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

DE-AC22-91PC91154

**Quarterly Progress Report 4
October through December 1992**

We have no objection from a patent
standpoint to the publication or
dissemination of this material.

H. W. Allen 6/14/93
Date
Office of Intellectual
Property Counsel
DOE Field Office, Chicago

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

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

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MASTER

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QUARTERLY PROGRESS REPORT 4 (October through December 1992)

INTRODUCTION

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

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

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

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

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

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

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

PROJECT WORK

Task 1—Project Work Plan

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

Task 2—Concept Definition and Analysis

Subtask 2.1—Preliminary Cycle Analysis

The plant size has been established at approximately 290 MWe. Two basic cycles are being developed. One cycle uses a ceramic air heater and natural-gas firing in the topping combustor. It is referred to as the Natural-Gas HITAF (NG-HITAF). This cycle will have a low-pressure pyrolyzer. The other cycle will have fuel gas fired in the topping combustor and no ceramic air heater. It is referred to as the Fuel-Gas HITAF (FG-HITAF), and its pyrolyzer will operate at approximately 18 atm.

Table 1 compares the NG-HITAF and FG-HITAF systems. We cannot be certain at this time which system will be the best. Each system has potential advantages and disadvantages, and further investigation is required before we can make a choice. As Table 1 shows, the decision rests mainly on economics issues. For this reason, both concepts are being developed to the point where a reliable COE analysis can be made for comparing the two systems. The

Date: February 1993

Figure 1 Simplified Process Flow Diagram

Table 1 Comparison of Fuel-Gas HITAF and Natural-Gas HITAF Systems

Differences	Technical Implications	Economic Implications	Means of Resolution
FG-HITAF: Pressure 18 atm NG-HITAF: Pressure 2 atm	<p>Pyrolyzers have been run at both pressures. The solids feed system may be less reliable at higher pressures, but even low-pressure operation will require pressurized feeding systems.</p> <p>Both systems have been demonstrated. There have been many applications of slurry systems. The NG-HITAF feed system could probably be a Firth solids pump. This pump is newer and less proven, but it has the promise of being more reliable.</p>	<p>The higher pressure feed system may be more expensive, but the pyrolyzer vessels will be less expensive at the higher pressure because the size will be reduced.</p>	<ul style="list-style-type: none"> ■ Comparison of plant COEs
FG-HITAF: Slurry Feed NG-HITAF: Dry Feed	<p>Both systems have been demonstrated. There have been many applications of slurry systems. The NG-HITAF feed system could probably be a Firth solids pump. This pump is newer and less proven, but it has the promise of being more reliable.</p>	<p>With fine feed size to the pyrolyzer, nitrogen requirements make lock hoppers uneconomical. It is likely that an inexpensive Firth solids pump could be used for the NG-HITAF pressure, but a slurry system will probably be required for the FG-HITAF.</p>	<ul style="list-style-type: none"> ■ Comparison of plant COEs
FG-HITAF: No Natural Gas Fired in Topping Combustor NG-HITAF: Natural Gas Fired in Topping Combustor	<p>A topping combustor needs to be designed for either application. With the NG-HITAF, there are no potential pollution or turbine corrosion problems. With the FG-HITAF, these potential problems need to be considered. Analysis and available data indicate that alkalis will not be sufficient to cause turbine corrosion. NO_x generation in the topping combustor needs to be addressed in R&D. Alkali removal by cooling the fuel gas will probably be required in both systems. If topping combustor NO_x levels are too high with the FG-HITAF, a turbine exhaust De-NO_x system will be required.</p>	<p>The FG-HITAF will have lower fuel costs because natural gas will not be required. Also the uncertainty of future natural gas price and supply may deter investment in an NG-HITAF.</p> <p>There may be additional capital costs for a De-NO_x system with the FG-HITAF.</p>	<ul style="list-style-type: none"> ■ GE topping combustor NO_x tests ■ FWDC ceramic corrosion tests ■ Comparison of plant COEs

Table 1 (Cont) Comparison of Fuel-Gas HITAF and Natural-Gas HITAF Systems

Differences	Technical Implications	Economic Implications	Means of Resolution
<p>FG-HITAF: No Ceramic Air Heater</p> <p>NG-HITAF: Ceramic Air Heater</p>	<p>The FG-HITAF System has no ceramic air heater. Air will be heated indirectly to approximately 1400°F in the char-fired furnace. Since there is no ceramic air heater, no furnace is required for the fuel gas combustion.</p>	<p>Cost of fuel-gas furnace and ceramic air heater will be included in NG-HITAF capital cost but not in FG-HITAF capital cost.</p>	<ul style="list-style-type: none"> ■ Comparison of plant COEs
<p>FG-HITAF: Fuel Gas Cleanup Will Require Barrier Filter</p> <p>NG-HITAF: Fuel Gas Cleanup Can Possibly Be Done With Cyclones</p>	<p>The fuel gas cleanup will be at 1000°F, so barrier filters will be more reliable than other systems that require gas cleanup at higher temperatures. However, if cyclones can be used with the NG-HITAF, they will be even more reliable. Corrosion tests and particle carryover modeling will determine whether this is possible.</p>	<p>If barrier filters are not needed for the NG-HITAF, capital costs will be reduced.</p>	<ul style="list-style-type: none"> ■ FWDC ceramic corrosion tests ■ Comparison of Plant COEs
<p>FG-HITAF: 44% Higher Coal Feed Rate</p> <p>NG-HITAF: Base Coal Feed Rate</p>	<p>Coal and sorbent preparation and feeding equipment must have larger capacity for FG-HITAF.</p>	<p>Capital cost will be higher for FG-HITAF coal and sorbent preparation and feeding equipment.</p>	<ul style="list-style-type: none"> ■ Comparison of Plant COEs
<p>FG-HITAF: 10% Lower Flue Gas Flow Rate to De-SO_x System</p> <p>NG-HITAF: Base Flue Gas Flow Rate to De-SO_x System</p>	<p>Flue gas De-SO_x systems will be the same design.</p>	<p>Slight difference in capacity should not affect capital cost.</p>	<ul style="list-style-type: none"> ■ Comparison of Plant COEs

Table 1 (Cont) Comparison of Fuel-Gas HITAF and Natural-Gas HITAF Systems

Differences	Technical Implications	Economic Implications	Means of Resolution
FG-HITAF: 48% Higher Char Feed Rate NG-HITAF: Base Char Feed Rate	At this point, it appears that the higher char flow rate can be accommodated with two combustors, but it is conceivable that the size will get too large.	If a third burner is required, the capital cost will increase.	<ul style="list-style-type: none"> ■ TRW char combustor analysis ■ Comparisons of Plant COEs
FG-HITAF: 1400°F Air Piping NG-HITAF: 1800°F Air Piping	Refractory-lined pipe with an inner protective shroud has been built. There are no commercial applications at this high a temperature, but the design should work with the proper alloys. Air at 1400°F can be transported in unlined stainless steel pipes.	Refractory-lined pipe with inner metallic shrouds is expensive. Hot air piping will be more expensive with the NG-HITAF.	<ul style="list-style-type: none"> ■ FWDC design analysis ■ Comparison of plant COEs
FG-HITAF: 78% Higher Fuel Gas Flow Rate NG-HITAF: Base Fuel Gas Flow Rate	More heat-transfer surface will be required in the fuel gas cooler.	Capital cost of the fuel gas cooler will depend primarily on heat-transfer surface, number of vessels, and vessel diameter. It is not certain which system will have lower capital cost.	<ul style="list-style-type: none"> ■ Comparison of plant COEs
FG-HITAF: Vitiated Air Is Approximately 15% O ₂ NG-HITAF: Vitiated Air Is Approximately 19% O ₂	The lower O ₂ content of the FG-HITAF vitiated air tends to lower combustor temperatures, and a mixture of ambient air and vitiated air may be required. This would tend to lower cycle efficiency.	Any reduction in FG-HITAF efficiency will increase fuel cost. However, this effect will be small compared with the fuel savings from not burning natural gas.	<ul style="list-style-type: none"> ■ TRW analysis of char burner ■ Bechtel analysis of cycle ■ Comparison of plant COEs

best system will then be developed further in Task 4 so that a COE comparison can be made between the HITAF system and a PC system.

Performance characteristics of the FG-HITAF and NG-HITAF were analyzed and compared to ascertain whether the FG-HITAF is capable of meeting the system efficiency goal of 47 percent. As part of this analysis, performance of a totally indirectly fired HITAF cycle was investigated. This cycle was based on the assumption that, at some future date, materials would be available to allow indirect heating of air up to the gas turbine inlet temperature.

Lastly, during this quarter, detailed plant heat and material balances were made for both the NG-HITAF and FG-HITAF systems. These balances are based on preliminary R&D and trade-off decisions made to date. Although there will surely be changes to these balances both in configuration and flow stream composition, it was important to get the cycles quantified in sufficient detail to support further analysis. Team members are analyzing their subsystems based on these balances and will recommend the modifications needed for the next iteration.

Further information on all these activities follows:

Plant Size for Conceptual Design. The nominal plant size of 100 MWe was suggested in DOE's PRDA and used as the basis for our proposal. Further analysis indicated that this plant size was less than ideal. It did not take advantage of economies of scale enjoyed by larger plants, and it did not appear to take full advantage of the modular capacities of the major components.

In response to these considerations, Bechtel requested that all team members provide data on the physical size and performance limitations of the largest practical module for the major equipment associated with the original NG-HITAF system offered in our proposal. Specifically, the equipment of interest included:

■ Gas turbine*	■ Ceramic air heater*
■ Pyrolyzer*	■ Air heater/furnace
■ Char combustor	■ Steam turbine

The items shown with an asterisk on this list turned out to be the critical items, with the air heater/furnace and steam turbine having sufficient flexibility to meet the restrictions set by the other systems.

An examination of the data was undertaken by Bechtel with the goal of achieving the best fit of the individual modules while providing a reasonable plant size attractive to prospective power producers (mainly the utilities) and sufficiently large to take advantage of capital savings associated with the economy of scale. It soon became apparent that the gas turbine should be the controlling piece of equipment. General Electric's 7F series is the largest commercial available machine on the U.S. market; it can generate a nominal 150 MWe when

firing natural gas. Since the gas turbine generates about 50 percent of the total power, the full plant can produce an estimated 290 MWe of net power.

The energy demands of the 7F gas turbine also had the benefit that it appeared to match the modular sizes of the other key components. When this work was being conducted, the data received for the other systems indicated that a 7F gas turbine could be matched with two pyrolyzers, two slagging char combustors, and four ceramic air heaters (HTHEs). In addition, the nominal 300 MWe meant that the size of the supporting equipment and balance-of-plant (BOP) systems would be sufficient to take some advantage of the economies of scale. Bechtel has found for most systems that the break point on capital requirements per kilowatt for supporting BOP systems occurs in the 200- to 300-MWe size range. Therefore, while there is considerable savings to be gained in using multiple trains of pyrolyzers, char combustors, and air heaters, there is less to be gained from using multiple trains of gas turbines.

Updated GATE Simulation. Over the past quarter, several adjustments were made to the original flow diagram. These changes were the result of better data from the Task 3 experimental work, trade-off studies, and limitations uncovered on certain pieces of equipment. As more data became available, the system performance calculations were updated to reflect the new information. Some of the more significant changes include:

- **Directly Feeding Char From Pyrolyzer to Char Combustor.** We earlier determined that material considerations would not allow us to crush the hot char leaving the pyrolyzer to meet sizing limitations set by TRW for the char combustor. Previous analyses assumed the char would have to be cooled to between 400 and 600°F to meet current equipment limitations. FWDC determined through tests conducted on their pilot-scale pyrolyzer that agglomeration can be avoided with proper design and operation of the pyrolyzer. Thus if the coal were properly sized before being fed to the pyrolyzer, the resultant char would meet TRW's requirements and the need for both the char cooler and pulverizer would be eliminated.
- **Adding Recuperator for Air Heating.** FWDC made a preliminary examination of the use of a recuperator to exchange heat between the gas turbine outlet and compressed air and found it to offer some potential benefits, including lower air-side pressure drop, lower capital cost, and better system response.
- **Cooling Pyrolyzer Fuel Gas to 1000°F.** Based on work completed during the previous reporting period, we determined it beneficial to cool the fuel gas leaving the pyrolyzer cyclone to a nominal 1000°F in a first-stage steam superheater to condense out any alkali components in the gas stream. Work on FWDC's pilot plant has shown that alkalis tend to condense on particles in the gas stream; these particles can be removed in a ceramic filter or high-temperature baghouse before combustion.
- **Allowing for Fuel Gas Trapped in Char Product.** FWDC estimates about 4 percent of the fuel gas leaving the pyrolyzer will be used to depressure and transport the char to the char combustor. Although lost to the fuel gas combustor, this fuel gas will provide a source of volatiles in the char combustor, which should assist in stabilizing combustor operation.

- Using Higher Temperature Vitiated Air in Char Combustor. To further assist in maintaining proper combustion/slugging temperatures in the char combustor, TRW requested that we move the source for the vitiated air from downstream of the recuperator to upstream. This move will increase the temperature from a nominal 850°F to about 1050°F.
- Using Coal in Char Precombustor. Based on work completed in the last reporting period, coal is used in place of fuel gas to provide the necessary energy and volatiles needed for the char precombustor.
- Providing 20-Percent Excess Oxygen to Char Combustor Based on Incoming Char and Coal. This change corrects a misunderstanding as much as anything. Because we knew that the char combustor operates in a reducing atmosphere, using only about 80 percent of the stoichiometric amount of oxygen, Bechtel assumed that the 20-percent excess in oxygen suggested by TRW applied to the unburned material leaving the char combustor and would therefore apply to the secondary air. However, FWEC confirmed that additional oxygen was required to ensure proper combustion of the residual carbon monoxide and that the 20-percent excess should apply to the coal and char feed—not just to the residual carbon monoxide. This change will provide approximately 100-percent excess oxygen in the lower furnace based on the unburned products.

The results of these revised cycle analyses are included as part of the topics that follow.

Examine Alternative HITAF Configurations. The basic NG-HITAF configuration is presented in Figure 2. In this system the gas turbine combustion air is preheated in a series of heaters, culminating in a high-temperature ceramic air heater that raises the air temperature to 1800°F. Methane is used to top the cycle and raise the gas turbine inlet temperature to 2400°F (nominal); air is introduced in the first stage. The amount of methane or natural gas required to top off the air going to the gas turbine amounts to about 35 percent of the total energy feed to the system. As part of the long-term development of the HITAF program, this natural gas consumption must be reduced to less than 10 percent.

It appeared that a natural extension of this philosophy was the introduction of pyrolyzer fuel gas in place of the natural gas to top off the air heating. This choice was supported by some recent pyrolyzer balances that suggested revised operating conditions could provide fuel gas in excess of that needed to heat the air in the ceramic air heater to 1800°F. Bechtel and FWDC quickly agreed that if we were willing to explore the replacement of the natural gas by fuel gas, why not eliminate the ceramic air heater altogether and heat the air leaving the furnace (1400°F) directly by burning fuel gas in the air stream.

Preliminary cycle analyses indicated that such a system should have performance levels equal to or better than the original system. Based on the positive results, FWDC prepared two balances for the pyrolyzer operating at 18 atm pressure. One balance assumed a dry coal feed

Figure 2 NG-HITAF (Dry Coal Feed)

using lock hoppers, while the second assumed a slurry feed system. These systems are shown in Figures 3 and 4.

Using the new pyrolyzer data, Bechtel updated the cycle analysis for the two pressurized cases. The results for the two pressurized, fuel-gas-fired cases along with the natural-gas-fired base case are presented in Table 2. As these results show, even given the advantage of having a third of the energy coming from a premium fuel, the NG-HITAF configuration was only marginally better than the FG-HITAF system using a dry feed. Neither of these systems could match the slurry-fed FG-HITAF configuration. The improved fuel gas composition and increased flow resulting from the presence of steam in the pyrolyzer boosted the energy expected from the gas turbine to almost 170 MWe and the power from the gas turbine to almost 53 percent. The beneficial results coming from this shift in power generation are further portrayed in Figure 5.

In the initial stages of examining the FG-HITAF option, the question was raised about whether we might be trading a system with a better ultimate potential for the sake of apparent short-term gains. It was argued that, as materials develop, the temperature limits currently being imposed on the NG-HITAF system would be raised, and these higher temperatures should allow improved performance.

To better understand these limits, Bechtel made a preliminary examination of the impact on the overall cycle efficiency of indirectly heating air to approximately 2400 °F. Two options were considered:

- Option 1—Option 1 used the same basic configuration as the 2-atm base case currently under consideration, but raised the temperature of the air leaving the furnace from 1400 to 1600°F. The temperature of the air leaving the ceramic air heater was increased to 2420°F, and the methane combustor was eliminated.
- Option 2—In Option 2 the analysis was taken one step further. If we were free to ignore materials considerations, why not heat the air all the way to 2420°F in the furnace? So, for Option 2 the pyrolyzer and ceramic air heater were both eliminated, and coal was fed directly to the slagging combustor.

The results showed no difference between Options 1 and 2. On hindsight, this result appears perfectly logical. The only heat loss in the pyrolysis process is the relatively small ambient heat loss. Thus the efficiency of the pyrolyzer is nearly 100 percent. If true, then indeed Options 1 and 2 become essentially the same, since the air in both is eventually heated to 2420°F by the coal, either directly or indirectly. The only potential difference is a reduced pressure drop between the compressor outlet and the turbine inlet. Conceivably, the pressure drop through the furnace air heater in Option 2 may be less than the combination of furnace air heater and HTHE in Option 1. However, we did not account for this difference, assuming any gain (or loss) would be minor.

Figure 3 FG-HITAF (Dry Coal Feed)

Ref.: DE-AC22-91PC91154

Date: February 1993

Figure 4 FG-HITAF (Slurry Coal Feed)

Table 2 Summary of Three Cases

Performance	FG-HITAF (Slurry)		FG-HITAF (Dry)		NG-HITAF (Dry)	
	MWe	%	MWe	%	MWe	%
Gas Turbine Gross Power	169.1	52.7	151.5	46.0	151.4	50.1
Steam Turbine Gross Power	151.8	47.3	177.7	54.0	151.0	49.9
Auxiliary Power	11.3	3.5	11.6	3.5	10.7	3.5
Net Power	309.6		317.6		291.6	
	LHV	HHV	LHV	HHV	LHV	HHV
Heat Rate, Btu/kWh	6804	7064	7079	7368	6931	7252
Efficiency, %	50.15	48.3	48.2	46.31	49.23	47.05

Figure 5 Impact of Gas Turbine Power on Performance

Since there should be some heat loss in the pyrolyzer, there should be some reduction in overall efficiency for Option 1 compared with Option 2. However, while Bechtel was unable to make this determination based on the data available, we expect that the loss in overall efficiency will be less than 1 percent.

The comparison between Options 1 and 2 and the current NG-HITAF configuration is more critical. As seen in Table 3, the calculated improvement in overall efficiency is modest—less than 1 percent. In addition, based on the results presented in Table 3, the ultimate performance for the NG-HITAF system is comparable to the slurry-fed FG-HITAF system.

Table 3 Comparison of Indirect and Direct Heating Options

Performance	Base Case Methane Topping	Option 1 HTHE and Carbonizer	Option 2 Coal to Furnace	Direct (Slurry)
Gas Turbine Gross Power (MWe)	151.4	152.7	152.8	169.1
Steam Turbine Gross Power (MWe)	151.0	127.7	133.6	151.8
Total Gross Power (MWe)	302.4	280.5	286.3	320.9
Auxiliary Power (MWe)	10.7	15.9	16.1	11.3
Net Power (MWe)	291.6	264.6	270.2	309.6
Heat Rate				
LHV (Btu/kWh)	6931	6812	6826	6804
HHV (Btu/kWh)	7252	7066	7081	7064
Efficiency				
LHV (Btu/kWh)	49.2	50.1	50.0	50.2
HHV (Btu/kWh)	47.1	48.3	48.2	48.3

Preliminary Material and Energy Balances. The next phase of the project is the preparation of the conceptual design (Task 4). To initiate this process, Bechtel prepared material balances and flow diagrams for the two most-likely options based on the cycle analysis discussed earlier—FG-HITAF with a slurry feed to the pyrolyzer and the original NG-HITAF system. At the time of their preparation, the balances included only those streams around the heart of the HITAF system; they did not extend into the low-temperature heat-recovery or flue-gas desulfurization (FGD) areas, nor did they include any of the boiler feedwater/stream systems that are part of the bottoming cycle. The balances are presented in Tables 4 and 5, and the corresponding process flow diagrams are shown in Figures 6 and 7.

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Table 4 (Cont) NG-HITAF (Dry Feed
to Pyrolyzer)

Stream No.	8	9	10	11	12	13	14
Stream	Flue Gases to HTHE %wt lb/hr	Air to Compressor %wt lb/hr	Bypass Air %wt lb/hr	Air to Recuperator %wt lb/hr	Air to Air Heater %wt lb/hr	Flue Gas to Furnace %wt lb/hr	Air to HTHE %wt lb/hr
Carbon							
Hydrogen							
Oxygen							
Nitrogen							
Sulfur							
Ash							
Moisture							
CaCO ₃							
MgCO ₃							
CaO							
MgO							
CaS							
CaSO ₄							
CH ₄							
C ₂ H ₄							
C ₂ H ₆							
C ₃ H ₈							
CO							
H ₂	18.55%	1.99%	1.99%	1.99%	1.99%	18.55%	1.99%
CO ₂	7.61%	2.38%	2.38%	2.38%	2.38%	7.61%	2.38%
H ₂ O	20.881	697.835	101.884	595.951	595.951	20.881	595.951
O ₂	2.54%	75.49%	75.49%	75.49%	75.49%	2.54%	75.49%
N ₂	71.13%	2,615,909	381,923	2,233,986	2,233,986	71.13%	2,233,986
H ₂ S							
COS							
SO ₂	0.03%	224				0.03%	224
C ₆ H ₆ +							
Argon							
NH ₃							
NO ₂	0.14%	1,112				0.14%	1,112
Total Gas, lb/h	100.00%	3,465,405	505,949	2,959,456	2,959,456	819,892	2,959,456

Table 4 (Cont) NG-HITAF (Dry Feed
to Pyrolyzer)

Stream No.	15	16	17	18	19	20	21
Stream	Air to GT Combustor %wt lb/hr	Net Gas to GT Comb. %wt lb/hr	FG Im GT Combustor %wt lb/hr	Total Gas to GT %wt lb/hr	Gas to Recuperator %wt lb/hr	Coal to Precombust. %wt lb/hr	Sorbent to Char Comb. %wt lb/hr
Carbon						71.92%	2,742
Hydrogen						4.89%	179
Oxygen						6.33%	241
Nitrogen						1.28%	48
Sulfur						2.98%	114
Ash						10.32%	393
Moisture						2.50%	95
CaCO ₃							187
MgCO ₃							20,331
CaO							43.40%
MgO							635
CaS							0.50%
CaSO ₄							54.40%
CH ₄		100.00%	32.023				16,220
C ₂ H ₄							
C ₂ H ₆							
C ₃ H ₈							
CO							
H ₂			3.00%	2.85%	2.85%		97,924
CO ₂	1.99%	58,952	4.86%	4.49%	4.49%		154,551
H ₂ O	2.38%	70,566	15.94%	16.56%	16.56%		569,331
O ₂	20.14%	595,951	78.17%	76.07%	76.07%		2,615,909
N ₂	75.49%	2,233,986					
H ₂ S							
CO ₂			0.01%	0.01%	0.01%		191
SO ₂							
C ₆ H ₆ +							
Argon							
NH ₃							
NO ₂							
Total Gas, lb/h	100.00%	2,959,456	100.00%	32.023	100.00%	100.00%	3,812
							100.00%
							37,374

Table 4 (Cont) NG-HITAF (Dry Feed to Pyrolyzer)

Stream No.	22	23	24	25	26	27	28
Stream	Char to Char Comb.	Prim. Air to Char Comb.	Sec. Air to Char Comb.	Flue Gas to Char Comb.	Slag to Char Comb.	F. Gas to Air Htr.	F. Gas to Air Htr.
	%wt	%wt	%wt	%wt	%wt	%wt	%wt
	lb/hr	lb/hr	lb/hr	lb/hr	lb/hr	lb/hr	lb/hr
Carbon	51.04%	26,873					
Hydrogen							
Oxygen							
Nitrogen	0.80%	423					
Sulfur	1.77%	932					
Ash	22.27%	11,723			27.72%	12,752	
Moisture							
CaCO ₃							
MgCO ₃							
CaO	5.76%	3,032			30.56%	14,057	
MgO	8.92%	4,695			27.00%	12,448	
CaS	9.44%	4,972			8.85%	3,978	
CaSO ₄					8.01%	2,765	
CH ₄							
C ₂ H ₄							
C ₂ H ₆							
C ₃ H ₈							
CO							
H ₂	2.85%	11,119	2.85%	22.45%	142,854	20.25%	294,985
CO ₂	4.49%	17,628	4.49%	4.45%	28,289	6.23%	90,756
H ₂ O	16.56%	64,936	16.56%	2.22%	14,100	2.40%	34,981
O ₂	78.07%	298,364	76.07%	70.34%	446,991	70.79%	1,031,000
N ₂							
H ₂ S							
COS	0.01%	22	0.01%	0.27%	1,705	0.13%	1,929
SO ₂							
C ₆ H ₆ +							
Argon							
NH ₃							
NO ₂	0.03%	109	0.03%	0.27%	1,710	0.19%	2,822
Total Gas, lb/hr	52,651	392,227	195,385	635,449	48,001	1,458,452	1,458,452
	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Ref.: DE-AC22:91PC91154
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Table 5 FG-HITAF (Slurry Feed
to Pyrolyzer)

Stream No.	1		2		3		4		5		6		7	
Stream	Coal to Carbonizer		Air to Carbonizer		Sorb. to Carbonizer		Char fm Carbonizer		Fuel G. fm Carbonizer		Fuel Gas to Comb.		Air to Compressor	
	%wt	B/hr	%wt	B/hr	%wt	B/hr	%wt	B/hr	%wt	B/hr	%wt	B/hr	%wt	B/hr
Carbon	47.94%	113,812					43.02%	33,522						
Hydrogen	3.13%	7,421												
Oxygen	4.22%	10,014					0.85%	507						
Nitrogen	0.84%	1,991					1.44%	1,119						
Water	2.00%	4,736												
Solids														
Bulk														
Ash	6.86%	16,326			1.70%	647	21.76%	16,973						
Moisture	35.01%	83,116			0.50%	190								
CaCO3					54.40%	20,890	13.82%	10,768						
MgCO3					43.40%	16,508								
CaO							10.12%	7,888						
MgO							9.18%	7,151						
CaS														
CaSO4									0.91%	6,081	0.91%	5,838		
CH4														
C2H4														
C2H6														
C3H8														
CO									17.22%	114,631	17.22%	110,048		
H2									1.25%	8,294	1.25%	7,963		
CO2									17.29%	115,097	17.29%	110,493		
H2O									9.81%	63,952	9.81%	61,394		
O2													0.82%	28,277
N2									53.53%	356,388	53.53%	342,113	23.08%	799,689
									0.07%	469	0.07%	450	78.11%	2,637,439
H2S														
COS														
SO2														
C6H6+									0.12%	775	0.12%	744		
NH3														
NO2														
Total Gas, B/hr	100.00%	237,405	100.00%	466,964	100.00%	38,032	100.00%	77,928	100.00%	665,684	100.00%	639,057	100.00%	3,465,405

Table 5 (Cont) FG-HITAF (Slurry Feed
to Pyrolyzer)

Stream No.	8	9	10	11	12	13	14
Stream	Bypass Air %wt lb/hr	Air to Recupcrator %wt lb/hr	Air to Furnace %wt lb/hr	Air to GT Combustor %wt lb/hr	FG In GT Combustor %wt lb/hr	Total Gas to GT %wt lb/hr	Gas to Recupcrator %wt lb/hr
Carbon							
Hydrogen							
Oxygen							
Nitrogen							
Sulfur							
Solids lb/h							
Ash							
Moisture							
CaCO ₃							
MgCO ₃							
CaO							
MgO							
CaS							
CaSO ₄							
CH ₄							
C ₂ H ₄							
C ₂ H ₆							
C ₃ H ₈							
CO							
H ₂					9.71%	299,411	299,411
CO ₂					5.42%	167,028	171,553
H ₂ O	0.82%	0.82%	0.82%	0.82%	13.35%	411,555	539,505
O ₂	23.08%	23.08%	23.08%	23.08%	71.43%	2,202,166	2,624,156
N ₂	76.11%	76.11%	76.11%	76.11%			
H ₂ S							
COS					0.03%	846	846
SO ₂							
C ₆ H ₆ +					0.07%	2,009	2,009
NH ₃							
NO ₂							
Total Gas, lb/h	554,465	100.00%	2,443,976	100.00%	3,083,016	3,637,480	3,637,480

Table 5 (Cont) FG-HITAF (Slurry Feed to Pyrolyzer)

Stream	15	16	17	18	19	20	21
	Coal to Precombust.	Serbet to Precombust.	Char to Char Comb.	Prim. Air to Char Comb.	Sec. Air to Char Comb.	Flue Gas to Char Comb.	Slag to Char Comb.
	%wt	%wt	%wt	%wt	%wt	%wt	%wt
Carbon	71.91%	5.924	32.06%	33.522			
Hydrogen	4.89%	368					
Oxygen	6.33%	521					
Nitrogen	1.26%	104	0.48%	507			
Sulfur	2.89%	247	1.07%	1,119			
Ash	10.32%	860	16.23%	16,973			16,709
Moisture	2.50%	208					
CaCO ₃		94.40%	10.30%	10,768			
MgCO ₃		43.40%					
CaO			7.54%	7,868			21,450
MgO			8.84%	7,151			18,707
CaS							5,721
CaSO ₄							3,859
CH ₄			0.23%	243			
C ₂ H ₄							
C ₂ H ₆							
C ₃ H ₈							
CO			4.36%	4,585			
H ₂			0.32%	332			
CO ₂			4.40%	4,604	8.23%	24,937	261,132
H ₂ O			2.46%	2,558	4.72%	14,288	53,078
O ₂					14.83%	44,934	17,175
N ₂			13.83%	14,255	72.14%	218,569	872,487
H ₂ S			0.02%	19			
CO ₂					0.02%	70	2,430
SO ₂							
C ₂ H ₄			0.03%	31			
NH ₃							
NO ₂							
Total Gas, Btu	100.00%	8,228	100.00%	104,555	100.00%	302,958	1,006,878
							68,448

Date: February 1993

Additional data were provided (for the FG-HITAF system only) in the form of a table summarizing the flows, temperatures, pressures, and duties associated with the major exchangers, as projected by the current GATE analysis. These results are presented in Table 6.

In addition to providing the team members with a consistent set of data to start building their designs, the release of these preliminary material balances allowed each team member to examine Bechtel's understanding of the performance expected from those pieces of equipment. As a result, several areas, including the flows around the char combustor and the fuel gas combustor, have since been modified. The results of these changes will be presented in the next report.

Task 3—Preliminary R&D

Subtask 3.1—Analytical Determination of Pyrolyzer Yields

The Institute of Gas Technology (IGT) and City College of New York (CCNY) pyrolyzer computer models were compared with the test results from the FWDC Second-Generation PFBC pilot plant. At a bed temperature of around 1600°F, the yields from both models are close; but at higher bed temperatures, the CCNY program predicts greater carbon conversion than the IGT program. The CCNY program results matched the results of the FWDC pilot plant tests well; thus we decided to use this model for the HITAF system.

The pyrolyzer computer model has been run for the various operating conditions of the cycles being studied. The pyrolyzer balances were used in the December 15, 1992, plant heat and material balances. The balance shown in Figure 8 is for the NG-HITAF. It uses dry coal and sorbent feeding at 2 atm/1700°F.

The pyrolyzer heat and material balance for the FG-HITAF is shown in Figure 9. Slurry feed is used for this system because of economics and cycle efficiency considerations. Because of its effect on pyrolyzer gas yields, the additional water for the slurry feed increases the cycle efficiency. Also, at the higher pressure of the FG-HITAF pyrolyzer, a slurry feed system will be more economical than a lock hopper system. It is important to note that although the coal and sorbent will be fed in one slurry, the coal and sorbent streams are shown separately in Figure 9 and all the water is shown with the coal stream.

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

Potential flue gas alkali levels in the secondary air heater have been analyzed and were reported in Quarterly Report 3. Based on these analyses, we decided to include a fuel gas cooler in the cycles being investigated. Cooling the fuel gas to approximately 1000°F will reduce alkali concentrations to levels where corrosion should not be a problem in either the NG-HITAF or the FG-HITAF.

Table 6 Summary of GATE Results for FG-HITAF (Slurry Feed)

Air Compressor

Air	In	3,465.4 M lb/h 60.0 °F	14.7 psia
	Out	680.6 °F	205.4 psia
Bypass		554.9 M lb/h 16.0%	

Gas Turbine 162.4 MWe

Comb. Gases	In	3,086.6 M lb/h 2,401.5 °F	191.7 psia
	Out	1,118.1 °F	16.4014 psia

Steam Turbine 134.5 MWe

Main Steam	In	734.1 M lb/h 1,049.6 °F	2,415.0 psia
	Out	615.2 °F	466.7 psia
Reheat Steam	In	709.5 M lb/h 1,050.1 °F	420.0 psia
	Out	91.9 °F	0.74 psia

Recuperator 268.0 MM Btu/hr

Comp. Air	In	2,447.5 M lb/h 680.6 °F	205.4 psia
	Out	1,100.0 °F	204.8 psia
Turbine Exhaust	In	3,637.5 M lb/h 1,118.1 °F	16.4 psia
	Out	850.3 °F	16.3 psia

Air Heater 199.6 MM Btu/hr

Comp. Air	In	2,447.5 M lb/h 1,100.0 °F	204.8 psia
	Out	1,400.0 °F	197.6 psia
Flue Gas	In	912.8 M lb/h 2,561.9 °F	15.5 psia
	Out	1,867.9 °F	15.4 psia

Table 6 (Cont) Summary of GATE Results for FG-HITAF (Slurry Feed)

DHS #3		153.3 MM Btu/hr		
Fuel Gas	In	639.1 M lb/h		
		1,700.0 °F		
SH Steam	Out	1,000.0 °F		
	In	734.1 M lb/h		
		774.0 °F	2,415.1 psia	
	Out	1,049.6 °F	2415 psia	
DHS #2		21.7 MM Btu/hr		
Flue Gas	In	895.8 M lb/h		
		1,771.2 °F	15.6 psia	
	Out	1,691.7 °F	15.5 psia	
SH Steam	In	734.1 M lb/h		
		750.0 °F	2,457.1 psia	
	Out	774.0 °F	2,415.1 psia	
DHS #1		125.5 MM Btu/hr		
Flue Gas	In	912.8 M lb/h		
		1,252.5 °F	15.4 psia	
	Out	765.7 °F	15.4 psia	
SH Steam	In	734.1 M lb/h		
		673.1 °F	2,586.4 psia	
	Out	750.0 °F	2,457.1 psia	
Slagging Comb		148.1 MM Btu/hr		
Fuel Gas	In	895.8 M lb/h		
		2,223.9 °F	15.7 psia	
	Out	1,771.2 °F	15.6 psia	
BFW	In	381.1 M lb/h		
		678.8 °F	2,722.5 psia	
	Out	673.1 °F	2,586.4 psia	
D REHEAT		169.2 MM Btu/hr		
Fuel Gas	In	912.8 M lb/h		
		1,867.8 °F	15.4 psia	
	Out	1,252.5 °F	15.3 psia	
SH Steam	In	709.5 M lb/h		
		615.2 °F	466.7 psia	
	Out	1,050.1 °F	420.0 psia

Table 6 (Cont). Summary of GATE Results for FG-HITAF (Slurry Feed)

C EVAP		115.6 MM Btu/hr	
Fuel Gas	In	2,790.5 M lb/h	
		850.3 °F	16.3 psia
BFW	Out	696.0 °F	16 psia
	In	350.4 M lb/h	
		678.8 °F	2,447.7 psia
	Out	673.1 °F	2,440.4 psia
C ECON #2		258.6 MM Btu/hr	
Fuel Gas	In	2,790.5 M lb/h	
		694.5 °F	16.0 psia
BFW	Out	337.9 °F	15.5 psia
	In	545.4 M lb/h	
		304.5 °F	2,750.0 psia
	Out	678.8 °F	2,722.5 psia
C ECON #1		110.8 MM Btu/hr	
Fuel Gas	In	2,790.5 M lb/h	
		337.9 °F	15.5 psia
BFW	Out	180.5 °F	15 psia
	In	541.8 M lb/h	
		88.6 °F	71.7 psia
	Out	291.7 °F	68.7 psia
D ECON #2		91.3 MM Btu/hr	
Fuel Gas	In	912.8 M lb/h	
		765.7 °F	15.1 psia
BFW	Out	396.2 °F	15 psia
	In	188.8 M lb/h	
		304.5 °F	2,750.0 psia
	Out	678.8 °F	2,722.5 psia
D ECON #1		39.6 MM Btu/hr	
Fuel Gas	In	912.8 M lb/h	
		396.2 °F	15.0 psia
BFW	Out	225.9 °F	14.8 psia
	In	188.9 M lb/h	
		88.6 °F	71.7 psia
	Out	296.7 °F	68.7 psia
Condenser		631.5 MM Btu/hr	
Steam Exhaust	In	652.7 M lb/h	
		91.9 °F	
CW	Out	91.9 °F	
	In	43,381.0 M lb/h	
		63.0 °F	
	Out	77.6 °F

Figure 8 NG-HITAF Pyrolyzer Heat and Material Balance

*Sr = Sulfur released.

Figure 9 FG-HITAF Pyrolyzer Heat and Material Balance

*Sr = Sulfur released.

Figure 10 shows the alkali concentration in the fuel gas for the NG-HITAF as the fuel gas temperature is reduced from the 1700°F pyrolyzer outlet temperature to 1000°F. The alkali concentrations of less than 1 ppm at 1000°F should not cause corrosion in the ceramic air heater. Corrosion testing in Subtask 3.8 will confirm this and whether higher levels can be tolerated.

In the FG-HITAF system, alkalis in the fuel gas are also a problem because of potential damage to the gas turbine. Alkali levels in the gas stream to the gas turbine need to be kept below 0.020 ppm(w). Because of the large dilution of the fuel gas with air, a fuel gas alkali level of about 0.1 ppm(w) is required to achieve the 0.020 ppm(w) gas turbine level. As shown in Figure 11, this level can also be obtained in the FG-HITAF system by cooling the fuel gas to about 1000°F.

The alkali concentrations in Figures 10 and 11 are conservatively high. The basis for the alkali concentrations in the analyses is that all the soluble alkalis in the coal go to the fuel gas. These alkalis include all the organically bound, water-soluble, and carbonate forms of the alkalis. This estimate is conservative because it is unlikely that all of these alkalis will be released.

Subtask 3.5—Char Reactivity and Transport Gas Requirements

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

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

In this quarter, work focused on the design of a pyrolyzer and char transport system that would not require char cooling or pulverizing. This approach requires finer coal feed to the pyrolyzer and makes a circulating fluidized bed a better choice than a jetting fluidized bed. A circulating fluidized bed pyrolyzer subsystem is shown in Figure 12. This type of a system uses higher superficial velocities than a jetting fluidized bed. There is a higher elutriation rate, and most of the elutriated solids are captured by the primary cyclone and returned to the bed.

This type of operation establishes a solids circulation rate that is much higher than the feed rate of coal and sorbent. Circulating fluidized beds require less bed cross-sectional area than jetting fluidized beds, but the height requirement is greater. The height of a circulating fluidized bed is established by the gas residence time required for sulfur capture and carbon conversion. This residence time is 2 to 3 seconds.

Figure 10 NG-HITAF—Fuel Gas Sodium Concentration vs. Temperature

Figure 11 FG-HITAF—Fuel Gas Sodium Concentration vs. Temperature

Figure 12 Pyrolyzer Subsystem—Elevation View

Foster Wheeler has a computer program that models solids behavior in a circulating fluidized bed. It is based on Particulate Solids Research Institute (PSRI) particle elutriation and cyclone capture equations. It also estimates particle attrition resulting from impact and carbon conversion. Although this model has mainly been used for combustion mode calculations, it does consider unburned carbon. The results should be valid for the pyrolyzer operation.

The model was run for several coal and sorbent feed size distributions, and the particle size distributions at different locations were studied. This analysis uncovered some interesting information that affects the design of the pyrolyzer and char transport system. The model analysis showed that the size distribution of solids elutriated from the bed was insensitive to the feed size distribution. This makes sense because the size of particles leaving the bed is determined primarily by the gas velocity. At extremes of fineness or coarseness, the feed size distribution would probably affect the elutriated particle size distribution, but this was not found to be the case with the feed size distributions considered.

Figure 13 shows the char particle size distribution leaving the bed for three different feed size distributions. As the figure shows, the elutriated size distributions are virtually identical. This situation is beneficial because it makes the coal and sorbent feed size and the particle size alterations in the bed less critical. The pyrolyzer is, in effect, a classifier. If particle feed is too coarse or agglomeration occurs, the bed inventory will increase. The system will have to be able to remove this material without losing the carbon heating value; however, the effect on the size distribution to the char combustor will be minor.

Figure 14 shows the size distribution of the char that escapes capture in the primary cyclone. These data are based on an analysis of an NG-HITAF system with a 15 ft/s superficial velocity in the bed. Also shown in this figure is the range of size distributions normally fed to a TRW combustor. Although the char particle stream escaping the primary cyclone is heavier in fines than the normal combustor coal feed, it will likely prove acceptable.

Since the char has fewer volatiles than coal, a finer particle size may be required to get the required carbon burnout. Work being done in Subtasks 3.6 and 3.10 will determine how different size particles will react in the combustor. Another reason that the finer particle distribution will probably be acceptable is that the main detriment of finer particle size is slag-capture efficiency. Cyclone slag-capture efficiency is not critical to the achievement of the particulate emissions goals.

As it turns out in this analysis, the quantity of char escaping the primary cyclone is about 75 percent of that required by the char combustor. The simplest way to increase the mass flow rate in this stream is to decrease the efficiency of the primary cyclone. This decrease can be achieved by proper (or really "improper") design of the cyclone. Cyclone operation can be altered by strategic injection of another flow stream. This approach requires fewer pieces of equipment than adding a char stream from the primary cyclone catch.

Figure 13 Char Particle Size Distribution (Elutriated From Bed for Different Feed Size Distributions)

Figure 14 Char Particle Size Distribution to Char Combustor (Combined Secondary Cyclone and Barrier Filter Streams)

Provision must still be made to remove solids from the pyrolyzer bed to prevent a buildup of particles that are never elutriated from the bed. This stream can probably be kept small with proper operation of the pyrolyzer (i.e., nonagglomerating conditions) and proper coal and sorbent feed size. It is also possible that the lower bed region of the pyrolyzer can be designed so that the char particles can be burned as they are withdrawn from the bed. A portion of the carbon is consumed to maintain bed temperature, and it would be of benefit to preferentially consume the larger char particles. Most likely that this can be done through the design of the air inlet and bed withdrawal areas of the pyrolyzer.

Subtask 3.6—Char Combustor Technical Assessment

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

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

During the previous quarter (July-September 1992), a number of issues related to the performance and operating requirements of the char combustor were initially addressed. These issues included:

- The size and combustion characteristics of the char feed
- The method of char transport to the combustor
- The combustor air preheat temperature
- The need for precombustor auxiliary fuel
- Combustor emissions and slag rejection requirements
- Combustor heat loads and cooling water requirements.

During this reporting period, these issues were reconsidered as efforts were made to zero in on combustor performance and operating requirements. The following summarizes the progress made on a number of these issues.

Selection of Char Particle Size Range. A slagging-type combustor has been selected as the baseline approach for achieving high combustion efficiency while firing the low-volatile char produced by the pyrolyzer. The primary advantages of such a combustor system are high combustion intensity, low NO_x formation, removal of up to 90 percent of the original coal ash as slag, and compact size. A slagging combustor also produces a high-temperature, well-mixed

gas product under conditions that are ideal for injection of lime-based sorbents for subsequent furnace calcination and sulfur capture.

The selection of char particle size is critical to slagging combustor design. Two basic combustion strategies have been considered:

- A wall burner, in which most of the combustion occurs along the walls of the combustor
- An entrained-flow burner, in which most of the combustion occurs while the char particles are entrained in the gas.

The first approach would allow for the use of crushed coal, with median particle sizes in the range of 1 to 5 mm; the second approach would require pulverizing the coal (either before or after the pyrolyzers) to produce a median particle size of approximately 60 microns.

Because of the importance of combustion efficiency and low NO_x formation to the overall design and operation of the HITAF plant, an entrained combustion approach has been selected as the baseline. Typically, this approach requires pulverized coal grinds in which 50 to 90 percent of the product passes through a 200 mesh screen. Another backup combustion approach, involving a conventional arch-type furnace, would also require a coal grind of this type. Within this range, the grind can be varied as desired to emphasize a particular aspect of combustor performance. To improve carbon burnout, a finer grind can be selected; however, a finer grind usually reduces combustor slag recovery, especially in larger units. A larger grind has the opposite effect.

As discussed in Subtask 3.5, it may be possible to design the primary and secondary cyclones of the pyrolyzers so that solids captured by the primary cyclone are recirculated to the bed, while char captured in the secondary cyclone is fed to the char combustor. The char would be transported by a slipstream of pyrolysis gas. In this case, the expected particle size distribution—approximately 70 percent through 200 mesh—appears compatible with combustor requirements.

Precombustor Fuel Selection. A precombustor is required to provide the operating flexibility to burn low-volatile char in the main stage of the combustor. Several different precombustor fuels were considered, including char, fresh coal, natural gas, fuel oil, and fuel gas, as well as various combinations of these. A more-detailed discussion of precombustor fuel selection is provided in Quarterly Report 3. Coal was selected as the fuel of choice, because it combined both lower cost and acceptable performance as a preheat fuel. The most likely option is to use a single, dedicated pulverizer to grind the coal to the desired size (approximately 70 percent through 200 mesh). The coal would then feed one or both precombustors, depending on load. The coal can be transported to the precombustors by the mill sweep air.

Combustion Air Temperature and Oxygen Content. The baseline plant is to use exhaust from the gas turbine as combustion air. This exhaust is available at up to 1120°F. For the NG-HITAF case, the oxygen content of this stream will be approximately 19.5 wt%; for the FG-HITAF case, the oxygen content of the turbine exhaust stream drops to 14.8 wt%.

Combustion calculations were performed to assess the impact of the lower oxygen levels on combustor performance. An analysis of the FG-HITAF case was performed first, as it was considered the worst case. The results of the NG-HITAF case will be reported in the next quarterly report.

Figure 15 plots precombustor exit temperature as a function of precombustor coal flow. The overall combustor stoichiometry was assumed to be 0.9 and was held constant. Two different vitiated air temperatures were considered, 850 and 1120°F. The higher temperature represents the case in which the combustor air is taken off directly downstream of the gas turbine, while the lower temperature represents the case in which the gas turbine exhaust stream passes through a heat exchanger before it enters the combustor.

The minimum temperature required at the precombustor outlet to achieve acceptable combustion and slagging performance for a low-volatile fuel is approximately 2000°F. A coal flow rate of 18,800 lb/h is required to achieve this temperature in the 1120°F case, representing 29.5 percent of the total char combustor thermal input. For the 850°F case, a coal flow rate of 29,500 lb/h would be required to achieve a precombustor exit temperature of 2000°F, representing 40 percent of the char combustor thermal input. The 850°F also results in an approximately 300°F lower main combustor temperature and thus tends to reduce combustor operating flexibility in controlling NO_x. Based on these results, a combustor air inlet temperature of 1120°F is recommended for the FG-HITAF case.

Effect of Combustor Stoichiometry. Combustion calculations were also performed for the main combustor to support char combustor heat and material balance activities for the FG-HITAF case. Figure 16 shows combustor temperatures as a function of combustor stoichiometry. The combustion air temperature was assumed to be 1120°F, with coal added in the precombustor to bring the temperature up to 2000°F. Three different curves are shown in Figure 16:

- The top curve represents the adiabatic flame temperature, or no heat losses to the combustor cooling water in the precombustor or main combustor.
- The second curve represents the gas temperature at the combustor slag baffle, located approximately halfway through the combustor. At this point, the combustor heat load to the cooling water is approximately 7 percent of the total fuel thermal input.
- The third curve represents the temperature at the combustor exit, consistent with a combustor cooling load of 15 percent.

Based on combustor analytical modeling results, as well as on previous combustor experience with low-volatile coals, a minimum main combustor temperature of 3000°F is required at the combustor slag baffle to ensure high combustion and slagging performance.

Figure 15 Relationship of Precombustor Exit Temperature to Coal Flow

Figure 16 Relationship of Combustor Exit Temperature to Combustor Stoichiometry

According to Figure 16, the minimum combustor stoichiometry would then be approximately 0.85. The maximum stoichiometry would be approximately 1.15, based on combustor temperature considerations. However, it will probably be lower, based on NO_x considerations. For the preliminary combustor heat and material balance for the FG-HITAF, a combustor stoichiometry of 0.9 was assumed.

FG-HITAF Char Combustor Heat and Material Balance. A preliminary char combustor heat and material balance was performed for the FG-HITAF case in support of Bechtel's plant heat and material balance activities. A schematic of the combustor, shown in Figure 17, indicates the various process streams. Coal is burned in the precombustor with vitiated air from the gas turbine. (A further refinement of this heat and material balance is required to include the coal carrier flow, which is expected to be air at approximately 130°F.) The precombustor flow exhausts tangentially into the slagging stage, creating a highly turbulent, confined vortex flow. A mixture of char and fuel gas is injected in the head end of the combustor. Molten slag is tapped from the combustor following the completion of combustion at slightly fuel-rich conditions. The flow is then exhausted into a furnace. The combustor is cooled with high-temperature boiler feedwater.

Table 7 lists the baseline combustor operating conditions for the FG-HITAF case. The total fuel thermal input is 818×10^6 Btu/h, in which the char accounts for 64 percent, the coal accounts for 30 percent, and the fuel gas accounts for 6 percent. The precombustor exit temperature is 1982°F, with a cooling load requirement of 7.3×10^6 Btu/h, or 3 percent of the coal thermal input. The main combustor is operated under slightly fuel-rich conditions, at a stoichiometry of 0.9. The combustor exit temperature is approximately 2800°F, with a cooling load requirement of 134×10^6 Btu/h. The total heat to the steam cycle from the cooling circuit is 141.3×10^6 Btu/h. Table 8 lists the process flow rates, temperatures, pressures, and compositions for the FG-HITAF case. The NG-HITAF case will be included in the next quarterly report.

Subtask 3.7—Candidate Air Heater Materials

Three materials were recommended for consideration in the HITAF secondary air heater: sintered alpha-silicon carbide (SA-SiC, Carborundum), siliconized-silicon carbide (NT-230, Norton-TRW), and a silicon carbide particulate/aluminum oxide matrix composite ($\text{SiCp}/\text{Al}_2\text{O}_3$, DuPont-Lanxide). Their reported properties, including high thermal conductivity, low thermal expansion, high strength, and high use temperature make them attractive candidates for the heat exchanger application. However, properties of these ceramics (such as mechanical strength) may become unsatisfactory at temperatures lower than their listed maximum use temperature, depending on the service environment. The heat exchanger environment during operation cannot yet be precisely defined; there is an inherent variability in the composition and heating value of coal-derived fuel gas, and complete cleanup of the gas stream may not be viable. The resistance to corrosion of the candidate materials, therefore, an important consideration for the final material selection.

Figure 17 Char Combustor Heat and Material Balance

Table 7 Combustor Operating Conditions—FG-HITAF Case

Coal Thermal Input	243×10^6 Btu/h
Char Thermal Input	526×10^6 Btu/h
Fuel Gas Thermal Input	49×10^6 Btu/h
Total Thermal Input	818×10^6 Btu/h
Precombustor Chamber Stoichiometry	0.9
Precombustor Exit Stoichiometry	2.95
Precombustor Exit Temperature	1982°F
Precombustor Cooling Load	7.3×10^6 Btu/h
Char Combustor Stoichiometry	0.9
Char Combustor Baffle Temperature	3110°F
Char Combustor Exit Temperature	2800°F
Char Combustor Cooling Load	134×10^6 Btu/h
Total Heat to Steam Cycle	141.3×10^6 Btu/h

Table 8 Char Combustor Heat and Material Balance

Stream	15	17	18	20	21
Stream Description	Pulverized Coal	Char from carbon- izer	Vitiated air from gas turbine	Flue gas to furnace	Slag from combustor
Flow (lb/h)	18,805	843,300	52,134 (Char) 25,794 (Spent Sorbent) 26,627 (Fuel Gas)	935,388	31,272
Temperature (°F)	70	1120	1700	2800	2400
Pressure (in. H ₂ O)	25	20	10	0	0
Composition	71.91% C 4.69% H 6.33% O 1.26% N 2.99% S 10.32% Ash 2.50% H ₂ O 12,916 Btu/lb m (HHV)	72.14% N 14.83% O 8.23% CO ₂ 4.72% H ₂ O 0.02% SO ₂ 0.06% NO ₂	<u>Char/Spent Sorbent</u> 32.06% C 0.49% N 1.07% S 16.23% Ash 10.30% CaCO ₃ 7.54% MgO 6.84% CaS 6750 Btu/lb m (HHV) <u>Fuel Gas</u> 13.63% N ₂ 4.39% CO 4.40% CO ₂ 2.45% H ₂ O 1840 Btu/lb m (HHV)	70.7% N 15.7% CO 9.2% H ₂ O 2.4% CO

As preparations for corrosion testing of the candidate materials were begun at Foster Wheeler, a literature search was begun at AiResearch for the corrosion of structural ceramics. Several programs have been conducted since the early 1980s to study the effects of coal combustion environments on structural ceramics. A variety of experimental parameters, including:

- Material composition (oxide or nonoxide ceramics, sintering aids)
- Environment (acidic or basic)
- Exposure temperature
- Oxygen partial pressure
- Presence or absence of coal slag coating (molten or fused)

have been investigated. In many cases, the coal-combustion environment was simulated, but in some experiments actual coal-derived fuel gases, slags, or both were used.

Although a complete understanding of ceramic corrosion in coal combustion environments has not yet been achieved, a number of books, articles, and reports were found which provide a basis for predicting the behavior of the three candidate materials in the expected service environment. Two of the three materials, sintered alpha-SiC and siliconized SiC, were included in many of the reported coal combustion experiments [1-11]. The Lanxide SiCp/Al₂O₃ composite was not included in those experiments, but its behavior in air, steam, and simulated glass-melt furnace environments has been reported [12-14]. Some reports were found on the corrosion of alumina and on an SiC/Al₂O₃ composite (not Lanxide) in coal-derived gas environments [1,2,15,16], which may relate to the corrosion resistance of the Lanxide composites. A brief summary of selected experiments and results is given in the following paragraphs.

In the early 1980s exposure testing of structural ceramic materials was performed by Ferber and Tennery, using hot combustion gases from coal/oil mixtures. The materials, including SA-SiC, siliconized-SiC, and alumina were exposed to acidic coal combustion environments for 500 hours at 2192°F and basic coal combustion environments for about 240 hours at 2264°F. The tests were designed to simulate the conditions that tubular heat exchanger elements would experience in service. In the acidic-ash coal exposure test, thick deposits of coal slag accumulated on all of the tubes. The SA-SiC and the siliconized SiC survived the exposure with minimal material degradation, but the alumina cracked extensively. The cracking was apparently due to strong bonding between the alumina and the slag, coupled with a thermal mismatch; large stresses developed in the tubes during their cooldown from the test temperature. The strength of the siliconized SiC increased significantly and the SA-SiC strength increased slightly after exposure. The strength of the alumina could not be measured because of the extensive cracking.

In the basic ash coal exposure tests, relatively thin deposits of coal slag accumulated on the tubes. Compared with the acidic-ash coal experiment, the samples exhibited extensive wall

thinning, with the greatest thinning on the upstream side of the tubes (which faced the combustor). The wall losses were greatest for siliconized SiC, less for SA-SiC, and mostly moderate for alumina. The losses in strength were greatest for siliconized SiC, less for alumina, and mostly moderate for SA-SiC. Investigators noted that the corrosion mechanisms depend strongly on the composition of the ceramic. The SiC-based ceramics corroded via formation of phases at the ceramic-slag interface (iron and nickel silicides), which resulted in pitting of the SiC surface. The pitting caused a loss of strength. The wall thinning of alumina was due to the dissolution of its primary reaction product (iron nickel aluminate) in the fluid slag. The resultant rough surface on the alumina contributed to its reduction in strength.

Also in the early 1980s, Adams, Larsen, and Ruh reported the performance evaluation of 14 ceramic materials in coal-derived gas-combustion products [15]. Two test units at the Morgantown Energy Technology Center were used, one to provide static exposures and the other to provide dynamic, high-velocity combustion product exposures. One of the tests materials was similar to a candidate secondary air heater material: an $\text{Al}_2\text{O}_3 + \text{SiC}$ composite made by Ceradyne/Westinghouse. The composite material was only available for static exposure testing. Weight gains were reported after exposure at 1832, 2192, and 2597°F for up to 1000 hours as a result of formation on an oxide layer. The strength of the composite decreased uniformly by about 24 percent. The gas provided for these tests was "relatively clean," coming from the end of the gasification fuel stream cleanup system.

Recently, a corrosion test was performed by Kern, Tressler, and McNallan on the Lanxide composite material [14]. In their dynamic corrosion tests, a simulated glass melting flue environment was used. Flue gas from a glass melting facility contains high concentrations of corrosive alkali compounds; in these experiments sodium silicate was continuously applied to samples at 1832 to 2372°F for 10 to 300 hours. At all conditions, the composite gained weight as a result of the formation of compounds containing Al_2O_3 and metal oxidation products. Corrosive removal of this material became significant only during the 2372°F exposure. The loss in strength (about 80 percent at room temperature after exposure) was caused by thermal damage and surface flaws that resulted from the corrosive removal of material.

During the mid-1980s, Easler and Poeppel conducted a series of experiments to determine whether alterations in a material or in its environment could enhance its resistance to corrosion and mechanical property degradation [7]. In their work, the effects of a simulated coal gasification environment on siliconized SiC in the presence or absence of coal slag coatings and on SA-SiC were studied. Two processing methods produced the silicon carbide exposure samples—extrusion and slip-casting. Because SiC forms a protective oxide layer on its surface, the key to long-term use of SiC is the stability of that protective layer. The results of experiments on SA-SiC showed that the simulated coal gas environment had little, if any, effect on the samples at 1832°F, whether coal slag was present or not. At that temperature, the slag remained solid and unreactive, and oxidation of the SiC was slow. At 1250 and 2372°F, the SA-SiC samples exposed with no coal slag present showed little change in their fracture strength; a protective oxide layer had formed because of the high partial pressures of steam and carbon dioxide. However, the SA-SiC specimens exposed at those temperatures with basic and acidic coal slag coatings experienced losses in weight and fracture strength. The greatest loss was in those samples coated with basic slag. Basic slag decreases in viscosity more

rapidly than the acidic slag as temperature increases, which accelerates the corrosion activity. The results of experiments on siliconized SiC showed that exposure to the simulated coal gas environment without slag resulted in weight gain at all temperatures (1832, 2282, and 2372°F). A protective silica scale formed on the samples. As in the case of SA-SiC, little corrosion activity was noted in slag-coated samples exposed at 1832°F, while the slag remained solid. Corrosion activity increased with higher temperature, with the greatest weight and strength losses occurring in those samples coated with basic coal slag.

Subtask 3.8—Evaluation of Secondary Air Heater Corrosion

The gas-side environment in the secondary air heater is determined by the fuel gas combustion products and the carryover of particles in the fuel gas stream. There are two regimes in the secondary air heater where corrosion is a concern. One is the gas inlet region, where the ceramic material is at its highest temperature. There, alkalis in ash particles may stick to the tubes and corrode them. This condition can occur where the tubes are from 2100 to 2300°F. The other regime is where the gas temperature drops to the point where gaseous-phase alkalis start to condense out of the gas stream. This condition occurs around 1800°F, and it is a concern because of increased alkali concentrations.

The exact conditions in these two regions are difficult to predict because of the many mechanisms that influence the final result. For example, the rate of particle deposition on the secondary air heater tubes depends on the solids circulation rate in the pyrolyzer, the size distribution of particles entering the fuel gas cleanup system, the fractional efficiency of the cleanup system, and the fraction of particles that will end up sticking to the tubes in the air heater. The condensation of alkalis is even more difficult to predict because there are more mechanisms involved.

The approach that has been taken is to analyze the system conditions to a reasonable extent with existing models and establish test conditions based on these analyses. Depending on the results in the tests, the conditions will be made more or less severe to give information on the range of alkali levels that are allowable.

Figure 18 shows a schematic of the fuel gas system from the pyrolyzer to the secondary air heater. Mass flow rates of particulates are shown at various locations in the fuel-gas stream. These mass flow rates are based on an analysis of the NG-HITAF system with the December 15, 1992, plant heat and material balance. The pyrolyzer and primary cyclone were analyzed using the computer model discussed in Subtask 3.5. This model predicts the mass flow rate and the size distribution of the particle stream escaping the primary cyclone. The performance of the secondary cyclone is predicted by the American Petroleum Institute (API) method, assuming no particles are lost in the fuel gas cooler. Two options are shown for final cleanup. One is a barrier filter, and the other is a multitube cyclone. The final reduction in particle mass in the fuel-gas furnace is due to the combustion of the carbon.

The estimate of the fraction of particles that will actually stick to the air heater tubes is based on an analysis done by Research-Cottrell during another project. The tube particle collection efficiency determined from this analysis is shown in Table 9 for different particle sizes.

Figure 18 NG-HITAF—Particulates in Fuel Gas Stream [Total for 290-MW Plant (lb/h)]

Table 9 Particle Collection Efficiency

■ Gas Temperature = 2500°F	
■ Tube Diameter = 2 in. O.D.	
■ Velocity = 150 ft/s	
Particle Diameter (μm)	Collection Efficiency (%)
15	30
10	10
5	0.02
1	0.01
0.5	0.00
0.1	0.01
0.01	0.12

The conditions in our air heater are very close to those in the previous study, and the collection efficiencies in Table 9 were used as a guide for the present analysis. We also assumed that all the deposition will occur on the front half of the tubes.

Based on this analysis of the total fuel gas system, the deposition rate is estimated to be 7.59 mg/cm²·h with a multitube cyclone and 0.019 mg/cm²·h with a barrier filter. The high-temperature corrosion tests were started based on an earlier, less-detailed analysis, and the deposition rate was set at 0.036 mg/cm²·h. This deposition rate is in the range of the heat rate that will result with a barrier filter, and the tests will be continued until the performance of the materials at this rate is determined.

The high-temperature tests are being run at 2300°F—the highest tube temperature predicted by the AiResearch thermal analysis. Coupons of the Hexalloy SA material (1 in. × 2 in. × 3/16 in.) have been coated with representative ash and are being heated in a furnace that has a controlled gaseous environment. The composition of the furnace gas listed in Table 10 is the expected composition of the flue gas entering the air heater.

Table 10 Flue Gas Composition for Ceramic Corrosion Tests

Description	wt%
CO ₂	18.55
H ₂ O	7.61
O ₂	2.54
N ₂	71.13

Three different ashes are being tested. These ashes have been made from samples of char and sorbent that were elutriated from the pyrolyzer bed in the Second-Generation PFBC pilot plant tests. The char/sorbent mixtures were from runs with the feedstocks listed in Table 11. These samples were then ashed, and the ash is being applied to the ceramic specimens every 100 hours. Analyses of the ash applied to the specimens is shown in Table 12.

The ash is being applied every 100 hours, and 500 hours will be completed before a decision is made on the next test conditions. The first set of tests will be completed in early February.

As previously mentioned, tests will also be run to simulate the low-temperature region where condensation of gaseous-phase alkalis will be of concern. An estimate was made of the rate of alkali condensation that would occur without a fuel gas cooler. This estimate was based on thermodynamic equilibrium modeling of the flue gas. The resultant concentrations of liquid-phase Na₂SO₄ and K₂SO₄ are shown in Table 13.

Table 11 Pyrolyzer Feedstocks

Coal	Sorbent
Pittsburgh No. 8	Plum Run Dolomite
Illinois No. 6	Longview Limestone
Eagle Butte	Longview Limestone

Table 12 Ash Composition for 2300°F Ceramic Corrosion Tests

Component	Pittsburgh No. 8	Illinois No. 6	Eagle Butte
SiO ₂	17.5	38.5	27.8
Al ₂ O ₃	10.0	17.1	15.5
TiO ₂	0.3	0.8	1.1
Fe ₂ O ₃	15.4	15.0	6.4
CaO	22.3	13.8	30.1
MgO	15.8	1.0	5.5
Na ₂ O	0.2	0.6	1.0
K ₂ O	0.9	1.8	0.5
SO ₃	19.0	10.9	10.8
P ₂ O ₅	0.1	0.1	0.7

Table 13 Condensed Alkali Concentration in Flue Gas at 1800°F (Mole/Mole Flue Gas)

Component	Pittsburgh No. 8	Illinois No. 6	Eagle Butte
Na ₂ SO ₄	1.27×10^{-5}	2.51×10^{-6}	1.02×10^{-4}
K ₂ SO ₄	5.31×10^{-7}	1.19×10^{-8}	6.91×10^{-7}

Admittedly, it is very difficult to predict how these condensed alkalies will deposit on the tubes. To get a reference point, an assumption is being made that alkalies condense on particles and then deposit on the tubes. The initial 1800°F corrosion tests will be based on the particle carryover estimates of the 2300°F corrosion tests with Na_2SO_4 and K_2SO_4 added to the ash to simulate the condensed alkalies. The first test will be with the ash from Pittsburgh No. 8 coal and all three candidate ceramics. The ash loadings will be as indicated in Table 14. The Case 1 loadings result from the analysis described earlier. The Case 2 loadings have been added to help determine an acceptable alkali level if the Case 1 samples fail.

**Table 14 Ash Loadings for 1800°F Corrosion Tests, mg/in²
(Pittsburgh No. 8 Coal)**

Component	Case 1	Case 2
Ash	22.9	22.9
Na_2SO_4	17.0	1.7
K_2SO_4	0.9	0.09

Subtask 3.10 Fuel Characterization Testing

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

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

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

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

Description of Experiments. The rates of char combustion, sulfur release, and nitrogen release will be determined in a flat-flame burner (FFB) experiment as a function of flame temperature, gas composition, particle residence times, and particle size. Both parent coal and char will be characterized. Gas temperatures and compositions will be similar to the actual slagging-stage combustor environment (approximately 2000 K/3000°F). Since the slagging combustor design calls for complete conversion of the char particle in 70 to 90 percent of stoichiometric air, reactivities are desired in both oxygen environments and in steam/CO₂ environments. The post-flame gases in the FFB experiment can be adjusted to contain 0 to 20 mol% O₂ by changing the stoichiometry of the flame. These post-flame gases generally contain 13 mol% steam and 6 mol% CO₂. CO₂ concentrations of up to 15 mol% may be required, which can be accomplished by adding additional CO₂ gas at the burner inlet. Char samples will be collected in the FFB at different residence times to determine kinetic rates. Residence times in the FFB will be determined by streak photography. Maximum residence time is 500 ms in the FFB.

A schematic of the FFB test configuration is shown in Figure 19. Air and methane are transported separately through a monolithic structure, as shown in Figure 20. 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. An adjustable collection probe with a nitrogen quench, above the FFB, collects and extinguishes the burner char particles. The char particles are then separated in a cyclone and retained for post-test analyses.

A preliminary test matrix is presented in Table 15. Key test parameters include coal type, particle diameter, flame temperature, gas concentration, and particle residence time. Tests will also be performed at a previously characterized gas composition and flame temperature to provide a baseline for comparison with an existing database.

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

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

Figure 19 Char Combustion Test Configuration

Figure 20 Flat Flame Burner

Table 15 Char Combustion Experiments

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

Summary of Results. Recent efforts have been concentrated on finishing the characterization of the FFB facility (i.e., gas temperatures, O₂ concentrations, and particle velocities), in preparation for conducting char sampling and analyses experiments. Theoretical studies were also started this quarter, using recently published kinetics, to show predicted amounts of char burnout.

Particle Sizing. Three samples were obtained from FWDC—the parent coal, the cyclone char (labeled 330), and the bed char (labeled 331). The parent coal and the bed char were in crushed form; the cyclone char was in pulverized form, with a fairly large grind size.

The desired size for combustion tests is the 63 to 74 μm fraction from dry sieving. The cyclone char (330) has now been sieved once, yielding 220 g in the 63 to 74 μm size fraction. The size distribution of the cyclone char (330) was measured with a Coulter Laser to estimate how much of the 63 to 74 μm cut could be obtained with straight sieving. On a mass basis, the cut was not as tight as desired, as shown in Figure 21. The average particle size was 81 μm .

The parent coal is being ground with a mortar and pestle, then sieved to obtain the 63 to 74 μm size fraction. Approximately 70 g of the parent coal in this size fraction has now been obtained, and an additional 150 g is being processed. The size distribution of the parent coal has not yet been measured.

Figure 21 Coulter-Laser Analysis of 63- to 74-Sieve Size Fraction of Cyclone (330) Char

Preexperimental Analysis. Both N_2 and CO_2 surface areas of the 63 to 74 μm size fractions of parent coal and cyclone char (330) were measured. The results are given in Table 16. The surface areas of the coal and char are very similar to those of other bituminous coals and chars.

Table 16 Surface Areas of Raw Coal and Unburned Char (m^2/g)

Area	Coal	330 Char
N_2 Surface	1.3	103.5
CO_2 Surface	137.6	279

The parent coal and cyclone char (330) samples were ashed in a muffle furnace, following ASTM procedures, for approximately 20 hours. The ash from the coal was a reddish brown, while the ash from the 330 char was a light tan. Each sample was ashed three times. The results are shown in Table 17. Proximate volatiles content and ultimate analyses have not yet been performed.

Table 17 Ash and Moisture Content of Parent Coal and Unburned Char, %

Ashing	Coal		330 Char	
	Ash	Moisture	Ash	Moisture
1	10.06	1.88	35.99	0.9
2	10.99	1.89	35.64	0.91
3	10.65	1.93	35.62	0.9
Average	10.6	1.9	35.8	0.9
St. Dev.	0.5	0.03	0.2	0.01

Flat Flame Burner Experiments. Four gas conditions were developed in the FFB for char combustion experiments, as shown in Table 18. A small flow rate of pure oxygen was used in conjunction with methane and air to obtain the two gas conditions containing 5 percent post-flame O_2 . The 1800 K, zero-percent post-flame O_2 condition required an additional stream of pure nitrogen to cool the flame. Gas temperature measurements vs. residence time at these four conditions were obtained with a silica-coated thermocouple and corrected for radiative losses; they are shown in Figure 22. All measurements were performed with a 10-in.-tall cylindrical quartz tower, yielding residence times of approximately 110 ms. Actual particle velocity measurements are currently being performed using streak photography.

Table 18 Gas Conditions for Flat-Flame Burner Experiments

Maximum Gas Temperature, K	Post-Flame O_2 (mol%)	Flow Rates Into Burner (standard cc/s)			
		Methane	Air	O_2	N_2
2000	5.0	71.4	623.9	41.7	---
1800	5.0	55.3	632.9	11.3	---
2000	0.0	68.5	690	---	---
1800	0.0	53.9	486.6	---	85.8

Figure 22 Gas Temperature Profile Measured in FFB for Four Gas Conditions Listed in Table 18 (Measurements obtained with a silica-coated thermocouple and corrected for radiation)

A preliminary experiment was performed for the 330 char (from the cyclone at the top of the pyrolyzer) in the 1800 K, 5-percent O₂ gas condition in the FFB. A mass balance indicated 40 to 50 percent char burnout in 100 ms. The ash content of the burned char sample was less than the ash content of the unburned char, indicating the probable release of inorganic material during char combustion—most likely the vaporization of the sorbent material. The char sample is currently being analyzed by ICP spectroscopy to determine the content of major inorganic elements (e. g., Ti, Al, Si, Fe, and Ca). Titanium, silicon and aluminum oxides were used as tracers to determine burnout in related experiments [17].

Char Combustion Predictions. Char combustion calculations were performed to approximate the range of burnout expected in the FFB in 5-percent post-flame oxygen. A linear gas temperature profile in these predictions approximated actual measured gas temperatures vs. residence time for the two flame conditions. Kinetic parameters for two coal chars were taken from related research at Sandia National Laboratories [17,18] and are summarized in Table 19. Based on the Foster Wheeler TGA experiments on the char from the fluidized bed pyrolyzer, the expected reactivity at high temperature should be similar to an unreactive char such as from the Pocahontas low-volatile bituminous coal. Predictions for the Pittsburgh No. 8 coal char were performed, since this coal is thought to be representative of the raw coal fed to the pyrolyzer.

Table 19 Apparent Reactivities of Two Coal Chars From PETC DU AR&TD Coal Suite

Seam	State, Rank	A*	E*	Ac†	Ec†	α§
Pocahontas No. 3 (PSOC-1508 D)	West Virginia, low-volatile bituminous	3.58 (114)	125 (30)	3 x 10 ⁸	251 (60)	0.3
Pittsburgh No. 8 (PSOC-1451D)	Pennsylvania high-volatile bituminous	0.91 (29)	100 (24)	4 x 10 ⁴	125 (30)	0.1
* Reaction rate (gm·C/cm ² ·s·atm ^{0.5}) = A exp(-E/RTp)(PO _{2,s}) ^{0.5} ; E in kJ/mol (kcal/mol); P in atm, A in kg·C/m ² ·s·Pa ^{0.5} (gm·C/cm ² ·s·atm ^{0.5}) † CO/CO ₂ ratio = Ac exp(-Ec/RTp), E _c in kJ/mol (kcal/mol) § Burning mode parameter; $\rho/\rho_0 = (m/m_0)^{\alpha}$ and $d/d_0 = (m/m_0)^{(1-\alpha)/3}$						

The CO/CO₂ ratio is a correlation for the percentage of carbon that forms CO₂ vs. CO at the surface of the particle and affects the particle energy balance. The reactions here are one-half order in oxygen. The initial char density was assumed to be 0.63 g/cc, as measured for the Pocahontas char at Sandia. The burning mode parameter (α) represents the relationship among diameter, density, and burnout; the limits are constant diameter burning (α = 1) or

constant density burning ($\alpha = 0$). The particle temperature is calculated from the time-dependent particle energy balance equation, based on the gas temperature, the heat and rate of reaction, and the radiative loss in the transparent-wall flow reactor.

Predictions of char burnout for the two coal chars, based on the parameters in Table 16, are shown in Figures 23 and 24. The current configuration for the FFB allows approximately 110 ms of residence time. The predicted burnout in the FFB system for the Pocahontas char was 44 percent in the 1800 K gas condition (5 percent O_2) and 74 percent in the 2000 K gas condition (5 percent O_2). Comparative predicted burnouts for the more-reactive Pittsburgh No. 8 char were 65 percent and 83 percent respectively for the two temperature conditions (5 percent O_2). This result means that sufficient burnout is probably achieved in the current configuration of the FFB system to conduct meaningful reaction-rate experiments.

To ascertain kinetic parameters for char reactivities, the char combustion must occur in a regime where the reaction process is not totally controlled by film diffusion (i.e., the mass transfer of oxygen from the bulk gas stream to the particle surface). The maximum possible particle burning rate occurs when the process is completely controlled by film diffusion. The ratio of the burning rate to the maximum burning rate, referred to as χ , approaches 1.0 near the film diffusion limit. The χ factor used here assumes that the gas temperature is constant, and therefore the particle temperature is changed to match the theoretical maximum burning rate. Predictions of χ vs. residence time are shown in Figures 23 and 24 for the two coal chars, indicating that the predicted burning rates approach 75 percent of the film diffusion limit at one point in the 2000 K gas condition.

Subtask 3.13—Preliminary Design of Secondary Air Heater

The overall ceramic heat exchanger design was revised during this reporting period. This redesign was necessary as a result of major changes in the gas-side flow rate and temperature. The revised design case for the secondary air heater is presented in Table 20.

Based on this revised problem statement for a 290-MWe power plant, a new air heater design was derived. Table 21 lists the new heat exchanger design parameters. In addition to the new design, an off-design performance point was evaluated. In this case, all the design conditions in Table 20 remained the same, with the exception of the gas inlet temperature, which was reduced to 2750°F. This change resulted in an air outlet temperature of 1743°F and a gas outlet temperature of 1942°F.

This analysis reached the conclusion that an approximate increase of 35 percent is the air heater size required to obtain an 1800°F outlet air temperature with a 2750°F gas inlet temperature, compared with a 2950°F gas inlet temperature.

Figure 23 Prediction of Char Burnout, Particle Temperature, and χ Factor for Pocahontas (lv) and Pittsburgh No. 8 (hv) Bituminous Coal Char in 1800 K, 5-Percent Post-Flame Oxygen Condition

Figure 24 Prediction of Char Burnout, Particle Temperature, and χ Factor for Pocahontas (lv) and Pittsburgh No. 8 (hv) Bituminous Coal Char in 2000 K, 5 Percent Post-Flame Oxygen Condition

Table 20 Secondary Air Heater Design Conditions

Parameter	Air Side	Gas Side
Inlet Temperature, °F	1400	2956
Outlet Temperature, °F	1800	2023
Heat Exchanger Effectiveness	---	0.600
Inlet Pressure, psia	198.54	15.62
Pressure Drop, psi	5	0.8
Flow Rate, lb/h	2,877,500	1,010,800
Composition, vol%	Vitiated Air	CO ₂ : 13.2 H ₂ O: 10.5 N ₂ : 72.7 O ₂ : 3.0 Ar: 0.6

Table 21 Revised Secondary Air Heater Design With Sintered Alpha-Silicon Carbide Tube Material

Description	Values
Total Number of Tubes	3776
Number of Tubes per Module	59
Number of Modules per Stack	8
Number of Modules	64
Active Tube Length, ft	6.5
Gas Flow Length, ft	5.2
No-Flow Length, ft (4 Units)	39.4
Tube Weight, lb	44,022
Core Volume, ft ³	1324
Tube O.D./I.D., in. *	2.0/1.7
Tube Spacing, in.	3.0 (Equilateral Triangles)
Minimum Tube Clearance, in.	1.0
*Internal Cruciform Fins; Thickness Equal to Wall Thickness.

Subtask 3.21 — Pollution Control Systems

As a result of the discouraging results of the laboratory tests on char adsorption, attention has focused on other SO₂ control technologies. The regenerable processes are of particular interest, since SO₂ removal efficiency is high, and little waste product is generated. Four near-commercial regenerable SO₂-removal systems are recommended for consideration:

- Tung process
- CANSOLV process
- SOXAL process
- Dow process.

The Tung process was initially designated as a candidate for consideration. This process is a modified Wellman-Lord, in which the SO₂ scrubbing occurs through the conversion of sodium sulfite to sodium bisulfite. The Tung process utilizes a two-step regeneration system to convert the bisulfite back to the sulfite form and extract concentrated SO₂. A similar process, the SOXAL process, utilizes electrochemical technology to regenerate the sulfite. Both of these processes will undergo DOE-sponsored pilot-scale testing at Niagara Mohawk's Dunkirk Station in 1993.

The CANSOLV and the Dow processes are basically identical. They scrub SO₂ from flue gas with an amine solution. The SO₂ is subsequently stripped from the amine solution by heating. The difference between the two processes is in their proprietary amines. The CANSOLV process will undergo full-scale testing at the 75-MW ALCOA Generating Corporation unit under a CCT-IV program, probably in 1994 or 1995. The Dow Corporation plans to install a full-scale system on a 250-MW plant, to be operating in 1995.

As discussed, the systems are very similar. All are scrubbers achieving 95-percent efficiency. Two use sodium sulfite solutions, and two use amine solutions. All produce concentrated SO₂ as a byproduct. As a result, the final selection of the process need not be done in Phase I. Since these four systems are essentially stand-alone systems and do not affect generating plant design or operation, it would be better to delay selection until the Tung and SOXAL testing is complete in 1993; thus we would have the benefit of the greatest amount of evaluation information.

Flow diagrams were constructed for the four SO₂-control technology candidates, as shown in Figures 25 through 28. These diagrams were sent to the respective technology developers for corrections and verification. Input/output diagrams were also constructed to identify the material and utility requirements for each process, and these diagrams were sent to the process developers for completion.

Dennis Helfritsch and Paul Feldman visited with Shao Tung in Brookline, Massachusetts, to discuss and collect more information on his SO₂-removal process. Dr. Tung provided a description of the evolution of the process, detailed process information, cost information, and an update of the Dunkirk Station design and construction.

Figure 25 Tung FGD Flow Diagram

Figure 27 CANSOLV FGD Flow Diagram

Figure 28 DOW FGD Flow Diagram

Emissions surveys were completed for the indirect- and direct-fired cases, using the mass flows provided by Bechtel in December. The flow systems surveyed are given in Figures 29 and 30, and examples of typical survey results are given in Tables 22 and 23. Initial conditions, such as coal sulfur content and NO_x production rates, are input. The flows of sulfur, NO_x , and particulate are then calculated in accordance with the initial conditions and the flow system. The results are given in terms of emissions rates in $\text{lb}/10^6 \text{ Btu}$.

The procedures used in estimating the NO_x emissions for the various combustors for three different cases are:

Pyrolyzer. The pyrolyzer transforms coal into gaseous and solid products at a relatively low temperature (1700°F) in a deficiency of air. The air for this combustor is vitiated air from the gas turbine, resulting in little or no air fixation and little or no conversion of fuel nitrogen to NO_x . It is assumed that no NO_x is formed in the pyrolyzer.

Fuel Gas Combustor. In the fuel gas combustor, low-Btu gas is burned with vitiated air. The fuel gas is close to 1700°F . The vitiated air contains approximately 19-percent oxygen. The fuel gas contains some ammonia, but test burns of similar gas by Foster Wheeler indicates that only small portion of the ammonia converts to NO_x . Foster Wheeler also operated a Chemically Active Fluid Bed (CAFB) gasifier, in which low-Btu gas at 1600°F was burned with air in a 20-MW gas-fired boiler with a maximum NO_x emission of $0.2 \text{ lb}/10^6 \text{ Btu}$. There were no extraordinary NO_x combustion controls on this boiler. Peabody estimated an NO_x generation value of $0.05 \text{ lb}/10^6 \text{ Btu}$. Using an 8 percent conversion of NH_3 in the fuel gas yields the same value as the Peabody estimate, based on the chemical heat (HHV) in the fuel gas and amount of fuel gas fired in the fuel gas combustor.

Gas Turbine Combustor (Natural Gas). The gas turbine is fired with natural gas and preheated air. It is assumed that the combustor is a series of combustors arrayed around the gas turbine, as in conventional gas turbine design. At present, the NSPS for gas turbines is 75 ppm at 15-percent O_2 . Recently, gas turbine suppliers claimed they would guarantee 25 ppm at 15 percent based on the application of NO_x combustion control technology. The 75 and 25 ppm convert to approximately 0.3 and $0.1 \text{ lb}/10^6 \text{ Btu}$ respectively. The 0.3 value is used in the emissions survey.

TRW Combustor. The TRW Combustor is the main combustor of the system. Two different solid fuels are burned in this combustor—coal and char—with vitiated air. Pulverized coal is burned in the precombustor with vitiated air. For the precombustor, we have assumed that the Clean Air Amendment Act limit of $0.5 \text{ lb}/10^6$ can be met, but that the use of vitiated air is analogous to flue gas recirculation through the pulverizer, which amounts to as much as a 15-percent reduction and thus an emissions factor of $0.425 \text{ lb}/10^6 \text{ Btu}$. The NO_x emissions were the calculated based on the heat input from the coal on a mass rate basis, combined with the NO_x emissions from the char, as described later.

Figure 29 NG-HITAF—Block Flow Diagram (Streams are listed in Table 22.)

Figure 30 FG-HITAF—Block Flow Diagram (Streams are listed in Table 23.)

Table 22 NG-HITAF Emissions — Typical Results

INITIAL CONDITIONS				SYSTEM EMISSION RATES			
COAL % ASH	10			LB/MM BTU SO ₂	0.1273		
COAL % S	3						
Ca/S TO PYROLYZER	3			LB/MM BTU NO _x	0.1423		
% ASH TO FUEL GAS	1						
% S TO H ₂ S	1			LB/MM BTU ASH	0.0065		
% ASH CAPTURE	80						
COMBUST % S CAPT	20			MM BTU/HR	2166		
BARRIER FILTER %	0						
PART CONTROL %	99.8			MW @ 48% EFF	305		
DESOX %	95						
DENOX1 %	0						
DENOX2 %	0						
FG COMB LB/MMBTU	0.05						
PRECOMB LB/MMBTU	0.425						
CHARCOM LB/MMBTU	0.25						
GT COMB LB/MMBTU	0.3						
VA COMB NO _x RED %	50						
HITAF FLOW CONDITIONS							
STREAM NUMBER	FLOW K LB/HR	PRESS PSIA	TEMP DEG F	S LB/HR	NO LB/HR	PART LB/HR	HHV BTU/LB
1 COAL	109.9	14.7	68	3297.0	0.0	33244.8	12916
2 FUEL GAS	244.5	45	1700	33.0	0.0	332.4	2112
3 FLUE GAS	821	45	1100	33.0	25.8	332.4	
4 NAT GAS	32	14.7	68	0.0	0.0	0.0	21800
5 AIR	2959	150	1800	0.0	0.0	0.0	
6 VIT AIR	3439	30	700	0.0	209.3	0.0	
7 VIT AIR	1458	30	700	0.0	88.7	0.0	
8 VIT AIR	1981	30	100	0.0	120.6	0.0	
9 VIT AIR	1981	14.7	100	0.0	120.6	0.0	
10 CHAR	52.7	45	1700	3264.0	96.6	32912.3	7333
11 COAL	3.8	14.7	68	114.0	20.9	380.0	12916
12 FLUE GAS	1456	14.7	300	2758.2	143.3	7057.4	
13 FLUE GAS	1456	14.7	300	2758.2	143.3	7057.4	
14 FLUE GAS	1456	14.7	300	2758.2	143.3	14.1	
15 FLUE GAS	1456	14.7	100	137.9	143.3	14.1	
16 STACK	3437	14.7	100	137.9	308.2	14.1	
LB/MMBTU				0.127331	0.142283	0.006516

Table 23 FG-HITAF Emissions—Typical Results

INITIAL CONDITIONS				SYSTEM EMISSION RATES			
COAL % ASH	10			LB/MM BTU SO ₂	0.4413		
COAL % S	3						
Ca/S TO PYROLYZER	2.5			LB/MM BTU NO _x	0.1803		
% SOLIDS TO FUEL GA	7						
% S TO H ₂ S	10			LB/MM BTU ASH	0.0051		
% ASH CAPTURE	80						
COMBUST % S CAPT	20			MM BTU/HR	2063		
BARRIER FILTER %	99.9						
PART CONTROL %	99.9			MW @ 48% EFF	290		
DESOX %	97						
DENOX1 %	0						
DENOX2 %	80						
NH ₃ TO NO CONV %	50						
% NH ₃ IN FUEL GAS	0.12						
PRECOMB LB/MMBTU	0.5						
CHARCOM LB/MMBTU	0.25						
GT COMB LB/MMBTU	0.50						
VA COMB NO _x RED %	50						
HITAF FLOW CONDITIONS							
STREAM NUMBER	FLOW K LB/HR	PRESS PSIA	TEMP DEG F	S LB/HR	NO LB/HR	PART LB/HR	HHV BTU/LB
1 COAL	154.3	226	68	4629.0	0.0	51594.1	12916
2 FUEL GAS	666	206	1700	462.9	0.0	8.0	2112
3 AIR	467	226	1100	0.0	0.0	0.0	
4 FUEL GAS	666	206	68	462.9	705.2	0.0	2112
5 AIR	2444	205	1800	0.0	0.0	0.0	
6 VITAIR	3637	205	700	462.9	705.2	0.0	
7 VITAIR	912	205	700	116.1	176.8	0.0	
8 VITAIR	2725	205	100	346.8	528.3	0.0	
9 VITAIR	2725	205	100	346.8	105.7	0.0	
10 CHAR	78	15	1700	4166.1	143.0	51586.1	7333
11 COAL	5.4	15	68	162.0	34.9	540.0	12916
12 FLUE GAS	1004	15	300	3611.0	177.9	10425.2	
13 FLUE GAS	1004	15	300	3611.0	177.9	10425.2	
14 FLUE GAS	1004	15	300	3611.0	177.9	10.4	
15 FLUE GAS	1004	15	100	108.3	177.9	10.4	
16 STACK	3729	15	100	455.2	372.0	10.4	
LB/MMBTU				0.441321	0.180323	0.005057

Values for char combustion in a slagging combustor were estimated by TRW in a range of 0.2 to 0.3 lb/10⁶ Btu. A value of 0.25 was used. In addition to the NO_x formed in the combustor, there is some NO_x in the vitiated air used as the oxidizer and in the flue gas from the fuel gas combustor, which is delivered to the low-temperature air heater at 1100°F. We have assumed that the NO_x is reduced by 50 percent as a result of the combustion processes in the low-temperature air heater.

The results from Tables 21 and 22 indicate that, to have an SO₂ emission rate less than 0.15 lb/10⁶ Btu, the flue gas desulfurization system must be 95-percent efficient for the NG-HITAF system. This analysis also indicates that it will not be possible to meet the SO₂ goals with the FG-HITAF unless some sulfur is removed from the fuel gas or gas turbine exhaust stream. These efficiencies are achievable using the regenerable SO₂ technologies being considered.

The NO_x emissions are shown to be less than 0.15 lb/10⁶ Btu, given the NO_x production rates described for the various combustors. The largest heat release comes from the fuel gas combustion, and the overall NO_x emissions rate is strongly affected by the fuel gas combustion NO_x generation rate. This rate was set at 0.05 lb/10⁶ Btu for both the NG-HITAF and FG-HITAF cases.

As determined from Tables 21 and 22, the particulate control equipment needs to be 99.9-percent efficient. Both baghouses and precipitators have demonstrated collection efficiencies better than this value; but in the case of baghouses, there is a great deal of uncertainty about how to design the baghouse to be sure of 99.9-percent collection efficiency, which is less than a 0.01 lb/10⁶ Btu emissions rate. Figure 31 shows the result of a utility baghouse survey of over 24 baghouses, representing 7750 MW of generating capacity [19]. As the figure shows, less than 20 percent of the baghouses surveyed had emissions rates less than 0.01 lb/10⁶ Btu. In a similar study, W. R. Lane comes to the same conclusion and complains that "If, for example, we had to design for one third lower emissions (than 0.03 lb/10⁶ Btu), 0.02 lb/10⁶ Btu, there would be only a 70 percent chance of achieving it, based upon experience at 57 plants. This is not a comfortable design margin." [20].

The electrostatic precipitator design criteria for specific emissions targets are better known. Kumar and Feldman show how precipitator collection efficiency is affected by coal sulfur content and specific collection area in Figure 32 [21]. The Figure 32 curve for high-sulfur coal is compared with the data of DuBard and Dahlin [22] in Figure 33, and it shows that the results are compatible. Such results show that it is possible to confidently specify an electrostatic precipitator to achieve 99.9-percent collection efficiency, and Figure 32 shows that the specific collection area must be 400 ft²/1000 ft³/min or greater.

Figure 31 Number of Baghouses Reporting Mass Emission Rates in Indicated Ranges

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

Figure 33 Typical Precipitator Performance on High-Sulfur Eastern Coals

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