOPMENT CORPORATION

ACCESS F

Figure 55 Plant Layout—Ceramic Air Heaters Closely Coupled to Fuel Gas and Char Furnace (Grade Level)

**Figure 56 Plant Layout—Gas Turbine
at 90-deg Angle to Fuel
Gas Furnace (Below
El. 25 ft)**

REFERENCES

1. Foster Wheeler Development Corporation, "Development of a High-Performance Coal-Fired Power Generating System With Pyrolysis Gas and Char-Fired High-Temperature Furnace (HITAF)—Quarterly Report 6 (April through June 1993)," DOE PETC under Contract DE-AC22-91PC91154, August 1993, pp. 2-20.
2. Foster Wheeler Development Corporation, "Development of a High-Performance Coal-Fired Power Generating System With Pyrolysis Gas and Char-Fired High-Temperature Furnace (HITAF)—Quarterly Report 5 (January through March 1993)," DOE PETC under Contract DE-AC22-91PC91154, May 1993, pp. 17-19.
3. N. S. Jacobson, et al., "Molten Salt Corrosion of SiC and Si₃N₄" *Handbook of Ceramics and Composites*, Vol. 1, 1990, pp. 99-136.
4. M. K. Ferber and V. J. Tennery, "Evaluation of Tubular Ceramic Heat Exchanger Materials in Basic Coal Ash From Coal-Oil-Mixture Combustion," DOE Contract W-7405-eng-26 with Union Carbide, October 1982.
5. W. A. Kern, R. E. Tressler, and M. J. McNallen, "Durability of SiC/Al₂O₃ Composites in Contact with Sodium Silicate," *Center for Advanced Materials Newsletter*, Vol. 6, 1992, pp. 1-6.
6. Foster Wheeler Development Corporation, "Development of a High-Performance Coal-Fired Power Generating System With Pyrolysis Gas and Char-Fired High-Temperature Furnace (HITAF)—Quarterly Report 6 (April through June 1993)," DOE PETC under Contract DE-AC22-91PC91154, August 1993, pp. 22-25.
7. M. G. Alliston, "The Integration of System Parameters in the Modeling of CFB Solids and Carbon Behavior," *Proceedings of the 1989 International Conference on Fluidized Bed Combustion*, pp. 31-36.
8. D. Landini, personal communication to S. Van Weele, Foster Wheeler Development Corporation, October 22, 1993.
9. 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, PA, 1992.
10. 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, PA, 1992, pp. 634-639.
11. R. H. Hurt, personal communication to Andrew Grove, TRW Inc., 1993.

12. H. Schreiber, "Combustion NO_x Controls for Combustion Turbines," *Proceedings of the 1991 Symposium on Stationary Combustion NO_x Control*.
13. S. J. Priebe, et al., "An Assessment of Nitrogen Oxide Formation in Preheated High-Temperature Combustion Air in Industrial Processes," Final Report EGG-2439 to the DOE Under Contract DE-AC07-76ID01570, 1986.
14. J. P. Smart and D. J. Morgan, "Multi-Fuel Reburning in a Coal-Fired Internally Fuel Staged Burner for NO_x Reduction," *Proceedings of the 1993 Symposium on Stationary Combustion NO_x Control*.
15. Foster Wheeler Development Corporation, "Development of a High-Performance Coal-Fired Power Generating System With Pyrolysis Gas and Char-Fired High-Temperature Furnace (HITAF)—Quarterly Report 3 (July through September 1992)," DOE PETC under Contract DE-AC22-91PC91154, November 1992, pp. 17-37.
16. Foster Wheeler Development Corporation, "Development of a High-Performance Coal-Fired Power Generating System With Pyrolysis Gas and Char-Fired High-Temperature Furnace (HITAF)—Quarterly Report 3 (July through September 1992)," DOE PETC under Contract DE-AC22-91PC91154, November 1992, pp. 8-10.
17. C. Rehmer, personal correspondence with J. Shenker, Foster Wheeler Development Corporation, January 22, 1993.
18. A. G. Hay, "The Metered Delivery of Solids Into Pressure: A Radically New Machine Concept," *Presented at the Bulk Solids Conference*, 1992.
19. Foster Wheeler Development Corporation, "Development of a High-Performance Coal-Fired Power Generating System With Pyrolysis Gas and Char-Fired High-Temperature Furnace (HITAF)—Quarterly Report 5 (January through March 1993)," DOE PETC under Contract DE-AC22-91PC91154, May 1993, pp. 41-46.
20. Foster Wheeler Development Corporation, "Development of a High-Performance Coal-Fired Power Generating System With Pyrolysis Gas and Char-Fired High-Temperature Furnace (HITAF)—Quarterly Report 6 (April through June 1993)," DOE PETC under Contract DE-AC22-91PC91154, August 1993, pp. 49-55.
21. S. Ubhayakar, "The Healy Clean Coal Project: Design Verification Tests," *Proceedings of the Second Annual Clean Coal Technology Conference*, Atlanta, GA, 1993.

**DATE
FILMED**

5/25/94

END