ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH-PERFORMANCE POWER SYSTEMS

Quarterly Technical Report

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Author: J. Shenker

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Foster Wheeler Development Corporation
12 Peach Tree Hill Road
Livingston, NJ 07039

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ABSTRACT

A High Performance Power System (HIPPS) is being developed. This system is a coal-fired, combined cycle plant with indirect heating of gas turbine air. Foster Wheeler Development Corporation and a team consisting of Foster Wheeler Energy Corporation, Bechtel Corporation, University of Tennessee Space Institute and Westinghouse Electric Corporation are developing this system. In Phase 1 of the project, a conceptual design of a commercial plant was developed. Technical and economic analyses indicated that the plant would meet the goals of the project which include a 47 percent efficiency (HHV) and a 10 percent lower cost of electricity than an equivalent size PC plant.

The concept uses a pyrolyzation process to convert coal into fuel gas and char. The char is fired in a High Temperature Advanced Furnace (HITAF). It is a pulverized fuel-fired boiler/air heater where steam and gas turbine air are indirectly heated. The fuel gas generated in the pyrolyzer is then used to heat the gas turbine air further before it enters the gas turbine.

The project is currently in Phase 2 which includes engineering analysis, laboratory testing and pilot plant testing. Research and development is being done on the HIPPS systems that are not commercial or being developed on other projects. Pilot plant testing of the pyrolyzer subsystem and the char combustion subsystem are being done separately, and then a pilot plant with a more integrated HIPPS arrangement will be tested.

This report contains preliminary results from the pyrolyzer pilot plant testing done to date, and information on modifications that have been done to the facility. It also includes computer modeling of the furnace for the combustion system pilot plant, and information on the modifications that are being made to the combustion pilot plant to facilitate the HIPPS testing.

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EXECUTIVE SUMMARY

The High Performance Power System is a coal-fired, combined cycle power generating system that will have an efficiency of greater than 47 percent (HHV) with NO_x and SO_x less than 0.025 Kg/GJ (0.06 lb/MMBtu). This performance is achieved by combining a coal pyrolyzation process with a High Temperature Advanced Furnace (HITAF). The pyrolyzation process consists of a pressurized fluidized bed reactor which is operated at about 926°C (1700°F) at substoichiometric conditions. This process converts the coal into a low-Btu fuel gas and char. These products are then separated.

The char is fired in the HITAF where heat is transferred to the gas turbine compressed air and to the steam cycle. The HITAF is fired at atmospheric pressure with pulverized fuel burners. The combustion air is from the gas turbine exhaust stream. The fuel gas from the pyrolyzation process is fired in a Multi-Annular Swirl Burner (MASB) where it further heats the gas turbine air leaving the HITAF. This type of system results in very high efficiency with coal as the only fuel.

We are currently in Phase 2 of the project. In Phase 1, a conceptual plant design was developed and analyzed both technically and economically. The design was found to meet the project goals. The purpose of the Phase 2 work is to develop the information needed to design a prototype plant which would be built in Phase 3. In addition to engineering analysis and laboratory testing, the subsystems that are not commercial or being developed on other projects will be tested at pilot plant scale. The FWDC Second-Generation PFB pilot plant in Livingston, NJ, has been modified to test the pyrolyzer subsystem. The FWDC Combustion and Environmental Test Facility (CETF) in Dansville, NY, is being modified to test the char combustion system. When these tests are complete, a more integrated pilot plant will be tested.

During this Quarter, some modifications to the Livingston Pyrolyzer Pilot Plant were made and two more test runs were completed. All planned modes of operation with a jetting type of bubbling bed pyrolyzer have been completed. Data reduction for the first two test points is complete, but laboratory analysis for the last two runs is still in progress. The results so far indicate that this type of pyrolyzer will give performance that is acceptable for a HIPPS plant. The bubbling bed pyrolyzer has been run with beds of limestone and alternatively with sand beds. The coal input to the pyrolyzer has been pulverized coal in all cases.

The pyrolyzer pilot plant test results are being used to benchmark a computer model that will be used to design a larger pyrolyzer for the integrated system test and ultimately the prototype plant. The testing so far has indicated that the computer model could be improved by some modifications, but basically it is predicting the pilot plant performance well.

A system to transport char was added to the pyrolyzer pilot plant for the last two runs, and it operated successfully. The char was depressurized in a lock hopper system and pneumatically transported through 19.5m (60 ft.) of pipe to a baghouse. This is the type of system is planned for the commercial plant where char will be transported to hoppers located near the burners.

Computer modeling is being done for the char combustion in the CETF furnace. PCGC3 is being used and runs have been made for various conditions to help establish the design and operating conditions for upcoming tests. During this Quarter, more runs were made at higher char input and with the burner position changed. These modifications were the result of changes that came about from analyses of previous runs and development of the system design.

INTRODUCTION

In Phase 1 of the project, a conceptual design of a coal-fired high performance power system was developed, and small scale R&D was done in critical areas of the design. The current Phase of the project includes development through the pilot plant stage, and design of a prototype plant that would be built in Phase 3.

Foster Wheeler Development Corporation (FWDC) is leading a team of companies in this effort. These companies are:

- Foster Wheeler Energy Corporation (FWEC)
- Bechtel Corporation
- University of Tennessee Space Institute (UTSI)
- Westinghouse Electric Corporation

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

- Total station efficiency of at least 47 percent on a higher heating value basis.
- Emissions:

  NO_x < 0.06 lb/MMBtu
  SO_x < 0.06 lb/MMBtu
  Particulates < 0.003 lb/MMBtu

- All solid wastes must be benign with regard to disposal.
- 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.

The base case arrangement of the HIPPS cycle is shown in Figure 1. It is a combined cycle plant. This arrangement is referred to as the All Coal HIPPS because it does not require any other fuels for normal operation. A fluidized bed, air blown pyrolyzer converts coal into fuel gas and char. The char

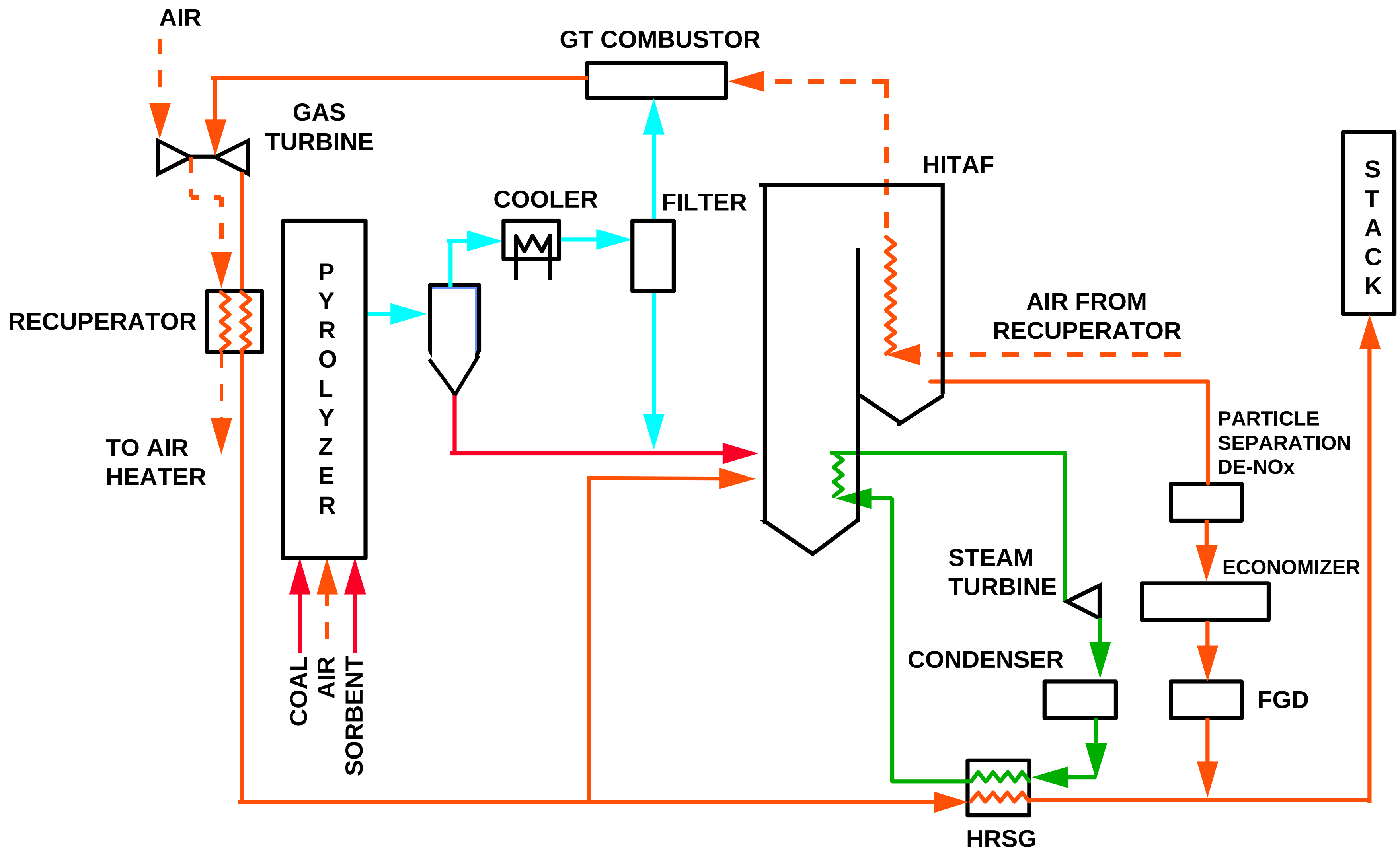


Figure 1 All Coal Fired HIPPS

is fired in a high temperature advanced furnace (HITAF) which heats both air for a gas turbine and steam for a steam turbine. The air is heated up to 760^{o}C (1400^{o}F) in the HITAF, and the tube banks for heating the air are constructed of alloy tubes. The fuel gas from the pyrolyzer goes to a topping combustor where it is used to raise the air entering the gas turbine to 1288^{o}C (2350^{o}F). In addition to the HITAF, steam duty is achieved with a heat recovery steam generator (HRSG) in the gas turbine exhaust stream and economizers in the HITAF flue gas exhaust stream.

An alternative HIPPS cycle is shown in Figure 2. This arrangement uses a ceramic air heater to heat the air to temperatures above what can be achieved with alloy tubes. This arrangement is referred to as the 35 percent natural gas HIPPS, and a schematic is shown in Figure 2. A pyrolyzer is used as in the base case HIPPS, but the fuel gas generated is fired upstream of the ceramic air heater instead of in the topping combustor. Gas turbine air is heated to 760^{o}C (1400^{o}F) in alloy tubes the same as in the All Coal HIPPS. This air then goes to the ceramic air heater where it is heated further before going to the topping combustor. The temperature of the air leaving the ceramic air heater will depend on technological developments in that component. An air exit temperature of 982^{o}C (1800^{o} F) will result in 35 percent of the heat input from natural gas.

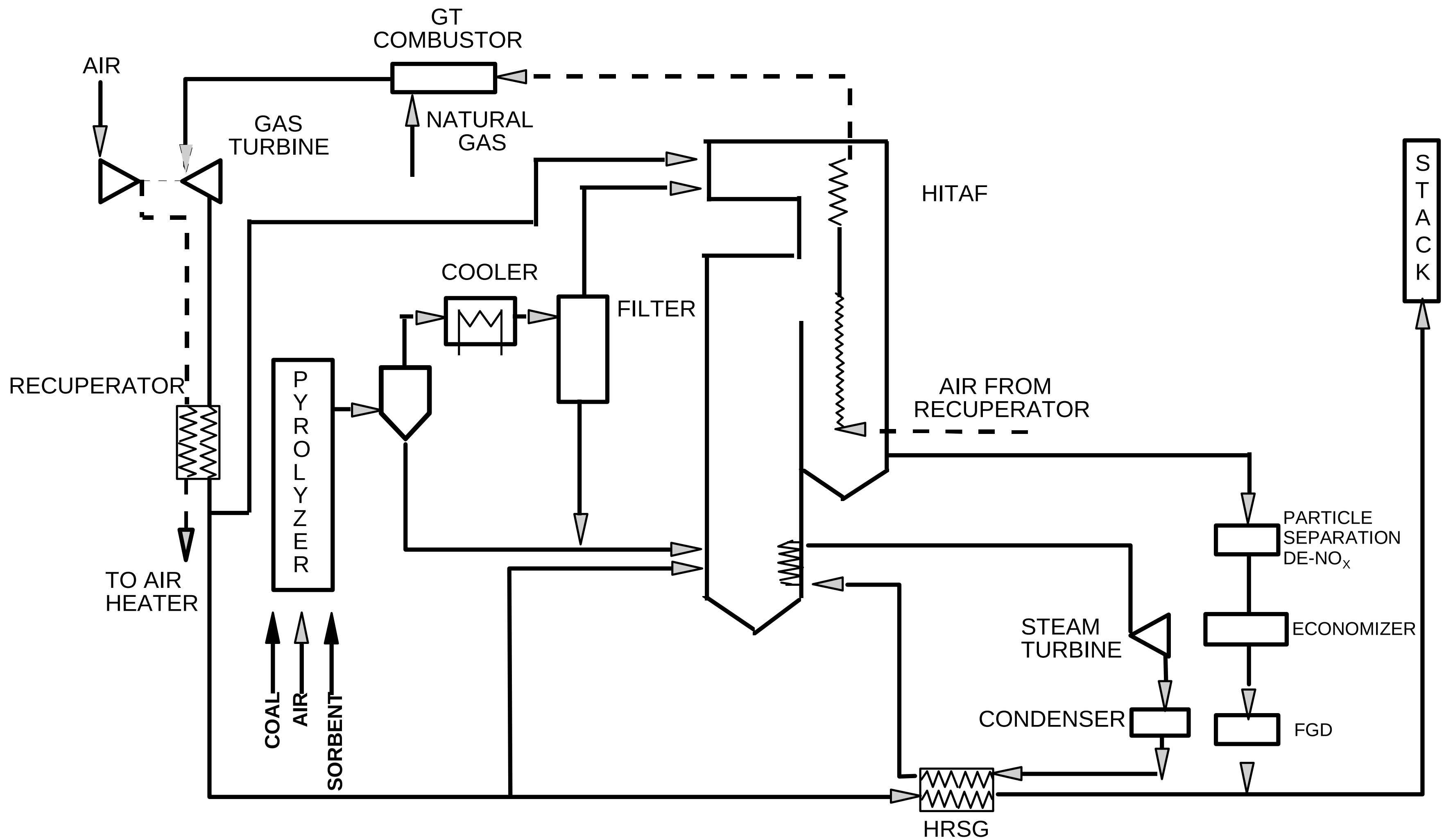


Figure 2 35-Percent Natural Gas HIPPS

TECHNICAL PROGRESS

Task 1 - Project Planning and Management

Work is proceeding in accordance with the Project Plan.

Task 2 - Engineering Research and Development

Subtask 2.2 - Solids Pump Development

A Stamet solids pump has been ordered to feed coal to the pyrolyzer pilot plant. This pump would take the place of a lock-hopper system and would have technical and economic benefits in a commercial plant. The pump has been completed and is undergoing testing at the Stamet facilities. When this testing is complete it will be shipped to FWDC for further off-line testing.

Subtask 2.4 - Pyrolyzer Computer Modeling

A data reduction program has been written on an ASPEN platform to analyze the pyrolyzer pilot plant data. This program takes the laboratory analyses of the gas and solids samples and applicable operation data to establish heat and material balances for each set point. By tagging certain elements we are able to establish char, sorbent and sand proportions in the various solids streams. For each set point, we are also running a computer model of the pyrolyzer that predicts the heat and material balance based on the input conditions. In this manner, we are benchmarking the computer program that will be used for the design of other pyrolyzers. This model was originally developed for Second-Generation PFB conditions, and it is being modified slightly based on the HIPPS results.

Subtask 2.7 - Combustion System Computer Modeling

The PCGC3 computer program is being used to model the furnace combustion in the CETF. Previous PCGC3 runs have been used to establish the test conditions for the CETF combustion tests that will be run in 1998 [1]. As the CETF process systems and burner designs were developed and pyrolyzer test results were obtained, some changes to the model input were required. In the current quarter, PCGC3 runs have been made with increased char flow rate and a burner location that is offset from the centerline of the furnace. The char flow has been increased to increase the furnace exit temperature, and the burner location has been changed to reflect physical restraints of the windbox. Also, the char/sorbent composition has been made more representative of the pyrolyzer product

Table 1 summarizes the input conditions for the latest PCGC3 runs. The char flow rate has been increased from 907 kg/h (2000 lb/h) to 1134 kg/h (2500 lb/h). This increased the furnace exit temperature about 55 ^{o}C (100 ^{o}F) to 880 ^{o}C (1616 ^{o}F). This furnace exit temperature is still relatively low, but it may be the highest we can practically get under HIPPS conditions. Since the testing is mainly to benchmark the furnace model, this should not be a problem.

Table 1
PCGC Input Conditions for CETF Testing

Char		
Mass Flow	1135 Kg/h	(2500 lb/h)
Temperature	27°C	(80°F)
Density	0.50 Kg/l	31.0 lb/ft^3
Ultimate Analysis (wgt., dry)		
C	70.5%	
H	0.3%	
N	1.2%	
S	2.1%	
O	0.4%	
Ash	25.5%	
Total	100.0%	
HHV	24.3 MMJ/Kg	(10,466 Btu/lb)
Sorbent (wgt., dry)		
Mass Flow	154 Kg/h	(340 lb/h)
Ultimate Analysis (dry)		
CaS	30.0%	
Other	70.0%	
HHV	4.86 MMJ/Kg	(2093 Btu/lb)
Vitiated Air (wgt.)		
Mass Flow	21,877 Kg/h	(48,188 lb/h)
Temperature	427°C	(800°F)
Composition		
N_2	78.5%	
O_2	15.0%	
H_2O	1.7%	
CO_2	4.8%	
Total	100.0%	
Support Coal		
Coal Mass Flow	117 Kg/h	(258 lb/h)
Air Mass Flow	170 Kg/h	(375 lb/h)

Figure 3 shows the temperature distribution at the vertical plane of the burner. The maximum flame temperature is approximately 1427 °C (2600 °F). Figure 4 shows the velocity vector distribution in the same plane, and Figures 5 and 6 indicate the carbon burnout for 70 micron and 173 micron particles respectively. Overall carbon burnout at the furnace exit (all particle sizes) is calculated to be 98.3 percent.

Task 3 - Subsystem Test Unit Design

Subtask 3.2 - Char Combustion Subsystem Design

The design of the furnace modifications and process systems for the CETF combustion tests has been completed. A schematic of the process systems is shown in Figure 7. Changes are being made to store and feed char, recirculate flue gas to the combustion air and heat the combustion air. Some of the runs will use commercial char and some will use char generated in the Livingston pyrolyzer tests. The commercial char will be pulverized on-site and pneumatically transported to a new char storage silo. The char from the Livingston tests will be transported directly to the silo. A weigh belt feeder and pneumatic transport system will meter the char flow and feed it to the burner. Sorbent will be added to the burner fuel stream when firing commercial char to simulate the pyrolyzer output. Existing equipment will be used for this function.

Other modifications to the CETF process systems are being made to simulate gas turbine exhaust for combustion air. In order to obtain the lower oxygen level and higher temperatures, flue gas is being recirculated back into the combustion air, and a duct heater is being installed in the duct to the windbox. This equipment will allow us to achieve oxygen levels of 15% and temperature up to $607^{o}C$ ($1125^{o}F$). Another duct heater is being added to the flue gas duct because under certain operating conditions with HIPPS, the temperature entering the baghouse would get too low.

The current HIPPS commercial plant design includes 10 percent coal firing along with the char. This coal will be pulverized off-site and shipped in supersacks. A system is being added to meter this coal and pneumatically feed it to the burner.

Subtask 3.3 - Integrated System Test Design

Since pyrolyzer operation with a jetting type of bubbling bed has been successful, the DOE Wilsonville facility is being considered as the site for the integrated system test. This facility is being built with the same type of pyrolyzer as part of an Advanced Pressurized Fluidized Bed system. The scale is similar to what was planned for UTSI which is approximately ten times the throughput of the Livingston pyrolyzer tests. The char generated would be transported by truck to the FWDC CETF for combustion testing. At Wilsonville, direct integration of the pyrolyzer and furnace would not be accomplished, however, the pyrolyzer would be integrated with the gas turbine. Gas turbine integration was not originally part of the planned UTSI tests because of budget restraints. The gas turbine-pyrolyzer operation is actually more tightly coupled than that of the pyrolyzer-char combustion system. So this integration will be of greater benefit.

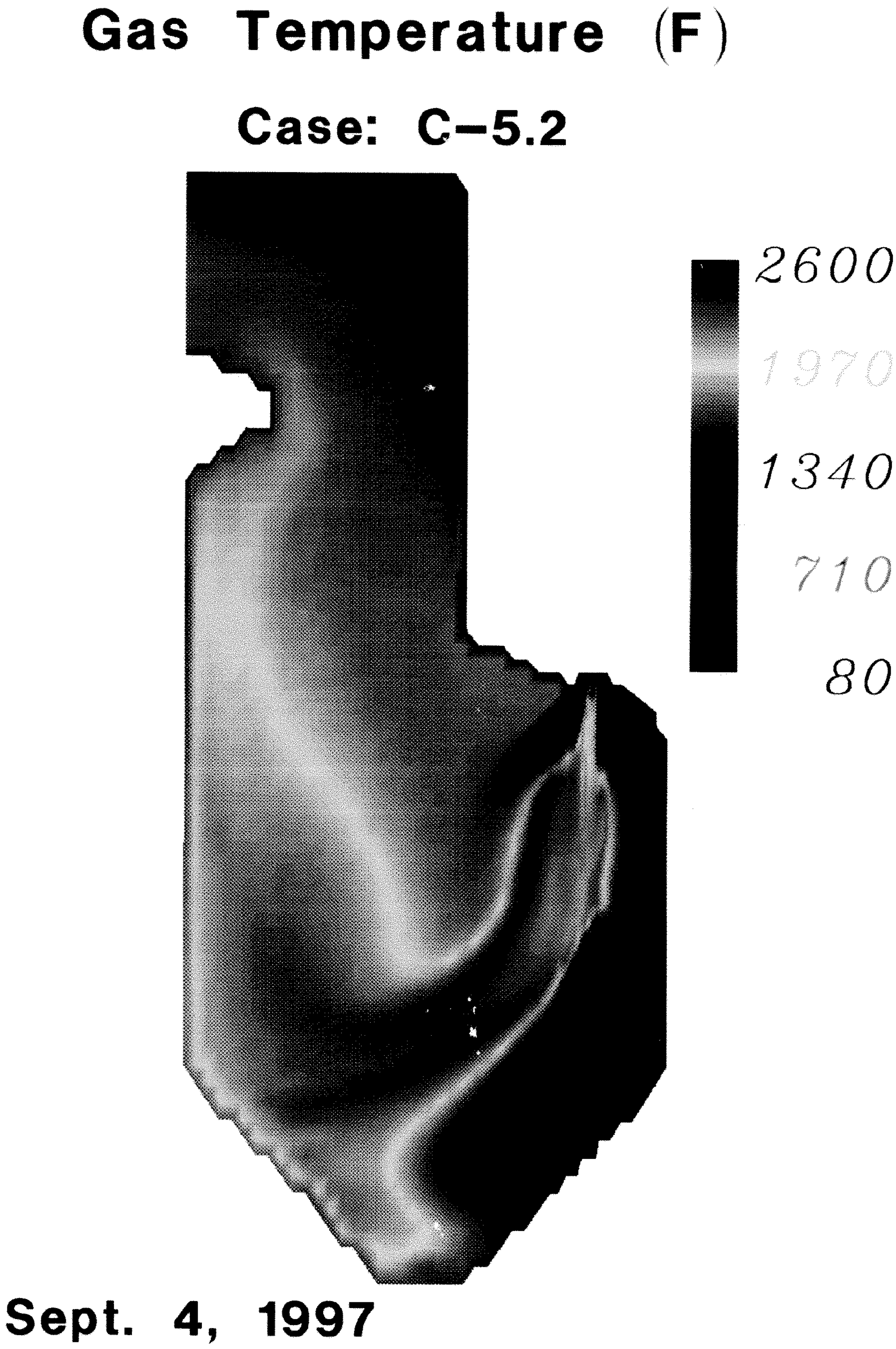


Figure 3

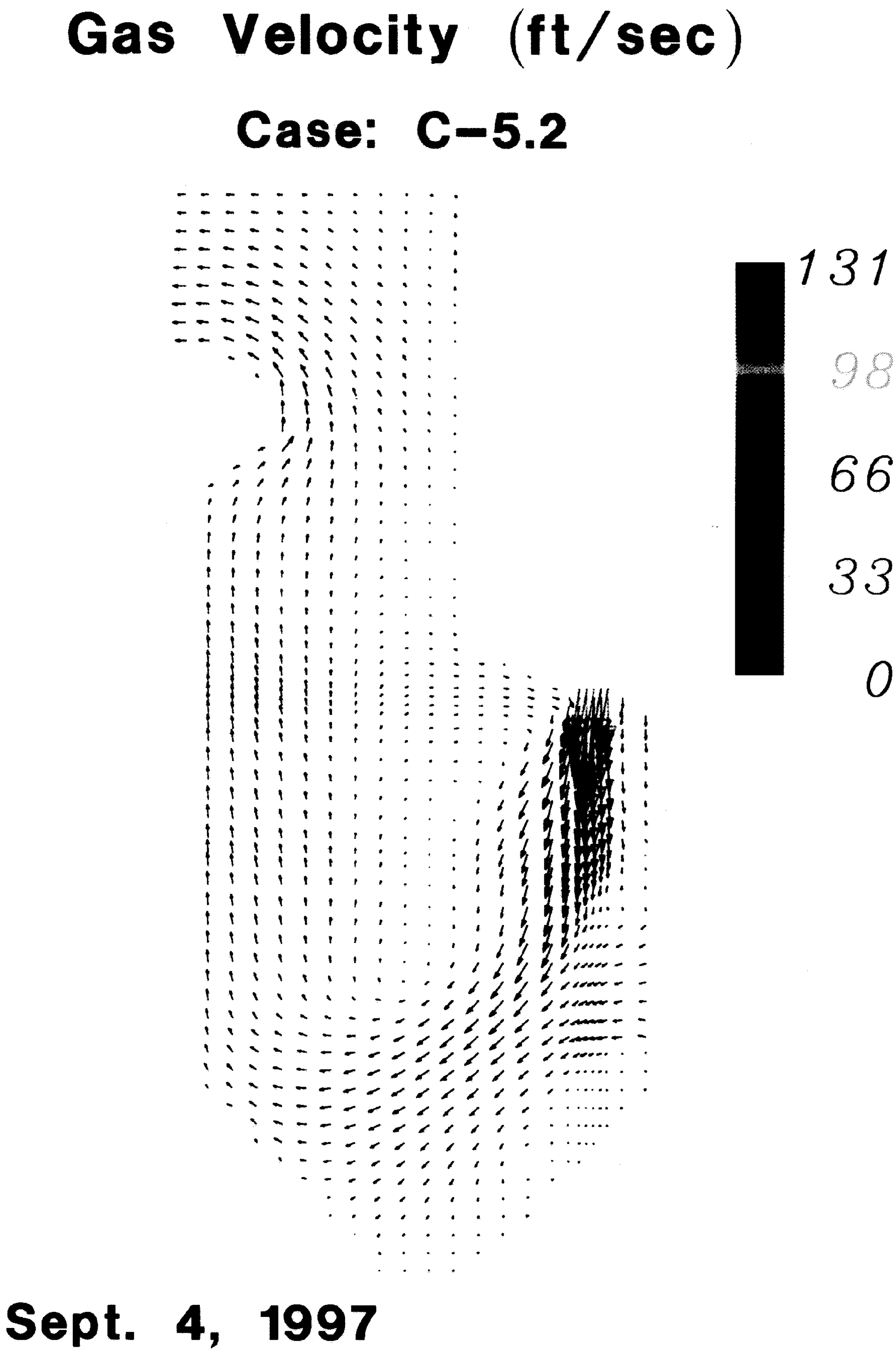


Figure 4

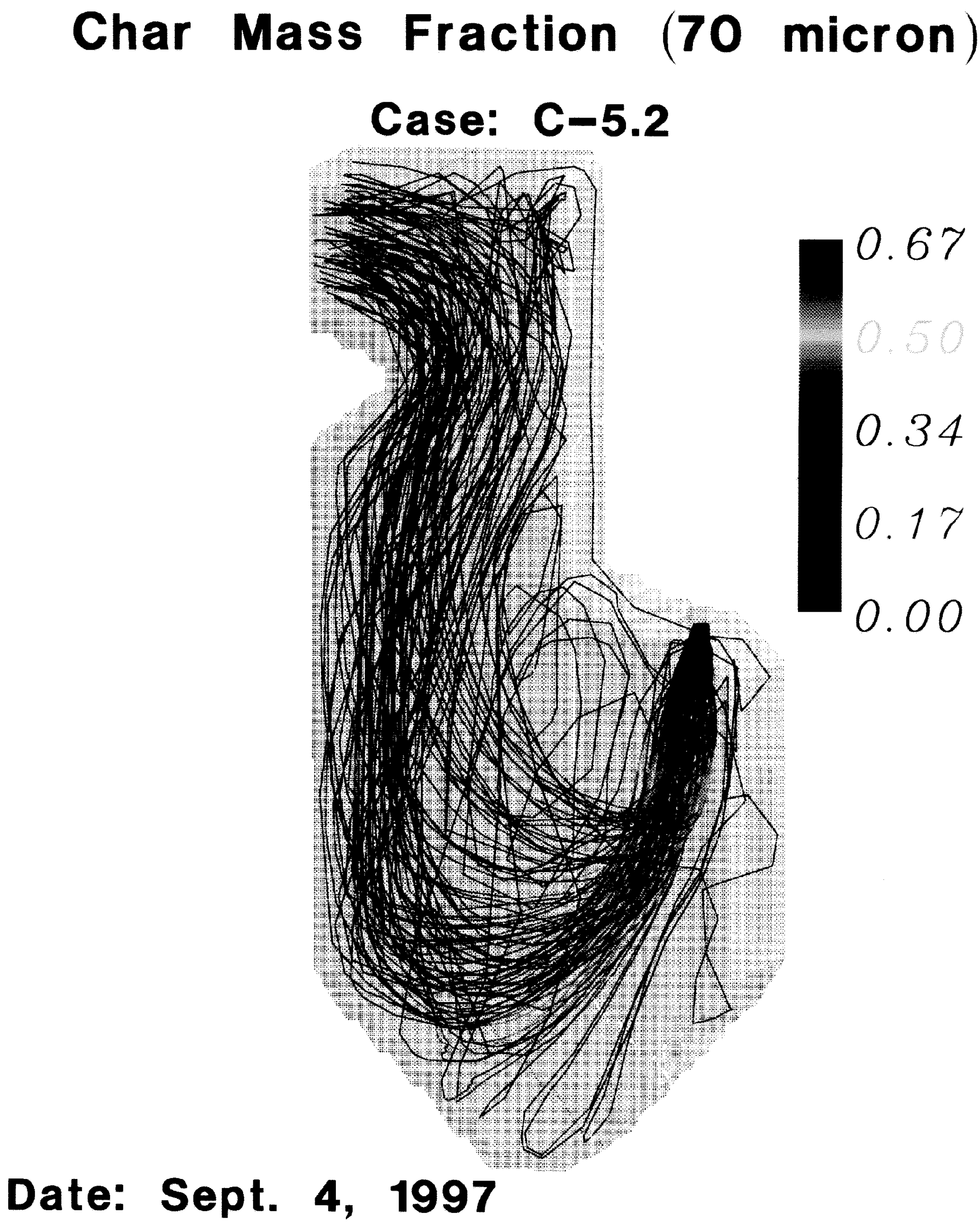

Char Mass Fraction (70 micron)
Case: C-5.2
0.67
0.50
0.34
0.17
0.00
Date: Sept. 4, 1997

Figure 5

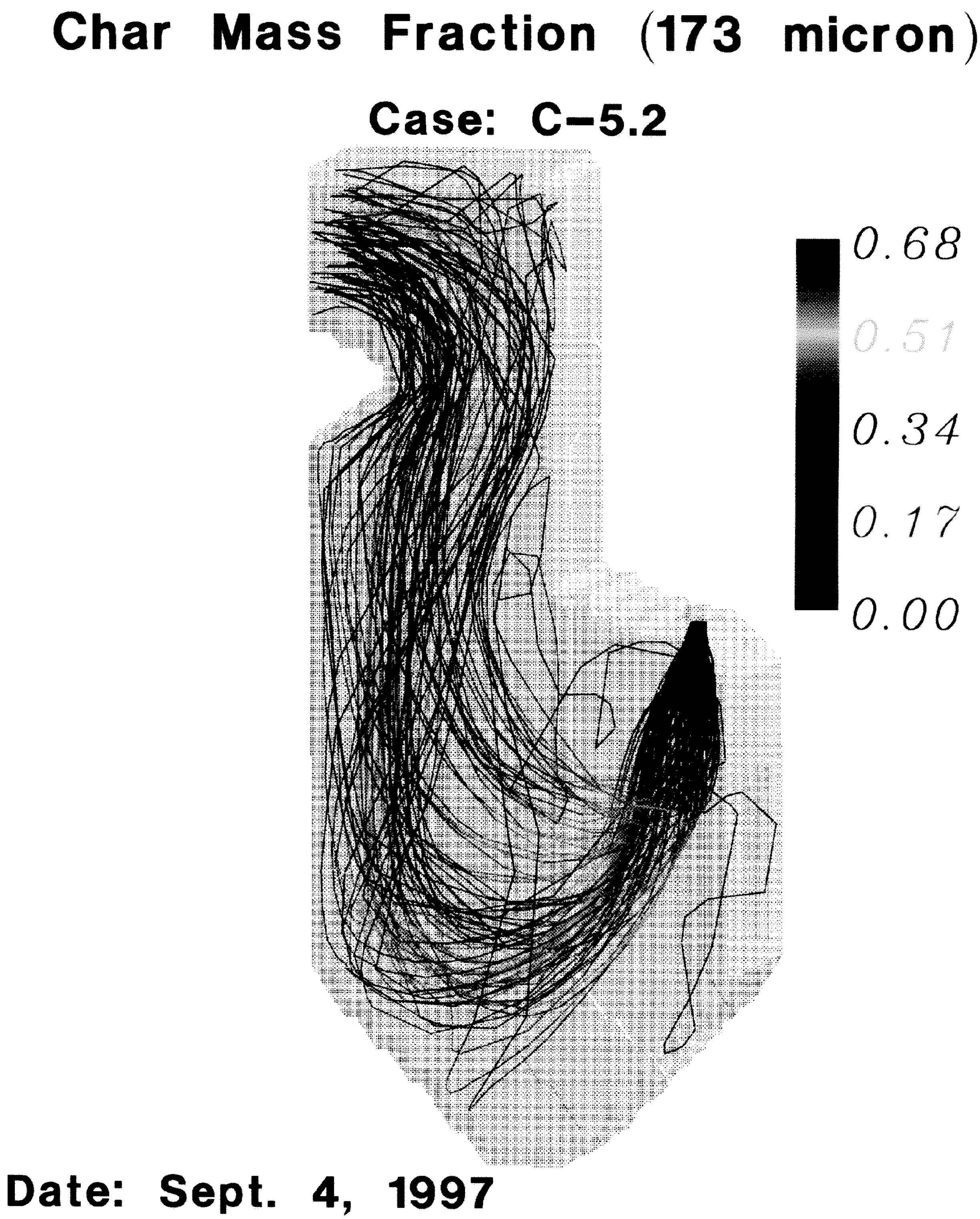
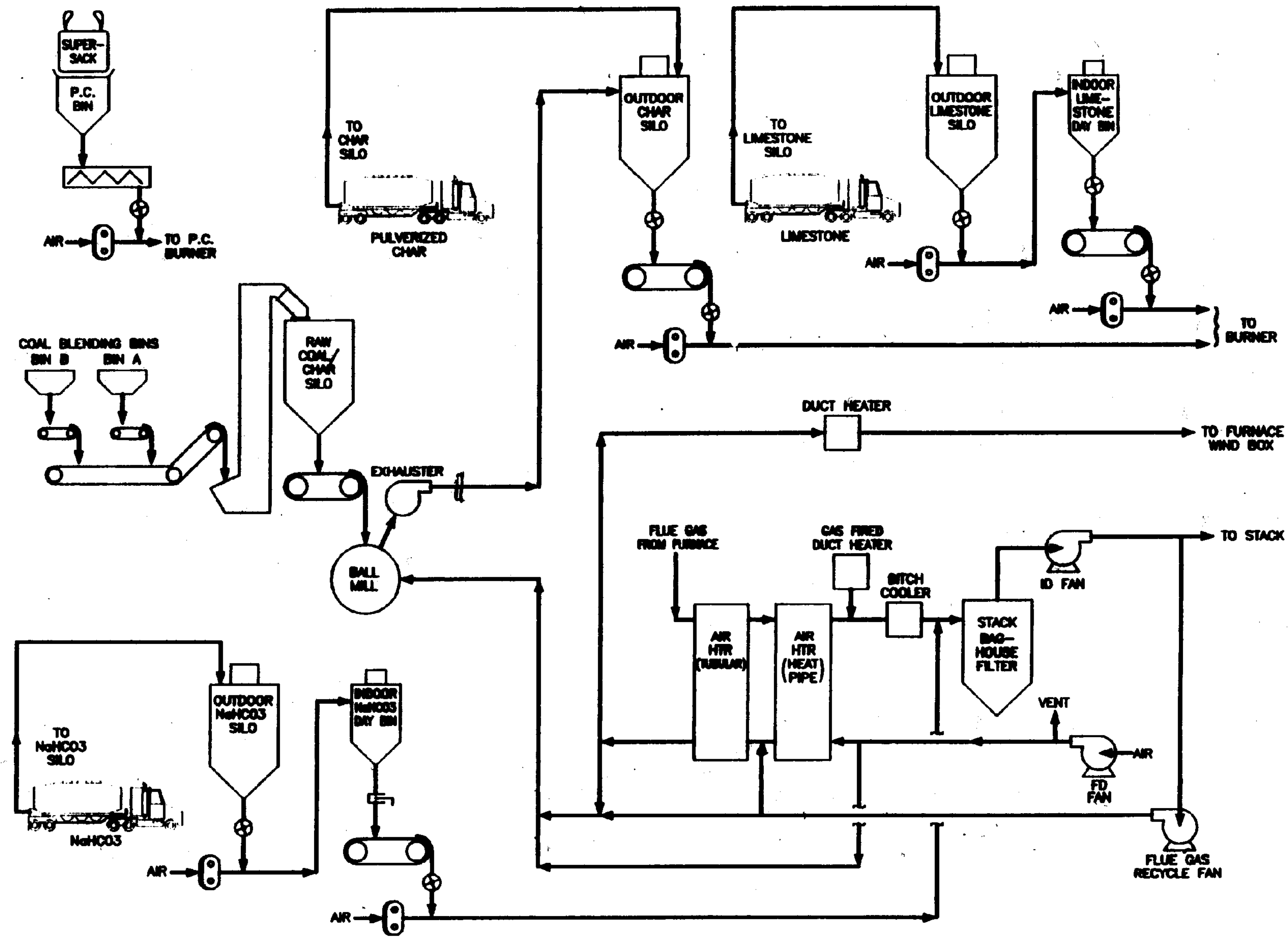

Char Mass Fraction (173 micron)
Case: C-5.2
0.68
0.51
0.34
0.17
0.00
Date: Sept. 4, 1997

Figure 6



HIPPS CONFIGURATION OF CETF

Figure 7

Task 4 - Subsystem Test Unit Construction

Subtask 4.1 - Pyrolyzer System Test Unit Construction

The modifications to the pyrolyzer pilot plant to improve solids feeding were completed during this quarter.

Subtask 4.2 - Char Combustion System Test Unit Construction

The CETF furnace has been modified into an arch-firing configuration, and an existing burner has been installed. During the next Quarter, runs will be made on anthracite coal. After these runs are complete, the unit will be operated on commercial char with the anthracite burners. This type of operation will give us an indication of the relative performance of char compared with low volatile coal in a conventional commercial system. By doing these tests, we can relate the char performance to our field experience in commercial arch-fired units. Subsequent to these tests, the CETF process systems will be modified to store and feed the HIPP's feedstocks and to generate the vitiated combustion air. Additional tests will then be run under the full HIPPS conditions.

Task 5 - Subsystem Test Unit Testing

Subtask 5.1 - Pyrolyzer/Char Transport Testing

During the present Quarter, two more pyrolyzer test runs were completed. These runs were with a sand bed and pulverized coal and limestone. Previous runs (SD-02 and TR-01) were with 1/8" x 0 limestone which was of sufficient coarseness to form a bed. In the latest test runs (TR-02 and TR-03), all the limestone and char were elutriated from the top of the sand bed. This type of operation simplifies the HIPPS plant by not requiring any sulfating or other processing of bed drains. In all cases, backend sulfur removal is necessary in HIPPS because of the pulverized fuel combustion and very stringent emissions limits. One approach to the commercial plant design is to not attempt to remove any sulfur in the pyrolyzation system. Sorbent may still be added to the pyrolyzer to reduce the corrosion potential in the stream going to the HRSG (see Figure 1). This spent sorbent would go to the HITAF with the char. The captured sulfur would most likely be released in the flame, but the backend system would capture this sulfur and the sulfur that was never released from the coal in the pyrolyzer. With this approach, a sand bed with pulverized limestone or a sand bed with no limestone at all may be the best choice. After the results from the different bed arrangements are completed, the impact on plant design will be investigated.

The pyrolyzer pilot plant arrangements for TR-02 and TR-03 are shown in Figure 8. The main changes since the last runs consisted of changing the sorbent feed to a rotary valve, modifying both feed hoppers and putting in a system to pneumatically transport the char. The rotary valve was necessary to successfully feed the pulverized limestone. The feed hoppers were modified to flat, fluidized bottoms in order to more reliably feed pulverized material. The char transport system was added to test the system proposed for the commercial plant. In this system, the char will be reduced in pressure and then pneumatically transported to hoppers near the burners.

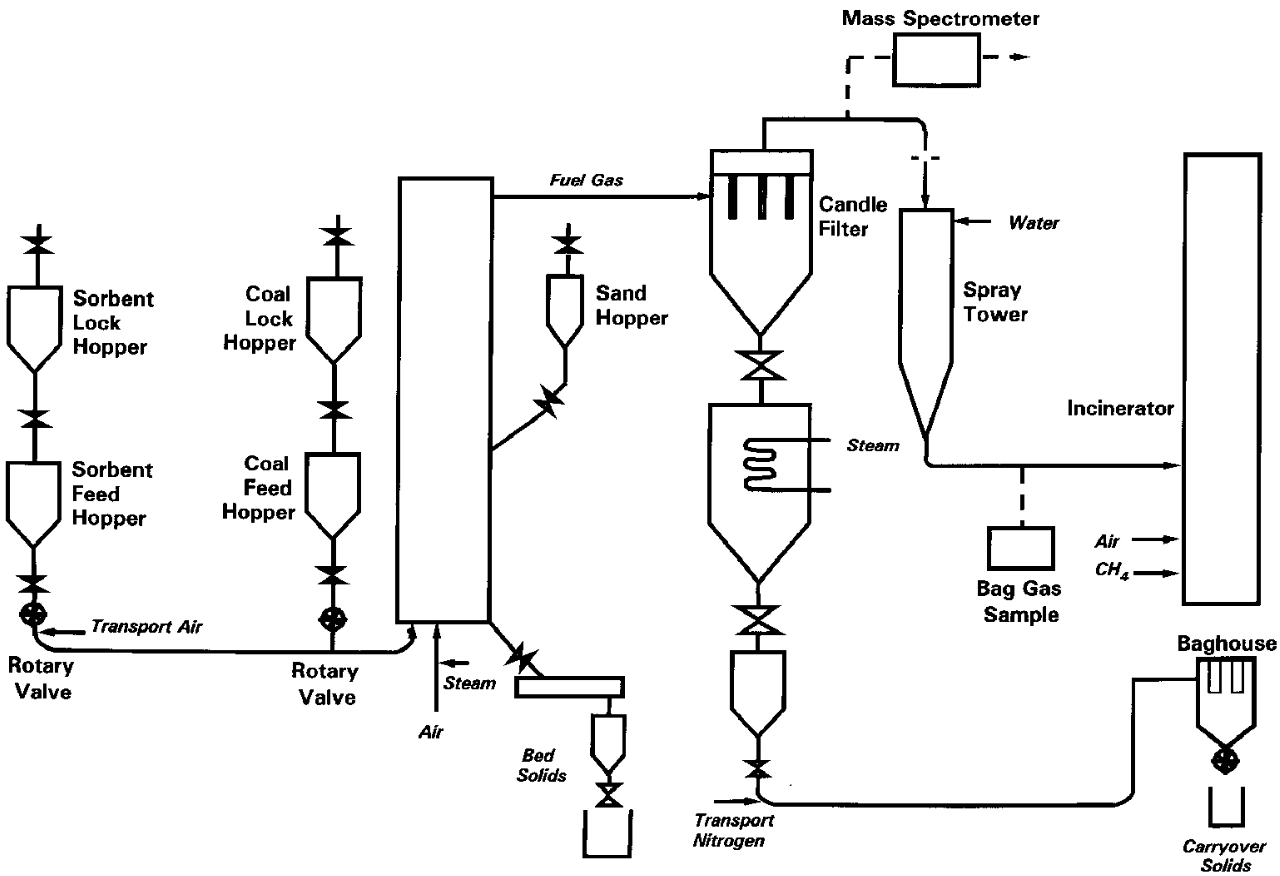


Figure 8

Figure 9 is a drawing that includes most of the changes to the pyrolyzer pilot plant. Of particular interest in this drawing is the design and layout of the char transport system. Char separated from the fuel gas in the barrier filter falls through the Char Hopper (CH-332). Steam coils in the Char Hopper cool the solids to less than 149 ^{o}C (300 ^{o}F). In normal operation between draining cycles, the valve between the Char Hopper and the Char Drain Hopper is open, and char falls into the Char Drain Hopper until a high level alarm is reached. The valve between the hoppers is then closed, and the Char Drain Hopper is depressurized and purged. When the purge is complete, nitrogen is introduced into the Char Drain Hopper and the transport line, and the outlet valve of the Char Drain Hopper is opened. The char is then pneumatically transported in a 2” pipe to a baghouse outside the building.

There is over 19.5 m (64’) of transport pipe with six close radius bends. The transport of char in this system was very reliable. The only pluggage that occurred was caused by pieces of a broken filter candle. This material was removed on-line and the system was returned to service. The system was operated with solids-to-gas ratios of up to 140.

A list of setpoint conditions achieved so far is shown in Table 2. Data from SD-02 and some of the data from TR-01 has been previously reported.[2]. During this Quarter, analysis of the test data continued, and all of the setpoints from TR01 were completed. Completion of the analysis of TR-02 and TR-03 will depend on the solids laboratory analysis, which is now in progress.

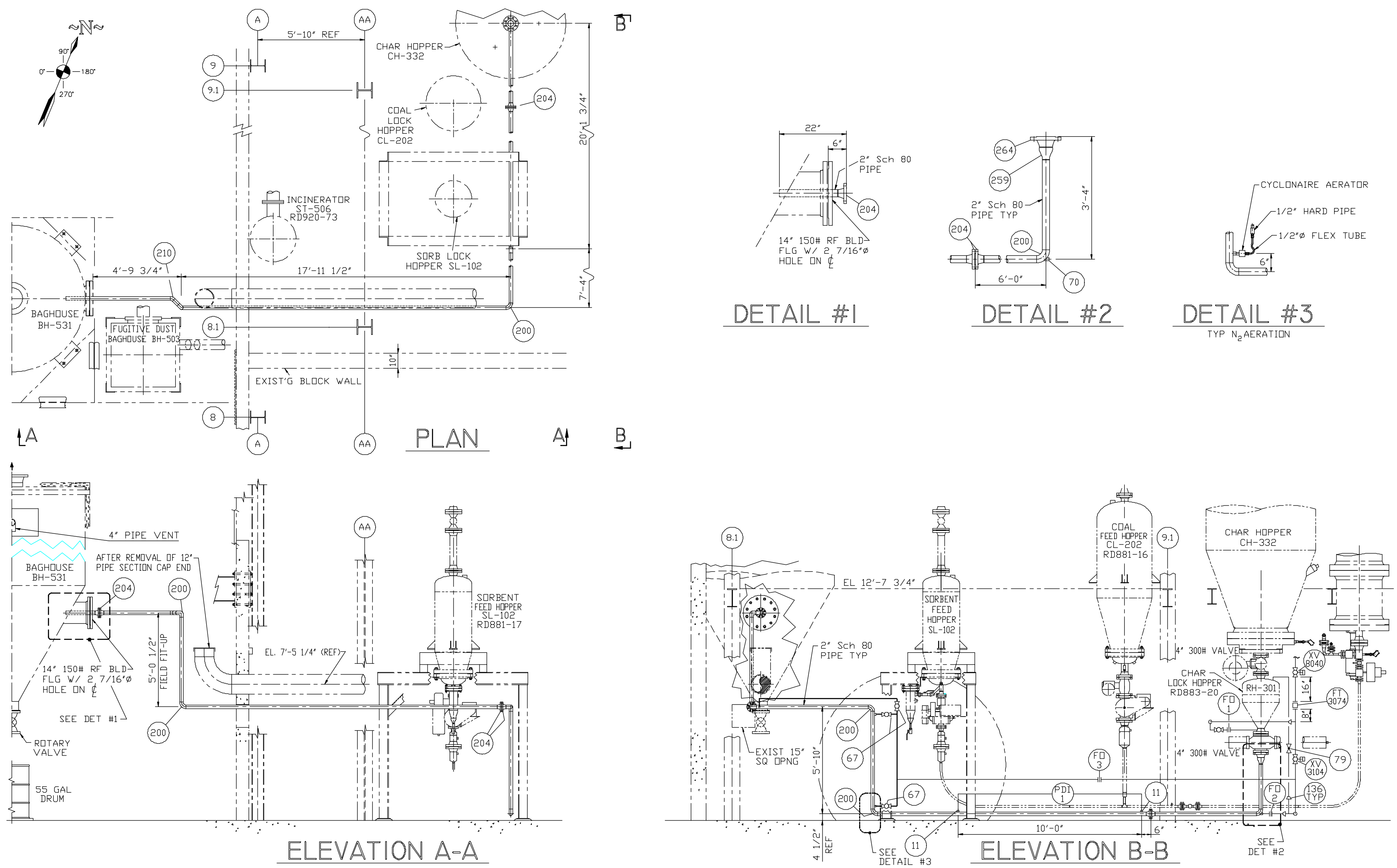

PLAN
ELEVATION A-A
DETAIL #1
DETAIL #2
DETAIL #3
TYP N2 AERATION
ELEVATION B-B
CHAR HOPPER CH-332
COAL LOCK HOPPER CL-202
INCINERATOR ST-506 RD920-73
SORB LOCK HOPPER SL-102
BAGHOUSE BH-531
FUGITIVE DUST BAGHOUSE BH-503
EXIST'G BLOCK WALL
4" PIPE VENT
AFTER REMOVAL OF 12" PIPE SECTION CAP END
14" 150# RF BLD FLG W/ 2 7/16"ø HOLE ON ℄
SEE DET #1
ROTARY VALVE
55 GAL DRUM
SORBENT FEED HOPPER SL-102 RD881-17
2" Sch 80 PIPE
CYCLONAIRE AERATOR
1/2" HARD PIPE
1/2"ø FLEX TUBE
COAL FEED HOPPER CL-202 RD881-16
CHAR LOCK HOPPER RD883-20
EXIST 15" SQ OPNG
SEE DETAIL #3
SEE DET #2
4" 300# VALVE

Figure 9

TABLE 2
HIPPS PYROLYZER TESTING TEST POINTS COMPLETED

Bed						
Sand	Longview Limestone	Pittsburgh No. 8	Bed Temp. (°F)	Coal Flow (lb/h)	Steam Flow (lb steam/lb coal)	Ca/S
Yes	1/8” x 0	70% thru 200	1680	150	0	2.0
Yes	“	“	1680	130	0.17	2.0
Yes	“	“	1680	150	0.30	2.0
No	“	“	1825	400	0.2	1.2
No	“	“	1675	260	0.2	2.3
No	“	“	1675	260	0.1	2.3
No	“	“	1690	260	0	2.3
No	“	“	1710	260	0	2.3
No	“	“	1600	300	0	1.0
No	“	“	1800	300	0	1.0
No	“	“	1675	300	0.2	1.0
No	“	“	1675	300	0.4	1.0
Yes	70% thru 200	“	1700	500	0	2.2
Yes	“	“	1750	300	0	1.3
Yes	“	“	1700	300	0	1.3
Yes	“	“	1750	300	0.2	1.2
Yes	“	“	1750	500	0	1.4

Table 3 contains some preliminary data on fuel gas and char composition from TR-01. This run was with a coarse sorbent bed (1/8” x 0) and pulverized coal feed. Bed temperatures during the run were from 871°C to 996°C (1600 °F to 1825°F) and steam to coal injection ratios up to 0.2. Operation was smooth across the range of conditions tested.

When reviewing the pilot plant data, it must be kept in mind that conditions will differ in larger scale units. That is why we are developing a computer model that will be benchmarked and modified if necessary as the scale of testing increases. In terms of the heat and material balance, the most significant difference between the pyrolyzer pilot plant and larger scale units is the larger proportion of nitrogen injected for purging and cooling and the larger heat loss as a percentage of the heat input. These effects are accounted for in the model. Table 4 lists typical pilot plant fuel gas data, the current model prediction for the pilot plant and the model prediction for a commercial plant operated at the same conditions. It can be seen that there will be a considerable improvement fuel gas quality as the scale of the pyrolyzer is increased.

TABLE 3
PRELIMINARY RESULTS OF PYROLYZER FUEL PRODUCT COMPOSITIONS
TR-01

	SP-1A	SP-1B	SP-2A	SP-2B	SP-2C	SP-2D	SP-3	SP-4A	SP-4B	SP-5	SP-6
Fuel Gas Composition v%											
N_2	56.11	59.16	61.94	59.00	66.03	64.48	65.73	66.42	65.00	61.15	58.34
O_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO	11.77	10.22	5.28	8.43	10.58	11.32	9.32	12.84	12.98	7.92	6.51
CO_2	8.82	8.46	9.85	11.37	9.21	9.04	9.20	7.17	6.83	10.13	10.73
H_2	11.17	10.10	8.12	8.54	6.85	7.54	7.71	7.53	8.46	8.68	8.95
H_2O	10.79	10.67	13.94	10.95	5.69	5.86	5.76	4.87	5.38	10.10	13.54
Ar	0.53	0.48	0.55	0.54	0.59	0.57	0.55	0.58	0.57	0.53	0.52
CH_4	0.68	0.84	0.10	0.97	0.94	1.04	1.57	0.53	0.76	1.37	1.05
C_2H_4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C_2H_6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_2S	0.07	0.06	0.08	0.02	0.06	0.04	0.02	0.02	0.02	0.07	0.15
COS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NH3	0.05	0.03	0.14	0.16	0.06	0.11	0.14	0.04	0.01	0.05	0.20
	100.00	100.01	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Elutriated Char Composition											
C	70.25	71.80	68.66	68.83	68.77	69.31	69.16	69.05	70.08	67.25	67.02
H	0.05	0.02	0.19	0.31	0.26	0.24	0.20	0.19	0.28	0.15	0.09
O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N	0.94	0.96	1.01	1.01	1.02	1.08	1.14	1.07	0.91	1.04	0.99
S	1.94	1.83	1.69	1.67	1.77	1.69	2.02	1.67	1.76	2.50	2.23
Ash	26.82	25.39	28.46	28.19	28.17	27.68	27.49	28.02	26.97	29.06	29.67
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 4
Typical Fuel Gas Composition (% vol)

	Measured Pilot Plant	Model Pilot Plant	Model Commercial Plant
N_2	61.15	60.42	42.43
O_2	0.00	0.00	0.00
CO	7.92	6.55	20.03
CO_2	10.13	9.83	6.65
H_2	8.68	10.24	18.57
H_2O	10.10	9.92	3.75
Ar	0.53	0.52	0.51
CH_4	1.37	2.21	2.24
C_2H_4	0.00	0.00	0.00
C_2H_6	0.00	0.00	0.00
H_2S	0.07	0.02	0.02
COS	0.00	0.00	0.00
NH_3	0.05	0.29	0.42
HHV(Btu/Scf)	70.79	80.47	150.3

REFERENCES

1. Foster Wheeler Development Corporation, "Engineering Development of High Performance Power Systems – Technical Progress Report January through March 1997," DOE PETC Under Contract DE-AC22-95PC95143, pg. 11-20.

2. Foster Wheeler Development Corporation, "Engineering Development of High Performance Power Systems – Technical Progress Report January through March 1997," DOE PETC Under Contract DE-AC22-95PC95143, pg. 28-36.