Engineering Development of High Performance Power Systems

Quarterly Technical Report

Reporting Period Start Date: 01/01/1999 End Date: 03/31/1999

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Report Issue Date: 06/10/1999

DE-AC22-95PC95143--15

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ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH-PERFORMANCE POWER SYSTEMS

DE-AC22-95PC95143

TECHNICAL PROGRESS REPORT NO. 15
JANUARY THROUGH MARCH 1999

Prepared for
Department of Energy
Federal Energy Technology Center
Pittsburgh, Pennsylvania

MAY 1999

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 pyrolysis process to convert coal into fuel gas and char. The char is fired in a High Temperature Advanced Furnace (HITAF). The HITAF is a pulverized fuel-fired boiler/air heater where steam is generated and gas turbine air is 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 after each experimental program has been completed, a larger scale pyrolyzer will be tested at the Power Systems Development Facility (PSDF) in Wilsonville, AL. The facility is equipped with a gas turbine and a topping combustor, and as such, will provide an opportunity to evaluate integrated pyrolyzer and turbine operation.

This report addresses the areas of technical progress for this quarter. The char combustion tests in the arch-fired arrangement were completed this quarter. A total of twenty-one setpoints were successfully completed, firing both synthetically-made char, and char generated from the pyrolyzer tests performed at FWDC's pilot plant in Livingston, New Jersey. Construction is to begin next quarter to retrofit the CETF for additional HIPPS char combustion studies in a wall-fired configuration. Design of the char transfer system for the PSDF also progressed during this quarter. A number of arrangements have been developed to modify the existing N-Valve configuration. As an experimental test facility, the PSDF needs to maintain operating flexibility in order to test under a wide range of conditions. Although a new char transfer design is needed to support the HIPPS testing at the facility, the Second Generation PFB program will also utilize this system.

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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, has been modified to test the char combustion system. Integrated operation of a larger scale pyrolyzer and a commercial gas turbine are planned for the PSDF in Wilsonville, AL.

A total of 21 experimental tests were completed to determine the optimum performance settings for the arch-fired char combustor. Preliminary data analysis indicates successful combustion of the char, without support fuel, and with oxygen concentrations as low as 15% by volume. The lower oxygen levels were obtained by mixing flue gas with incoming combustion air. In both the HIPPS repowering and greenfield arrangements, the gas turbine exhaust is directly conveyed into the PC boiler and HITAF, respectively.

Design efforts continued this quarter on the arrangement of the char transfer system at the PSDF. In an effort to reduce overall system cost, a number of alternative arrangements were proposed to SCS for review. Although the “three lock-hopper” arrangement provided complete isolation of oxidizing and reducing environments, the system was expensive and complicated to operate.

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 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.

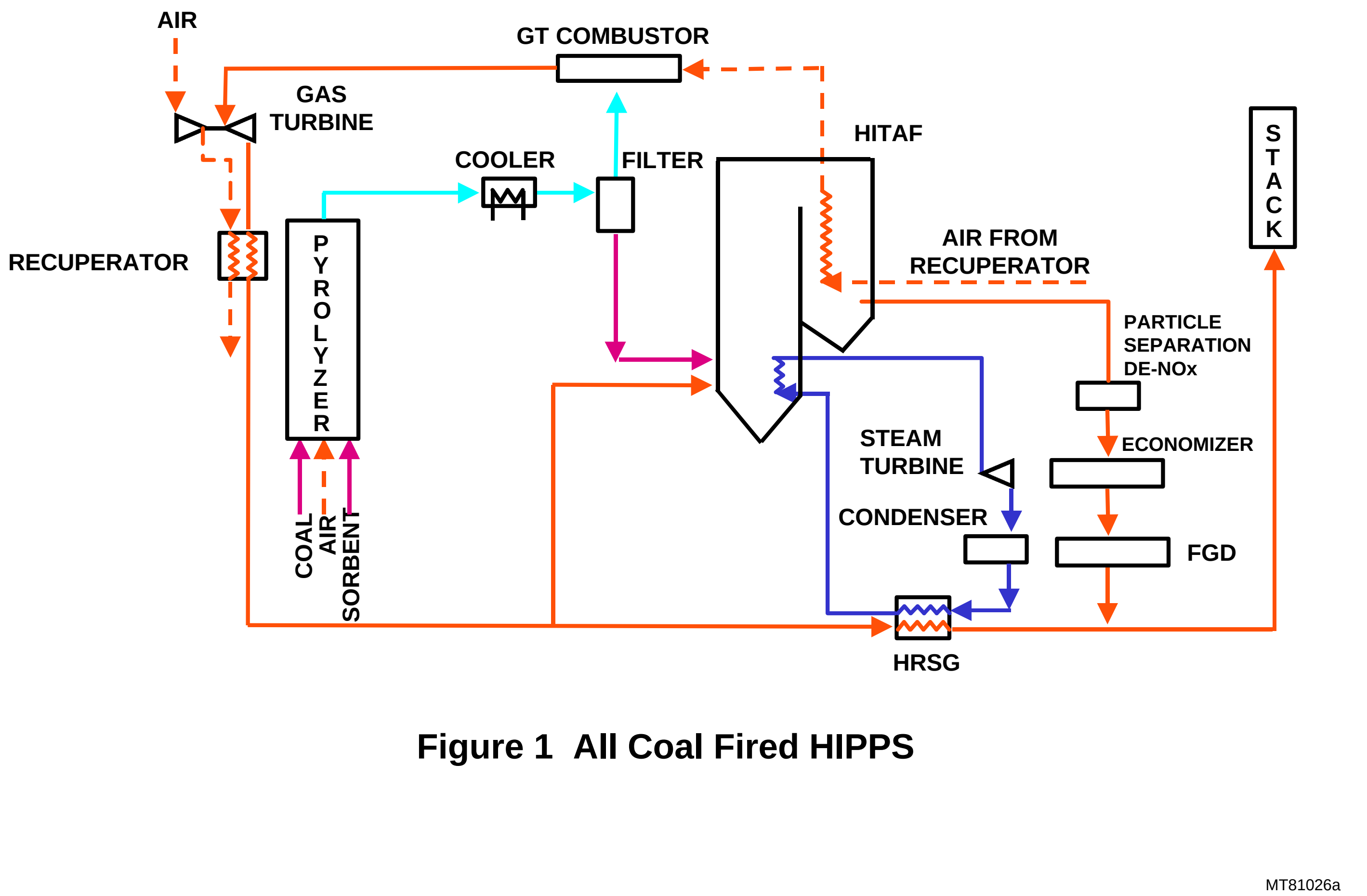

Figure 1 All Coal Fired HIPPS

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.

A simplified version of the HIPPS arrangement can be applied to existing boilers. Figure 3 outlines the potential application of the HIPPS technology for repowering existing pulverized coal fired plants. In the repowering application, the gas turbine exhaust stream provides the oxidant for co-fired combustion of char and coal. The existing boiler and steam turbine infrastructure remain intact. The pyrolyzer, ceramic barrier filter, gas turbine, and gas turbine combustor are integrated with the existing boiler to improve overall plant efficiency and increase generating capacity.

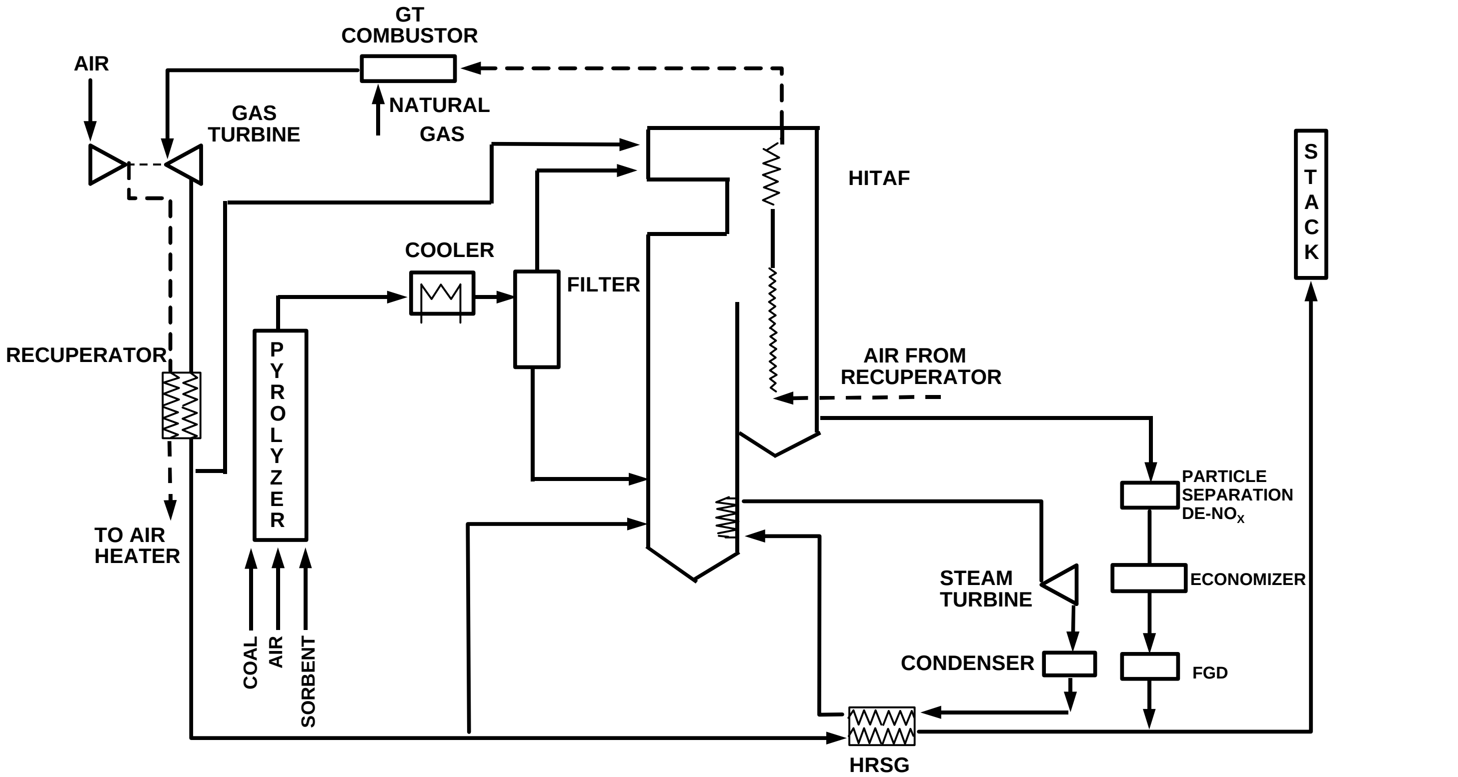

Figure 2   35-Percent Natural Gas HIPPS

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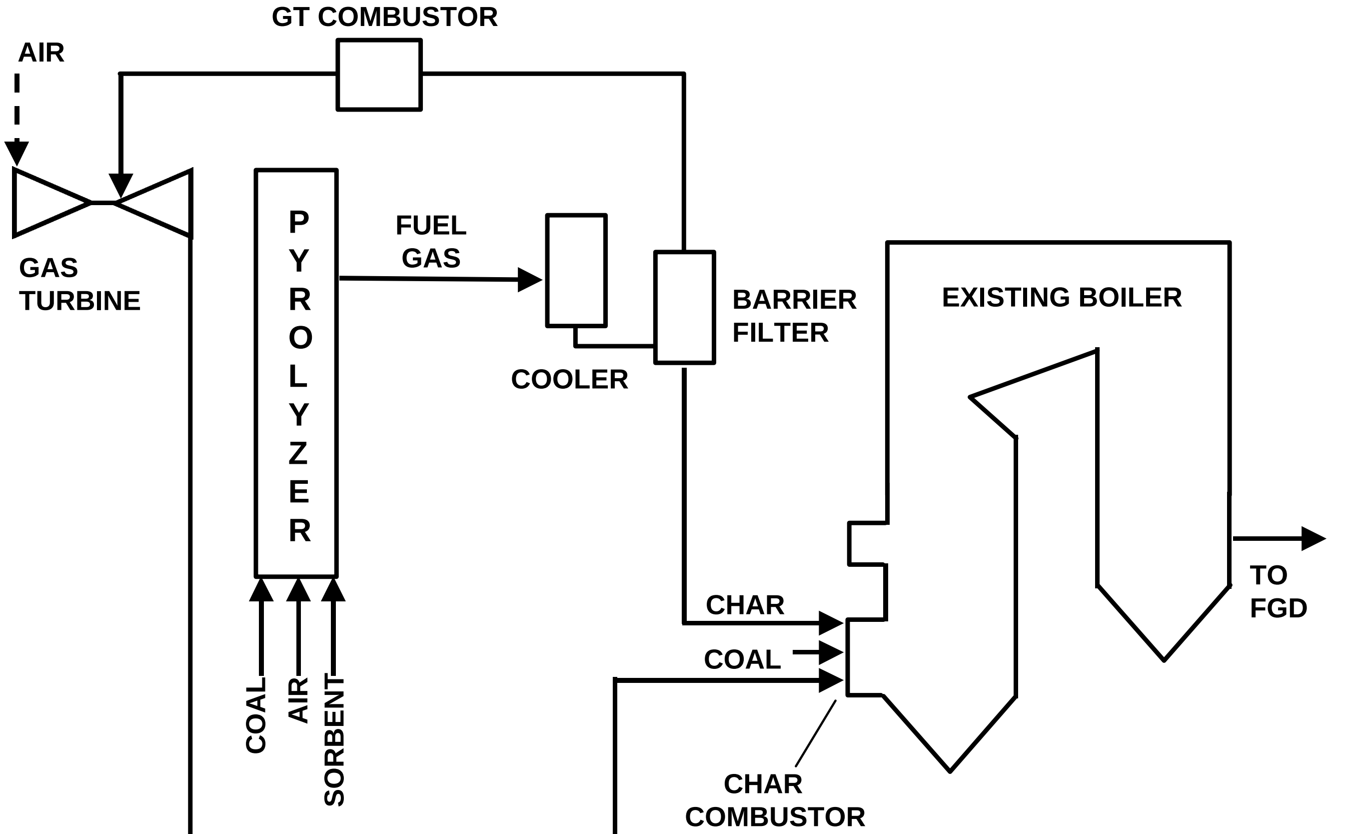

Figure 3 Simplified HIPPS Repowering Process Flow Diagram

TECHNICAL PROGRESS

Task 1 - Project Planning and Management

Work is proceeding in accordance with the Project Plan.

Task 2 – Engineering Research and Development

Subtask 2.1 – Alternative Cycle Analysis

During this quarter Bechtel has developed a revised heat and material balance for the HIPPS repowering arrangement. The updated balance (Figure 4.) utilizes a General Electric LM2500 gas turbine for the Brayton cycle. The turbine inlet temperature and pressure for the LM2500 is 2387 Deg. F. and 315 psia, respectively. Table 1. identifies the operating specifications for two repowering cases. The first case entitled "Original Repowering" lists the specifications for the Delmarva plant. The original repowering study for the Delmarva plant improved the overall efficiency by approximately 6%, with a corresponding increase in capacity of 23%, by using a Westinghouse (modified B251B12) gas turbine. The turbine inlet temperature and pressure for the Westinghouse turbine is 2100 Deg. F. and 164 psia, respectively. Preliminary results with the GE turbine suggest that the overall efficiency of certain plants can be improved up to 44% (HHV).

Task 3 - Subsystem Test Unit Design

Subtask 3.3 – Wilsonville Pilot Plant Design

The Power Systems Development Facility (PSDF) in Wilsonville, Alabama is to be used to support the objectives of both the PFB and HIPPS programs. The PFB test program at the PSDF is currently underway, and the intent is to complete all of the First Generation experiments prior to operating in the Second Generation mode. After completing all of the tests for the PFB system, the HIPPS program will utilize the facility to support the large scale development of the pyrolyzer. Although the HIPPS and PFB programs maintain different experimental objectives, both projects are developing a partial gasifier where the generated char needs to be transferred from the reducing environment into the combustion environment. In the HIPPS program the combustion environment is provided by the PC boiler, whereas in the PFB program the combustion environment is provided by the pressurized circulating fluidized bed boiler. In order to support both projects, a new char transfer system is being designed to meet the technical requirements of both modes of operation. This new system is to replace the existing N-Valve arrangement presently installed at the PSDF.

In our original char transfer design proposal to SCS (Figure 5.), a series of lock hoppers were utilized to maintain complete isolation of the oxidizing and reducing environments. This system was expensive and somewhat complicated to operate because of the total number of valves and pressure vessels. In an effort to reduce cost and simplify the overall design, an alternative system has been developed. Since the PSDF is to support both the PFB and HIPPS projects, and because the pilot

plant needs to maintain operating flexibility, the proposed char transfer system has been designed for three separate operating modes. Figure 6. depicts the arrangement in support of the baseline PFB program, Figure 7. illustrates the PFB configuration when evaluating candle filter performance without the primary cyclone, and Figure 8. defines the layout of the HIPPS baseline system.

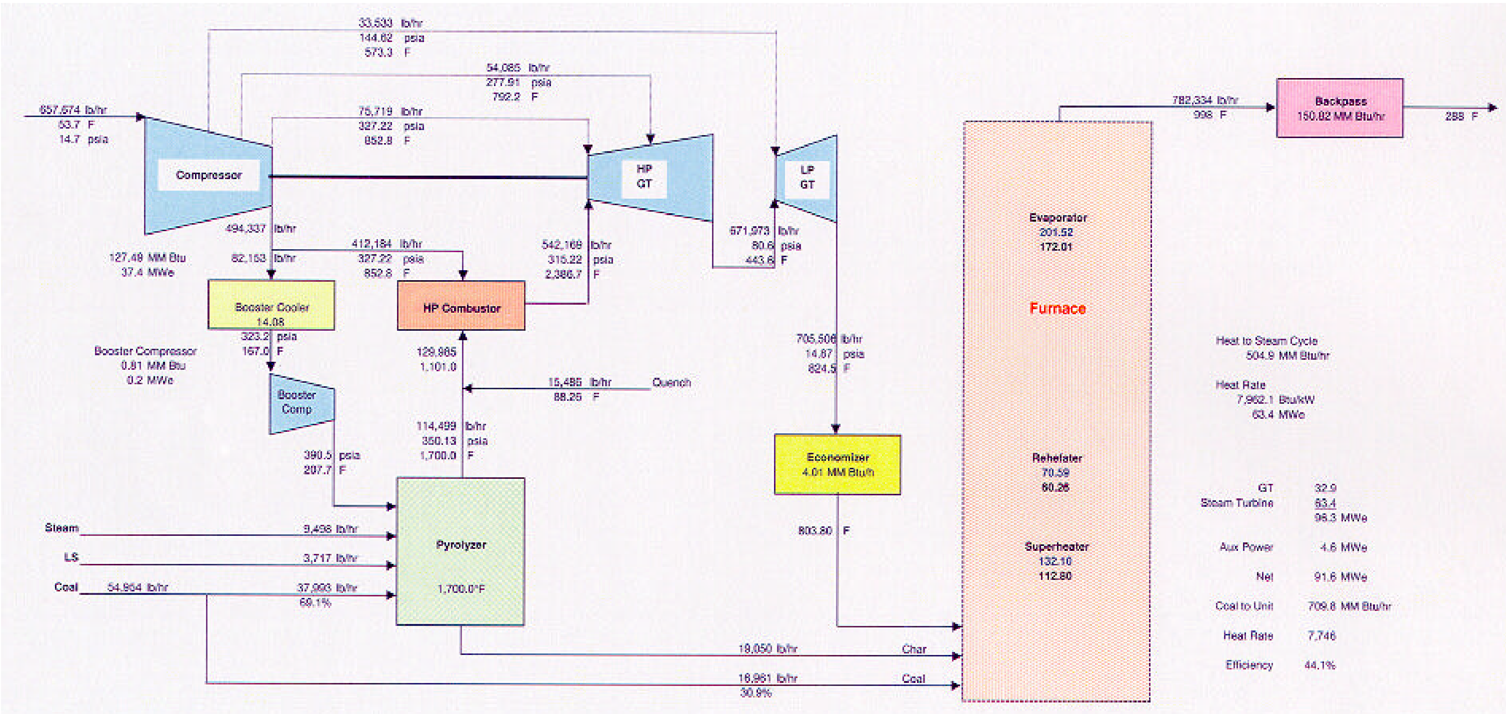

Figure 4 Advanced Repowering Schematic

Table 1 Typical Repowering Application

Description	Base Case	Original Repowering	Revised Repowering
Gas Turbine	None	Westinghouse Modified 251B12*	GE LM2500
Coal flow to Pyrolyzer, M lb/h	0.0	61.3	38.0
Coal to Boiler, M lb/h	73.0	16.4	17.0
Total Coal Flow, M lb/h	73.0	77.7	55.0
Pyrogas Flow, M lb/h		130.8	114.5
Char Flow, M lb/h		32.6	18.9
Coal HHV, M Btu/lb	13.05	13.05	12.92
Gas Turbine			
Inlet Temperature, F		2,100	2,387
Inlet Pressure, psia		164	315
Outlet Temperature, F		1,047	824
Gross Power, MWe		33	33
Steam Turbine			
Inlet Pressure, psia	1,815	1,815	1,815
SH/RH Temperature, F	1005/990	1005/990	1005/1004
Steam Flow, MM lb/h	0.67	0.51	0.40
Exit Pressure, psia	0.73	0.73	0.73
Outlet Temperature, F	91.3	91.3	91.3
Condenser Duty, MM Btu/h	481.0	455.0	330.7
Gross Power, MWe	99	90	63
Total Gross Power, MW	99	123	96
Total Coal LHV, MM Btu/h	922	980	687
Total Coal HHV, MM Btu/h	953	1,013	710
Auxiliary Power, MWe	5	6	5
Total Net Power, MWe	94	116	92
Efficiency – HHV	33.6%	39.2%	44.1%
Efficiency – LHV	34.7%	40.5%	45.5%

* Two blades removed from compressor to reduce air flow.

The baseline PFB mode of operation utilizes an overflow drain to maintain bed level in the partial gasifier. As defined in Figure 6. both the overflow drain and the cyclone discharge feed char into a common rotary valve. In this configuration if the inlet to the rotary valve is maintained at the same pressure as the cyclone discharge, the overflow loop seal must maintain sufficient pressure head to seal against the pressure drop of the cyclone. The performance of the cyclone -- designed and built by Fisher-Klosterman -- installed at the PSDF is shown in Figure 9. The two data points on the plot define the manufacturers' specifications for the 1600 Deg. F. partial gasifier operating condition, and claim "unloaded" and "fully loaded" pressure drops of 15 in. H_20 and 10.5 in H_20, respectively. In addition to providing a pressure seal, both loop seals are outfitted with cooling coils to reduce the temperature of the char from 1800 Deg. F. to 500 Deg. F. In order to avoid the high cost associated with water cooled rotary valves, the char must be cooled to 500 Deg. F. to satisfy the thermal limit of the shaft seals. The rotary valve serves to provide a seal against the pressure drop across the syngas cooler. Rotary valves are typically rated for a 15 psi. differential pressure. The char collected from the candle filter is mixed together with the overflow and cyclone char in the feed hopper. The feed hopper is outfitted with a conical bottom and is of sufficient volume to provide for four hours of reserve material. The char is delivered through a rotary valve and pneumatically conveyed to the PFB. It should be noted that the PFB is outfitted with a parallel feed system for coal, thus if char feed becomes unstable, the PFB can maintain temperature control by adjusting coal feed.

In an effort to study the performance of the candle filter, a series of tests are planned to operate the partial gasifier without an interposing cyclone. In this configuration of the facility (Figure 7.), all of the elutriated bed material will be directly conveyed into the candle filter. Although the filter inlet solid loading will be high in this arrangement, it is thought that the coarser particle size distribution will serve to improve overall filter performance. When the cyclone is removed, the loop seal cooler will be installed under the candle filter discharge. The loop seal coolers separate the cooling duty between the coarse overflow material and the fine char carried out of the partial gasifier. The duty of the syngas cooler is to be adjusted to maintain a candle filter inlet temperature between 1600 and 1000 Deg. F., and as such, the loop seal coolers are designed for the worst case scenario. It is expected that approximately ½ the generated char will flow through the overflow drain and ½ will be carried over to the candle filter. Because the candle filter and the feed hopper are at the same pressure, the loop seal cooler will discharge char directly into the feed hopper without the need for an in-line rotary valve. However, it should be noted that as the inlet solid loading to the candle filter increases, the pressure drop across the syngas cooler increases. As a result, the total pressure drop across the pyrolyzer overflow drain rotary valve will increase.

The HIPPS arrangement is shown in Figure 8. In this configuration all of the char is conveyed out of the reactor and into the candle filter. The particle size distribution of the elutriated char is suitable as a standard feedstock for a PC boiler. Under the HIPPS operating conditions, the candle filter and the syngas cooler will experience a high inlet solid loading. The original cycle configuration of the HIPPS greenfield plant provides for the cooling of the syngas below 1000 Deg. F. The syngas is cooled to this lower temperature to promote the precipitation of the alkali species on the char material conveyed out of the partial gasifier. Condensation of the gaseous alkali components upstream of the candle filter eliminates concerns of potential gas turbine blade corrosion. SCS is in the process of designing both the syngas cooler, and the candle filter to meet the demands of the high solid loading for the HIPPS arrangement.

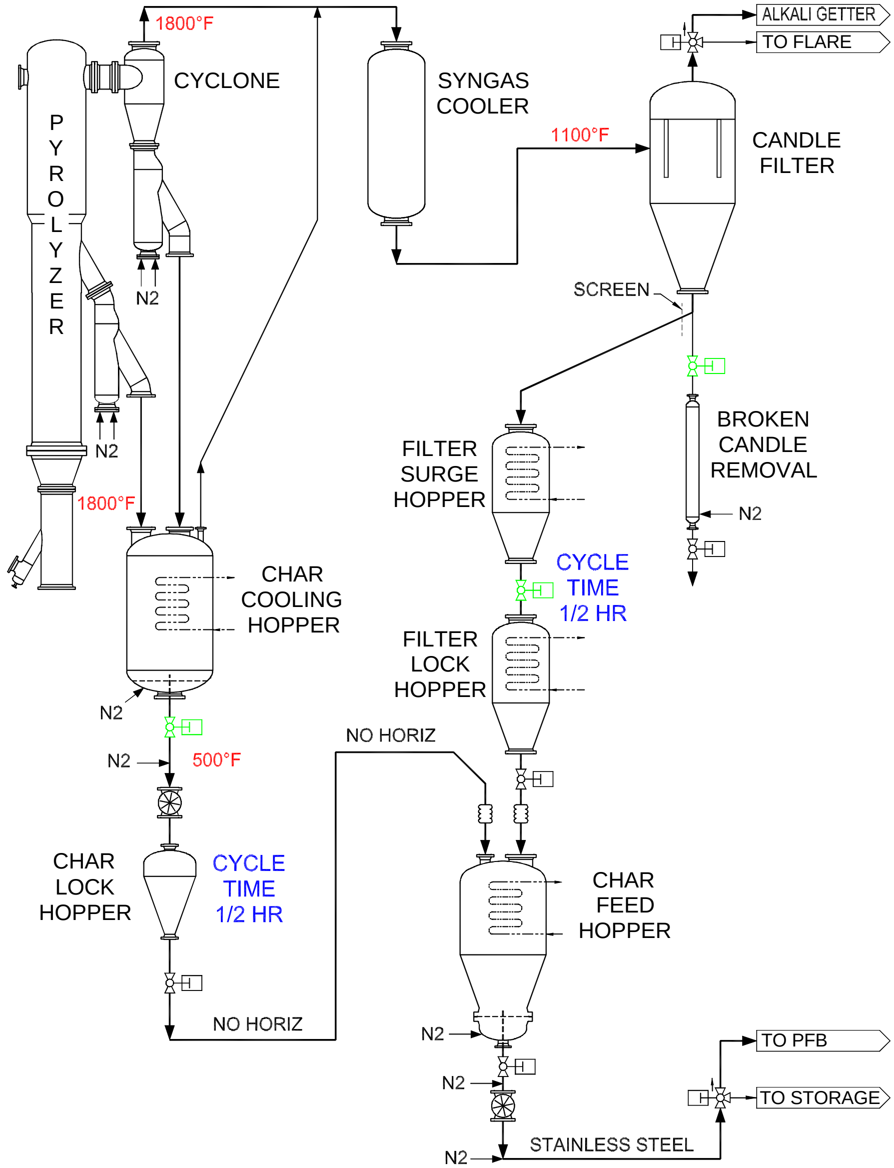

Figure 5. Char Transfer System: Three Lock Hopper Arrangement

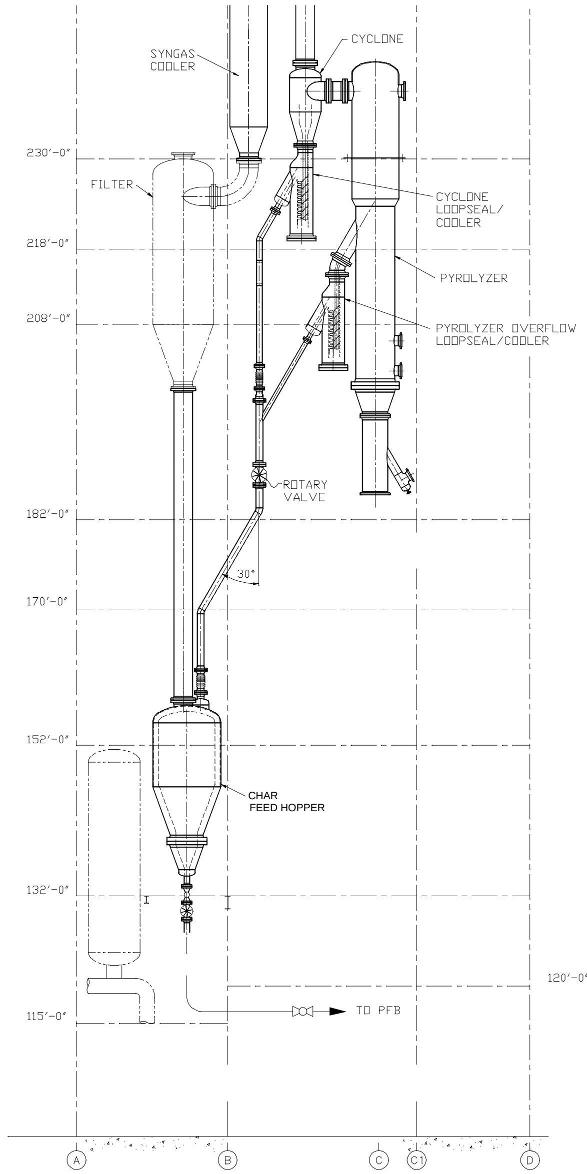

FIGURE 6. Char Transfer System for Baseline PFB Program

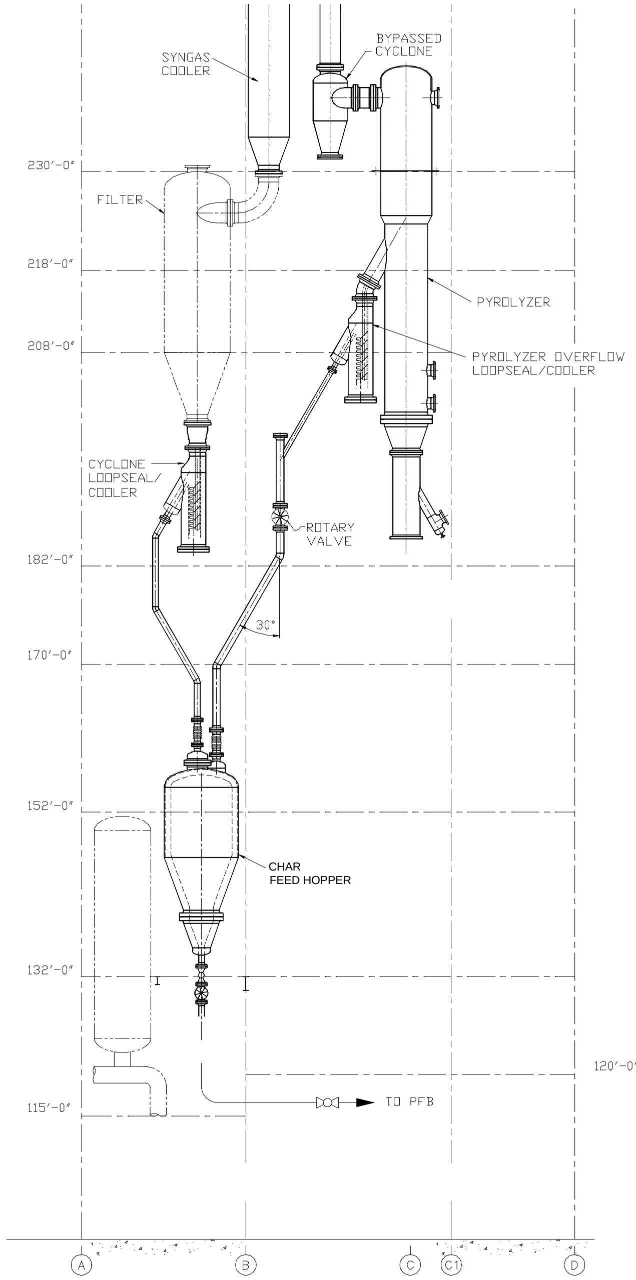

Figure 7. Char Transfer System without Primary Cyclone

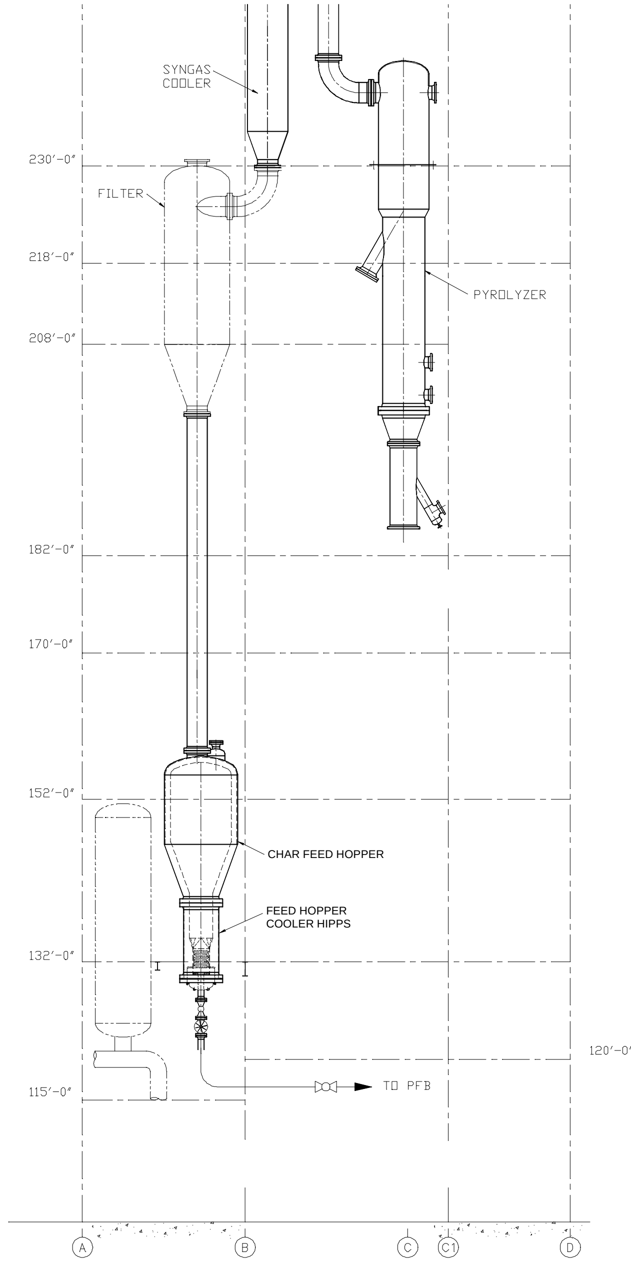

Figure 8. Char Transfer System: HIPPS Layout

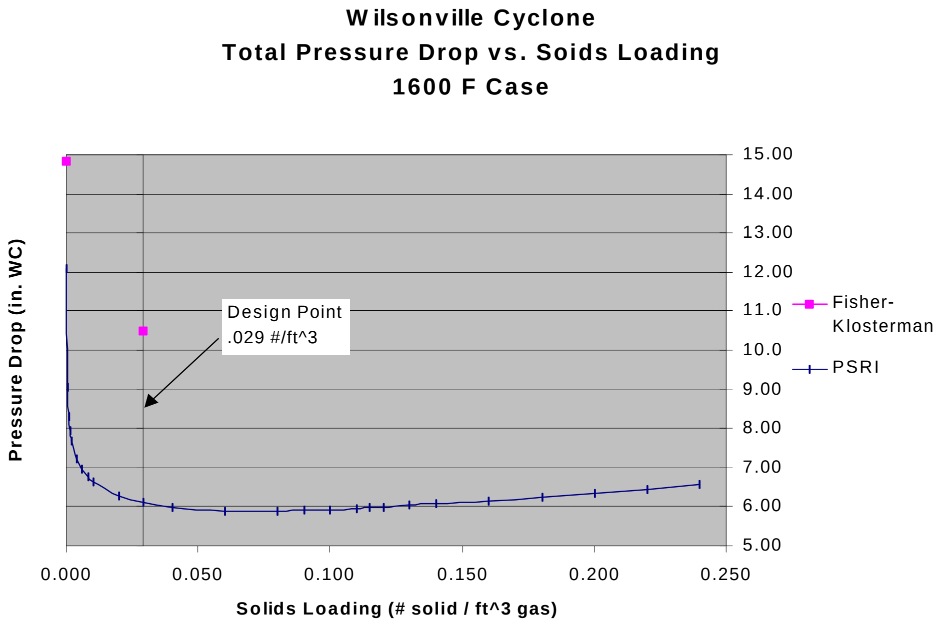

Figure 9. Wilsonville Cyclone Performance

Task 4 - Subsystem Test Unit Construction

No work was performed under this task for this quarter.

Task 5 – Subsystem Test Unit Testing

Subtask 5.2 – Char Combustion System Testing

Combustion testing of the HIPPS Char Combustor was conducted this quarter at FWDC's Combustion and Environmental Test Facility (CETF) in Dansville, NY. A test plan was developed using a Statistical Design of Experiments (SDOE) method to efficiently characterize burner performance. Table 2 identifies the test matrix designed to achieve optimum burner performance, and Table 3 lists the range of the variables tested.

Tests 1 – 18 were conducted firing char produced by McClain Corporation. These tests were conducted to optimize the burner settings. After analyzing the initial data from these tests, parameter settings were selected for Tests 19 – 21 that were considered to provide the optimum conditions for combustion. These tests were conducted firing char produced at FWDC's pilot plant located in Livingston, NJ. Three tests were conducted firing this char.

Preliminary data analysis indicates successful combustion of char, with and without support fuel, under normal furnace operating conditions, and with vitiated air as the oxidant. Levels of uncontrolled NO_X at the furnace exit ranged from 0.3 – 0.7 lbs/MMBtu. Unburned carbon (UBC) measured in the flyash and bottom ash were as low as 4.2%, lbs UBC / lbs fuel.

The effect of char fineness on combustion was studied extensively because of the flexibility provided by the indirect firing arrangement. McClain char fineness ranged from 78% - 98% < 200 mesh, (74µm), allowing the opportunity to study the effect on flame stability, UBC, and NO_X formation. The char produced at the pyrolyzer pilot plant had a fineness of 73% < 200 mesh.

Flame stability observations, provided by infra-red furnace wall-mounted scanners equipped with both flicker and intensity, and preliminary UBC analyses indicate that the fineness criteria for the HIPPS cycle may need to be increased to improve burner performance. Simply modifying the feed stock to the HIPPS Pyrolyzer from 70% to 80% < 200 mesh may have a significant effect on burner stability and performance.

Flame stability was also adversely affected when too much air was supplied to the front wall of the furnace. Figure 10 identifies the air wall distribution in the windbox of the furnace at the CETF. Some tests in the matrix could not be completed due to the lack of flame stability caused by poor air distribution in the furnace windbox. It became evident that the front wall air bias of 100/100/20 (see Table 2) provided the best distribution of air for optimum flame stability. Air distribution changes in the upper section of the windbox also affected flame stability.

Attempts made to achieve the lowest level of flue gas O_2 as defined in the test matrix resulted in poor burner performance. Attempts at lowering the flue gas O_2 to the prescribed 2.0% as defined in the test matrix resulted in poor flame stability and unit trips. Similar results were obtained when the flue gas recycle was used to reduce the vitiated air O_2 level to 13.0%, the lowest level defined in the test matrix. After numerous tests, it was discovered that flame stability was not compromised when flue gas O_2 levels were kept above 3.0%. In the case of the vitiated air O_2 level, the burner flame remained stable when the level of O_2 was kept at or above 15.0%.

Complete burner characterization and performance will be presented once data analyses have been performed on all tests run.

Table 2. Test Matrix

Test #	O_2 in Vitiated Air, % vol. wet	O_2 in Flue Gas, % vol. wet	Air Flow to Burner, lbs/hr	Tertiary Air Flow, lbs/hr	OFA, % total flow	Air Wall Bias, % open (t/m/b)	Support Fuel, % heat input	Straight. Vanes, relative position
1	18.0	2.0	2000	8800	20	100/100/20	10	IN
2	18.0	4.5	2000	4400	20	10/30/60	0	IN
3	18.0	2.0	4000	4400	20	100/100/20	0	OUT
4	15.5	3.3	3000	6600	10	50/50/30	5	MID
5	18.0	4.5	4000	8800	20	10/30/60	10	OUT
6	13.0	4.5	2000	4400	20	100/100/20	10	OUT
7	13.0	2.0	4000	4400	20	10/30/60	10	IN
8	13.0	4.5	2000	8800	0	10/30/60	10	IN
9	18.0	4.5	2000	8800	0	100/100/20	0	OUT
10	18.0	2.0	2000	4400	0	10/30/60	10	OUT
11	15.5	3.3	3000	6600	10	50/50/30	5	MID
12	18.0	4.5	4000	4400	0	100/100/20	10	IN
13	13.0	4.5	4000	4400	0	10/30/60	0	OUT
14	13.0	4.5	4000	8800	20	100/100/20	0	IN
15	13.0	2.0	2000	4400	0	100/100/20	0	IN
16	13.0	2.0	2000	8800	20	10/30/60	0	OUT
17	18.0	2.0	4000	8800	0	10/30/60	0	IN
18	13.0	2.0	4000	8800	0	100/100/20	10	OUT
19	15.5	3.3	4000	6000	0	100/100/20	10	IN
20	15.5	3.3	4000	6000	10	100/100/20	10	IN
21	15.5	3.3	4000	6000	0	100/100/20	0	IN

Table 3. Parameters for HIPPS testing at CETF

Variable Name	Units	*Range*
1. O_2 in Vitiated Air	% vol. wet	14.0 - 19.4
2. O_2 in Flue Gas	% vol. wet	3.1 - 8.4
3. Air Flow to Burner	lbs/hr	1400 – 4300
4. Tertiary Air Flow	lbs/hr	3200 – 7300
5. Over Fire Air (OFA)	% total flow	0 – 23
6. Air Wall Bias	% open (top / middle / bottom)	100/100/20; 50/50/30; 10/30/60
7. Support Fuel	% heat input	0 – 20
8. Straightening Vanes	relative position	IN, MID, OUT
9. Vitiated Air Temperature	ºF	800ºF
10. Char Fineness	% < 200 mesh	73.1 - 97.7
11. Char Flow	lbs/hr	1750 – 3300
12. Char Type	Origin	McClain Corporation, FWDC - Livingston Pilot Plant

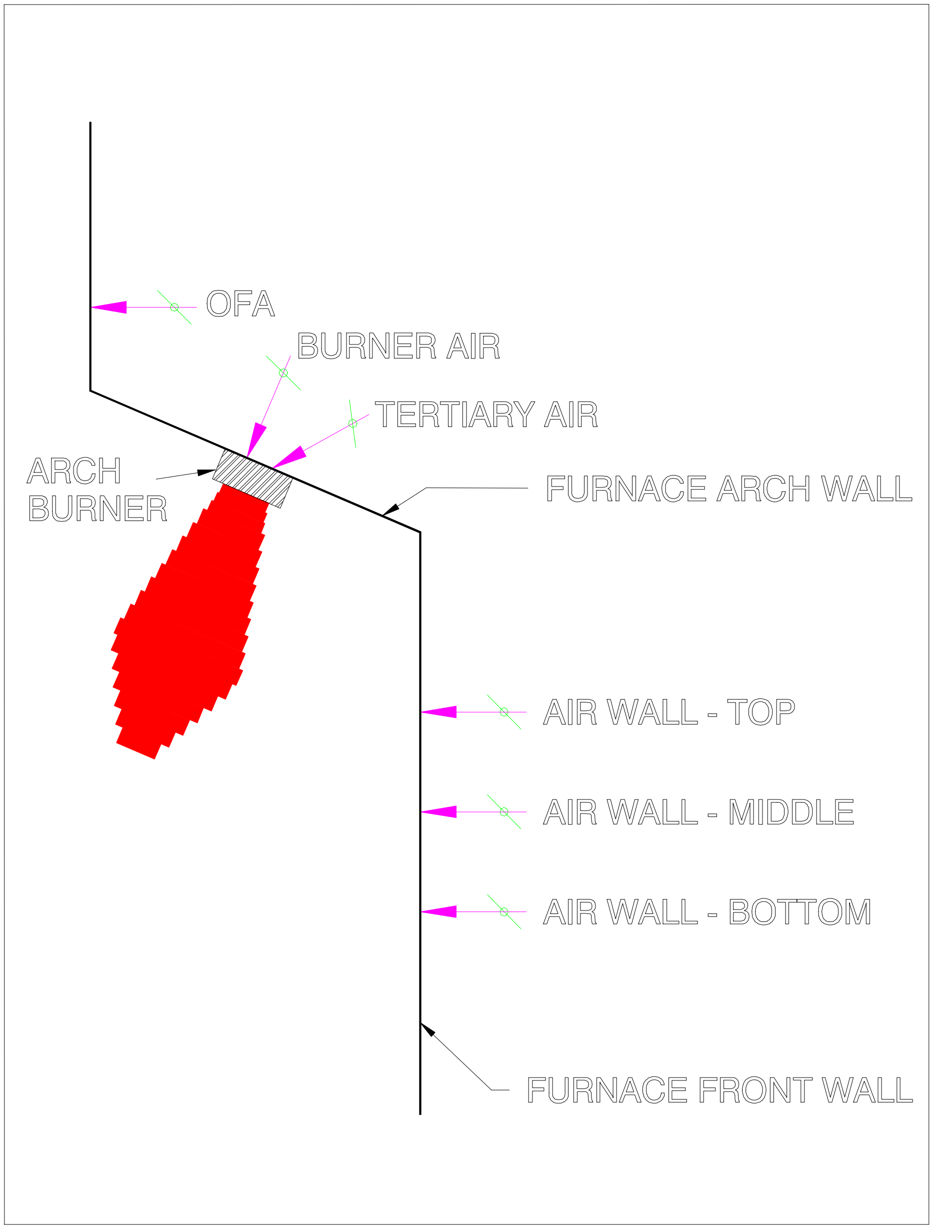

Figure 10. CETF Air Wall Distribution