ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH-PERFORMANCE POWER SYSTEMS

DE-AC22-95PC95143

TECHNICAL PROGRESS REPORT NO. 13
JULY THROUGH SEPTEMBER 1998

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

October 1998

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). 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. Preliminary process design was started with respect to the integrated test program at the PSDF. All of the construction tasks at Foster Wheeler's Combustion and Environmental Test Facility (CETF) have been completed in preparation for the char combustion test program, this includes installation of the char burner, and the on-line mass spectrometer. A test matrix has been defined, utilizing a statistical design of experiment (SDOE) methodology, for the char combustion program. The first phase of the CETF shakedown has been completed, and all analog devices (thermocouples, transmitters, etc.) have been calibrated.

TABLE OF CONTENTS

PAGE NO.

LIST OF FIGURES

FIGURE NO.		PAGE NO.

LIST OF TABLES

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.

Fifteen variables have been selected as the important parameters to be investigated during the HIPPS burner test program. Investigation of all these variables by applying a “traditional” matrix design method would require an overwhelming amount of tests, and as a result, delay the overall program schedule. In order to achieve comprehensive and meaningful results within a reasonable time frame, advanced statistical design of experiment (SDOE) methods were used during this quarter to plan the overall experimental test matrix for the char combustion program.

The construction effort at the CETF was completed during this quarter with the installation of the char burner and the on-line mass spectrometer. The char burner (35 MMBtu/hr.) represents a half-scale version of a typical commercial burner and will be initially tested in the arch-firing mode of operation. All three of the feed systems, char, limestone, and coal, have been connected to the burner.

Phase 1 of the CETF system shakedown has been completed. During this period, all of the analog instruments, including thermocouples, pressure transmitters, and flow transmitters have been calibrated to insure device integrity. In addition to the analog instruments, all of the discrete inputs have been checked for proper operation – this includes all pressure and level switches used for safety interlocking.

Preliminary design of the char transfer system to be installed at the PSDF in Wilsonville, AL, commenced during this quarter. A meeting was held at FWDC in Livingston, NJ, with personnel from Southern Company Services (SCS) to discuss the performance of the candle filter under HIPPS operating conditions. These discussions and exchange of performance data have allowed SCS to

define their design specifications for the new filter vessel to be installed at the PSDF. This vessel is to be designed to satisfy the experimental requirements for both the PFB and HIPPS projects. Initial review of the process and instrumentation drawings for the char transfer system have been completed.

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.

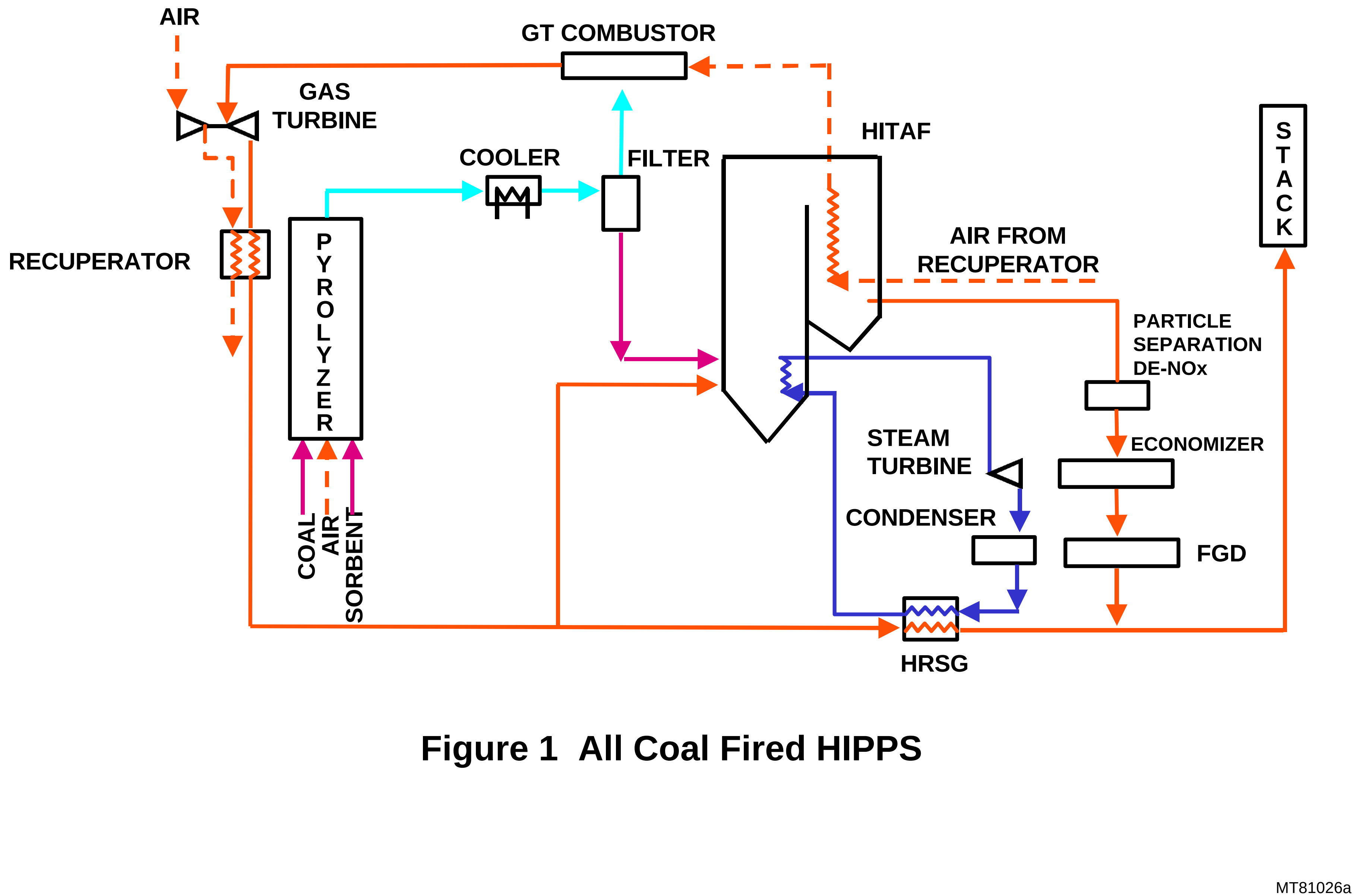


Figure 1 All Coal Fired HIPPS

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.

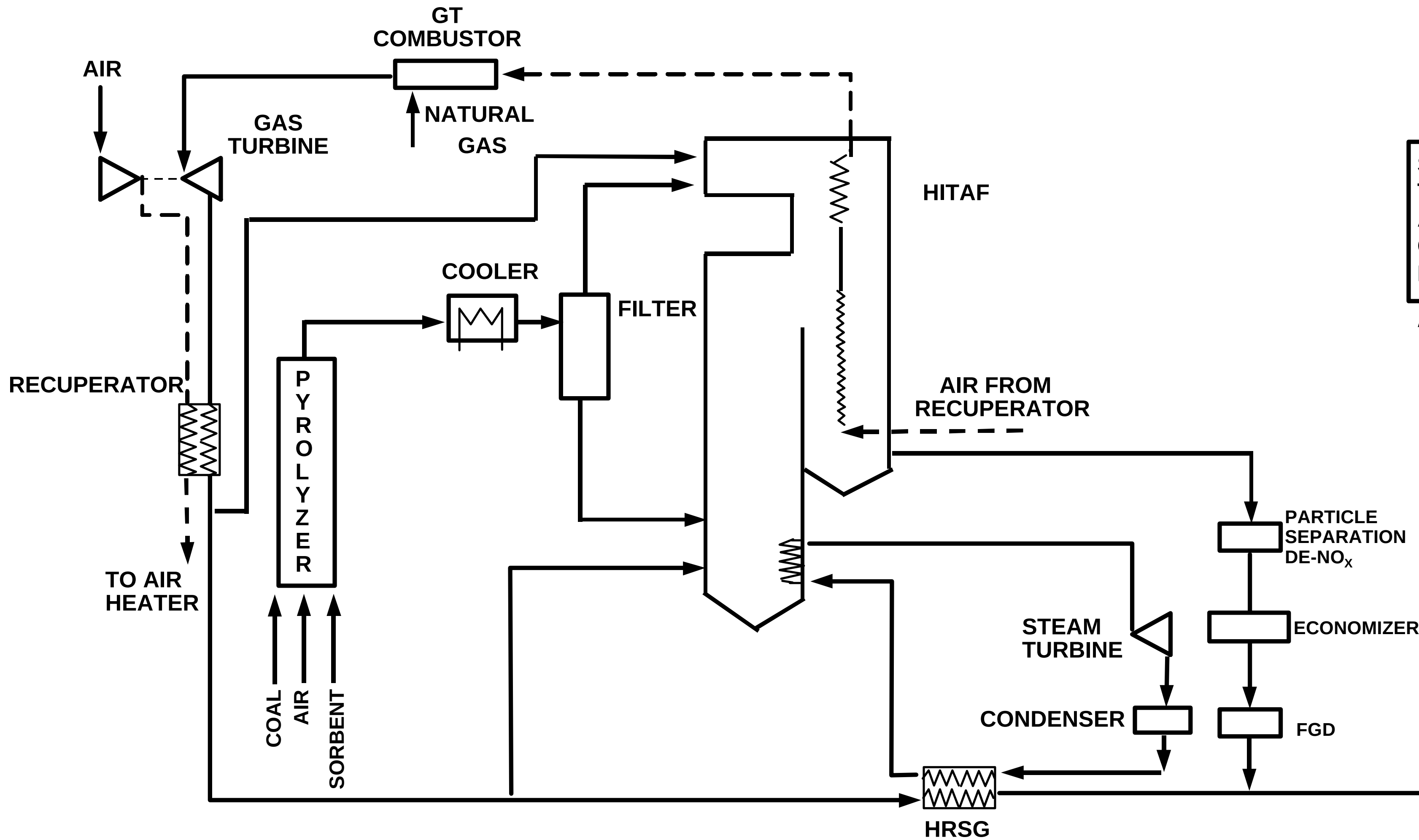


Figure 2 35-Percent Natural Gas HIPPS

MT81026b

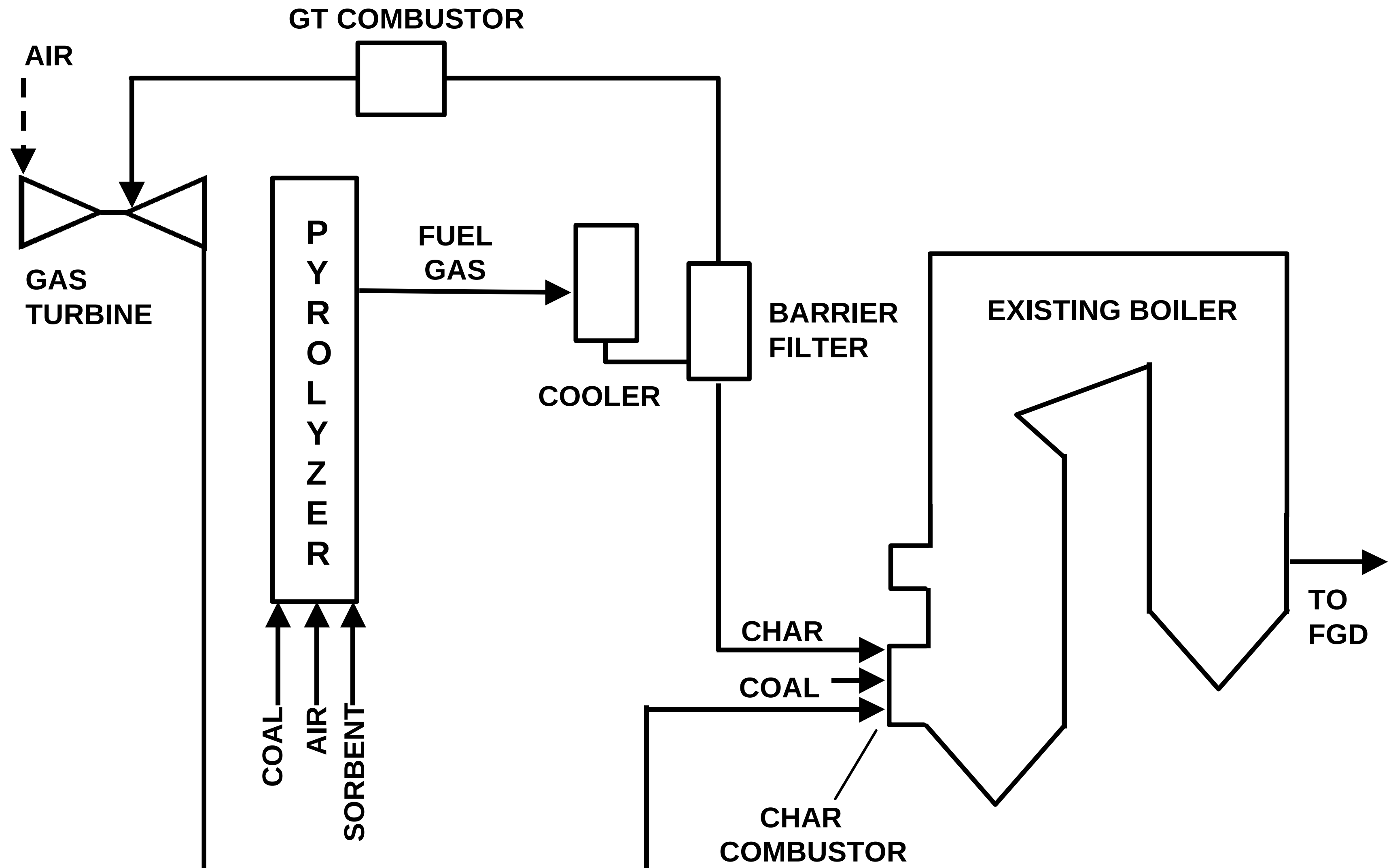


Figure 3 Simplified HIPPS Repowering Process Flow Diagram

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 - Char Combustor Two-Phase Flow Test

A HIPPS char combustor is scheduled to be tested at Foster Wheeler's Combustion and Environmental Test Facility (CETF). In order to gain an understanding of the fuel injector pressure drop and air/solids mixing characteristics prior to hot combustion testing at CETF, two-phase modeling of a one-half scale HIPPS injector was performed. Two-phase air-pumice tests have been completed and some significant results are presented below.

Visual observations of the air and pumice discharge into an exhaust chamber revealed the variation in outlet flow distribution due to differences in straightening vane location inside the fuel injector. Inserted straightening vanes, which were positioned flush with the injector outlet, tended to result in four concentrated pumice streams whereas retracted straightening vanes produced a hollow core of swirling pumice. The retracted straightening vanes were positioned inside the cylindrical shroud similar in shape to a blanked-off vortex tube. A swirler located in the tertiary air stream tended to pull out and spread the solids due to a recirculation zone. The swirler vanes swirled the tertiary air flow in the same direction as the tangential inlet.

Photographs of the injector's interior paint after the first twenty minutes of pumice flow provided a visual indication of possible wear areas of the full-scale injector. These areas included the outer edge of each straightening vane and outlet tube, lower portion of the two straightening vane push/pull rods, and along the outside barrel area near the tangential inlet.

Pressure drop data were taken and a regression analysis correlated in the following form:

$$\Delta P = C1 * Vhinlet + C2 * Vhoutlet$$

where : ΔP = Total Pressure Drop Across Char Injector (inches wc)
Vhinlet = Tangential Inlet Air Velocity Head (inches wc)
Vhoutlet = Injector Discharge Air Velocity Head (inches wc)
C1 = 5.79 for case of straightening vanes inserted
C2 = 1.43 for case of straightening vanes inserted
C1 = 5.72 for case of straightening vanes retracted
C2 = 0.91 for straightening vanes retracted

The application of this correlation to the full-scale CETF injector results in a total pressure drop of 4.2 inches wc and 3.6 inches wc for straightening vanes fully inserted and straightening vanes fully retracted, respectively. These pressure drop predictions are based on CETF operating conditions of 3056 lb/hr of 800°F tangential burner vitiated air, 284 lb/hr of ambient char carrier air, and 2500 lb/hr of char.

The energy balance across the injector revealed discharge temperatures that were within 4% of the theoretical equilibrium temperatures. The fact that the temperatures approached the theoretical equilibrium temperature, which assumes complete mixing of the hot primary air and ambient temperature pumice, is an indication of the ambient char particle being raised to a higher, reactive temperature that should aid in stable combustion.

In summary, the two-phase HIPPS char injector model data indicates the following:

- Operating at the design conditions, a total pressure drop on the order of 3.6 inches wc and 4.2 inches wc is predicted for the CETF prototype char injector when straightening vanes are fully retracted and fully inserted, respectively.

- Efficient mixing of the hot primary air and ambient char is predicted due to the high measured discharge temperature to equilibrium discharge temperature ratios observed during the two-phase modeling.

- Visual observations indicate four concentrated streams of solids discharging from the injector when the straightening vanes are fully inserted. It was observed that a hollow core of swirling solids discharged from the injector when the straightening vanes were retracted. The tertiary air swirler created a strong recirculation zone that tended to pull out the solid streams.

- Possible wear areas of the prototype CETF injector include the outer edge of each straightening vane and outlet tube, lower portion of the two straightening vane push/pull rods, and along the inside barrel area near the tangential inlet.

Task 3 - Subsystem Test Unit Design

Subtask 3.1 - Char Combustor Test Plan

A test plan for the char combustor at the Combustion and Environmental Test Facility (CETF) has been developed. Fifteen major variables and parameters for burner operation have been identified and are shown in Table 1. Investigation of all fifteen selected variables/parameters by applying a traditional matrix design method would require an overwhelming amount of tests and require an unreasonable budget and schedule. In order to achieve relatively comprehensive and meaningful results within the time and budget available, advanced SDOE (Statistical Design of Experiment) method is utilized. SDOE is a systematic approach to designing experiments to obtain the desired amount of information in the most efficient manner. SDOE also provides methods for estimation of experimental error and for dealing with uncontrolled variables. Since well-studied and known statistical tools are used both in the design and analysis of the experiments, ambiguity of results is avoided. The optimal burner design will be determined as the combination of burner and furnace flow rates which produce the best combustion efficiency, flame stability and the lowest NOx generation.

The char combustor test will consist of two phases. In the first phase of experiment, the effects of the burner variables (variables 1-8 of Table 1) will be explored to obtain an optimum burner design and a SDOE-based test matrix for this first phase is presented in Table 2. In the second phase, the boundaries of the optimum burner design will be investigated by varying the HIPPS system parameters (variables 9 B15 of Table 2). Testing and interpretation of results will be guided by the HIPPS-burner/CETF-furnace CFD analysis and previously completed two-phase flow model test results.

Subtask 3.2 - Char Combustion Subsystem Design

All of the design work for preparing the Combustion and Environmental Test Facility (CETF) for the HIPPS experimental test program were completed last quarter. No work was performed on this subtask for this quarter.

Subtask 3.3 – Wilsonville Pilot Plant Design

At the Advanced Coal-Based Power and Environmental Systems '98 Conference held July 21- 23, in Morgantown, West Virginia, Sierra Pacific Power Company (SPPC) presented a paper reviewing their operating experience with the hot gas filter system. One of the major problems associated with the overall design of their filter system has been with the bridging of fines in the lower discharge cone. If ash bridging continues undetected, the fine material builds up in the discharge cone, and eventually submerges the lower portion of the candle elements. If a candle element is submerged, it is likely to break during the blowback pulse cleaning due to thermal stresses imposed within the ceramic. The portion of the candle submerged in the ash remains "hot" during the blowback sequence because the ash material itself is hot, and the majority of the pulse cleaning flow is directed to the unsubmerged section of the candle. In an effort to discuss these problems, a meeting was held at Foster Wheeler Development Corporation in Livingston, N.J. from 8/3/98 to 8/4/98, with members from Southern Company, to address the design issues for the new filter system to be installed at the PSDF.

The design of the filter for the PSDF must satisfy the process requirements for both the PFB and the HIPPS test program. It was determined that the inlet solid loading to the filter under the HIPPS test conditions will be significantly higher than during the PFB test campaign. The higher loading is due to the fact that the cyclone between the carbonizer outlet and filter inlet for the PFB tests will be removed for the HIPPS tests. The HIPPS process arrangement provides direct coupling of the pyrolyzer outlet with the inlet of the candle filter. The presence of an interposing cyclone under the HIPPS test conditions, would adversely affect filter performance because of the fineness of the HIPPS feedstocks.

A set of preliminary process and instrumentation drawings (P&I drawings) were completed for the PSDF. These drawings layout the instrumentation requirements for a broken candle “catcher” system. For the new filter system, SCS is requiring the capability to remove broken candles on-line. In an effort to provide this capability, FWDC has offered a simple design which relies on a fluidized bed “dripleg”. As illustrated in Figures 4. and 5., the discharge nozzle from the bottom of the candle filter is split into two separate legs. The generated process char is diverted (@ 20 Deg. off vertical) through a screen, while the smaller vertical leg serves as a collection chamber for broken pieces of filter elements. The length of the collection leg is sufficiently long so as to accommodate a full length candle (approx. 6 feet). The inlet valve to the collection chamber is maintained in the open position under normal operation, while nitrogen is admitted just above the lower valve to fluidize the solid ash in the leg. The leg is outfitted with a series of differential pressure transmitters along its axial length to monitor the density of the contained material. Since the candle ceramic is of much higher density than the fine ash within the collection leg, any broken pieces of filter falling into the leg would displace the resident ash. The differential pressure measurements would be monitored to indicate the presence of any high density ceramic material, and as a signal to activate candle removal.

Figures 4. and 5. depict two possible process arrangements for the char transfer system to be installed at the Facility in Wilsonville, Al., a two hopper and three hopper configuration, respectively. Although the three hopper arrangement will have a higher total cost, it provides the safest alternative to the existing N-Valve arrangement. Presently at the PSDF, the pilot plant is equipped with an N-valve for the transfer of char from the carbonizer to the combustor as part of the Second Generation PFB program. However, since this arrangement is not suitable for the transport of fine HIPPS char, an alternative design is underway. The three hopper configuration is the safest to operate because under all conditions there is a complete isolation of the reducing and oxidizing environments. The char is generated under reducing conditions (pyrolyzer), while the char is consumed under oxidizing conditions (combustor). The development of general arrangement drawings are planned for the following quarter.

Table 1. Major Variables and Parameters for HIPPS testing at CETF

Variable Name:	**Units**	**Phase**	**Ranges/Levels**		
			Low	**Mid-point**	**High**
1. O_2 in Vitiated Air	% vol. wet.	1	13	15	18
2. O_2 in Flues (Excess Air)	% vol. wet.	1	2.0	3.3	4.5
3. Air Flow to Burner	Lbs/hr	1	2,000	3,000	max
4. Tertiary Air Flow	Lbs/hr	1	4,400	6,600	max
5. OFA	% Total Flow	1	0	10	max
6. Air Wall Bias	Set (top,	1	1^{st} set 100, 100, 20	2^{nd} set 50, 50, 30	3^{rd} set 10, 30, 60
7. Support Fuel	% heat input	1	0	5	10
8. Straightening Vanes	Relative Position	1	IN	Middle	Out
9. VA Temperature	^oF	2	To Be Determined		
10. Char Fineness	% through 200 mesh	2	To Be Determined		
11. Tertiary Air Swirl	Relative Position	2	To Be Determined		
12. Geometry	Nozzle Length	2	To Be Determined		
13. Sorbent Injection	% of Char Fuel Sulfur	2	To Be Determined		
14. Char Flow	Lbs/hr	2	To Be Determined		
15. Char Type	Origin	2	To Be Determined		

Table 2. Phase 1 Test Matrix

	O2 in Vitiated Air % vol. wet	O2 in Flue Gas % vol. wet	Char Flow to Burner Lbs/hr	Tertiary Air Flow lbs/hr	OFA % total Flow	Air Wall Bias set (top; mid; bot)	Support Fuel % heat input	Straightening Vanes Position
1	13	4.0	2,500	4,000	0	1	0	In
2	18	2.0	2,500	4,000	0	3	10	Out
3	13	4.0	2,500	4,000	10	1	10	Out
4	18	4.0	2,500	4,000	10	3	0	In
5	13	2.0	3,500	4,000	10	3	10	In
6	18	2.0	3,500	4,000	10	1	0	Out
7	13	4.0	3,500	4,000	0	3	0	Out
8	18	4.0	3,500	4,000	0	1	10	In
9	13	2.0	2,500	5,000	10	3	0	Out
10	18	2.0	2,500	5,000	10	1	10	In
11	13	4.0	2,500	5,000	0	3	10	In
12	18	4.0	2,500	5,000	0	1	0	Out
13	13	2.0	3,500	5,000	0	1	10	Out
14	18	2.0	3,500	5,000	0	3	0	In
15	13	4.0	3,500	5,000	10	1	0	In
16	18	4.0	3,500	5,000	10	3	10	Out
17	15	3.0	3,000	6,600	5	2	5	Middle
18	15	3.0	3,000	6,600	5	2	5	Middle

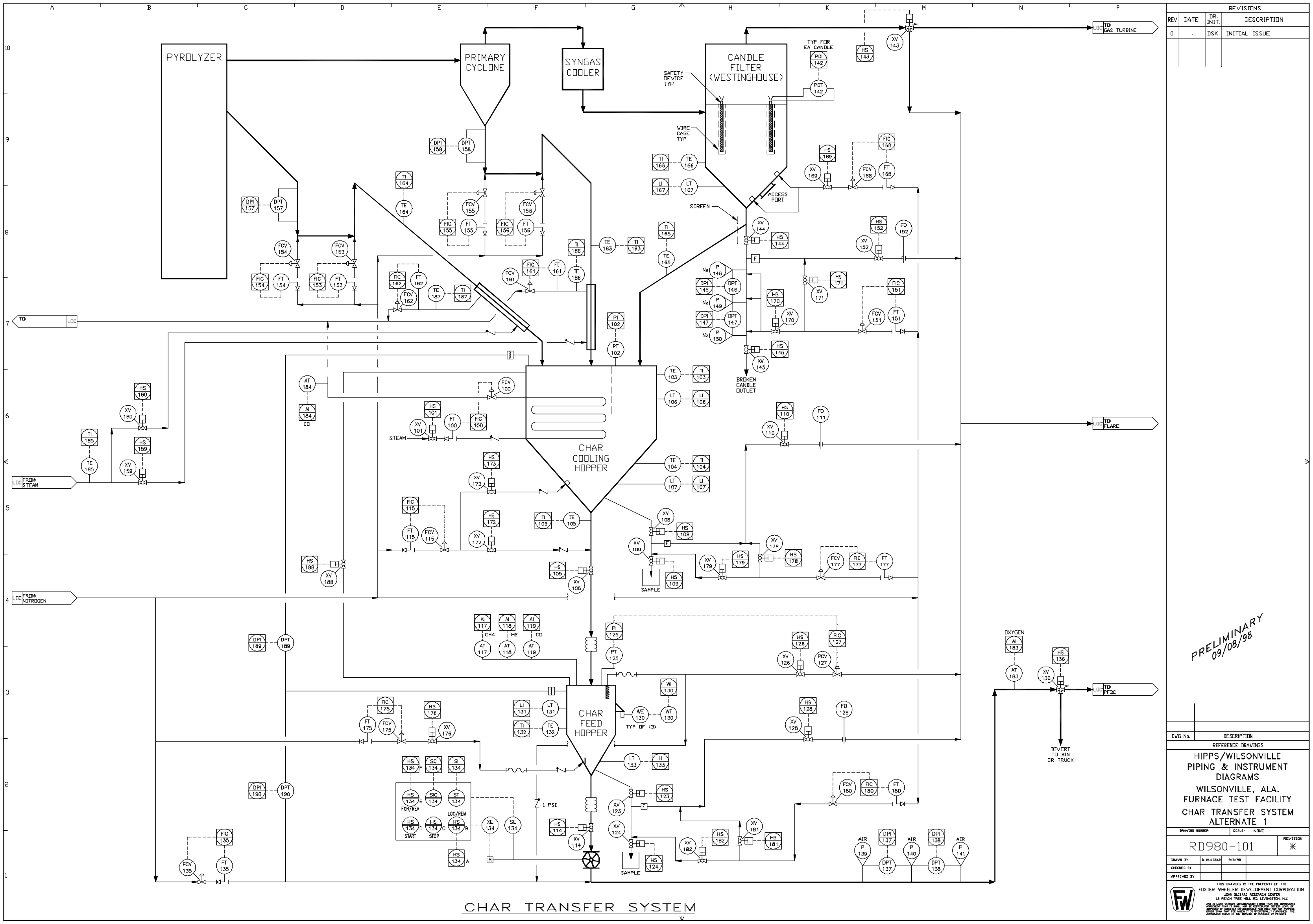

PYROLYZER
PRIMARY CYCLONE
SYNGAS COOLER
CANDLE FILTER (WESTINGHOUSE)
CHAR COOLING HOPPER
CHAR FEED HOPPER
BROKEN CANDLE OUTLET
TO: GAS TURBINE
TO: FLARE
TO: PFBC
FROM: STEAM
FROM: NITROGEN
DIVERT TO BIN OR TRUCK
STEAM
SAMPLE
OXYGEN
PRELIMINARY 09/08/98
REVISIONS
REV DATE DR. INIT. DESCRIPTION
0 - DSK INITIAL ISSUE
HIPPS/WILSONVILLE PIPING & INSTRUMENT DIAGRAMS
WILSONVILLE, ALA. FURNACE TEST FACILITY
CHAR TRANSFER SYSTEM ALTERNATE 1
RD980-101
FOSTER WHEELER DEVELOPMENT CORPORATION
CHAR TRANSFER SYSTEM

Figure 4

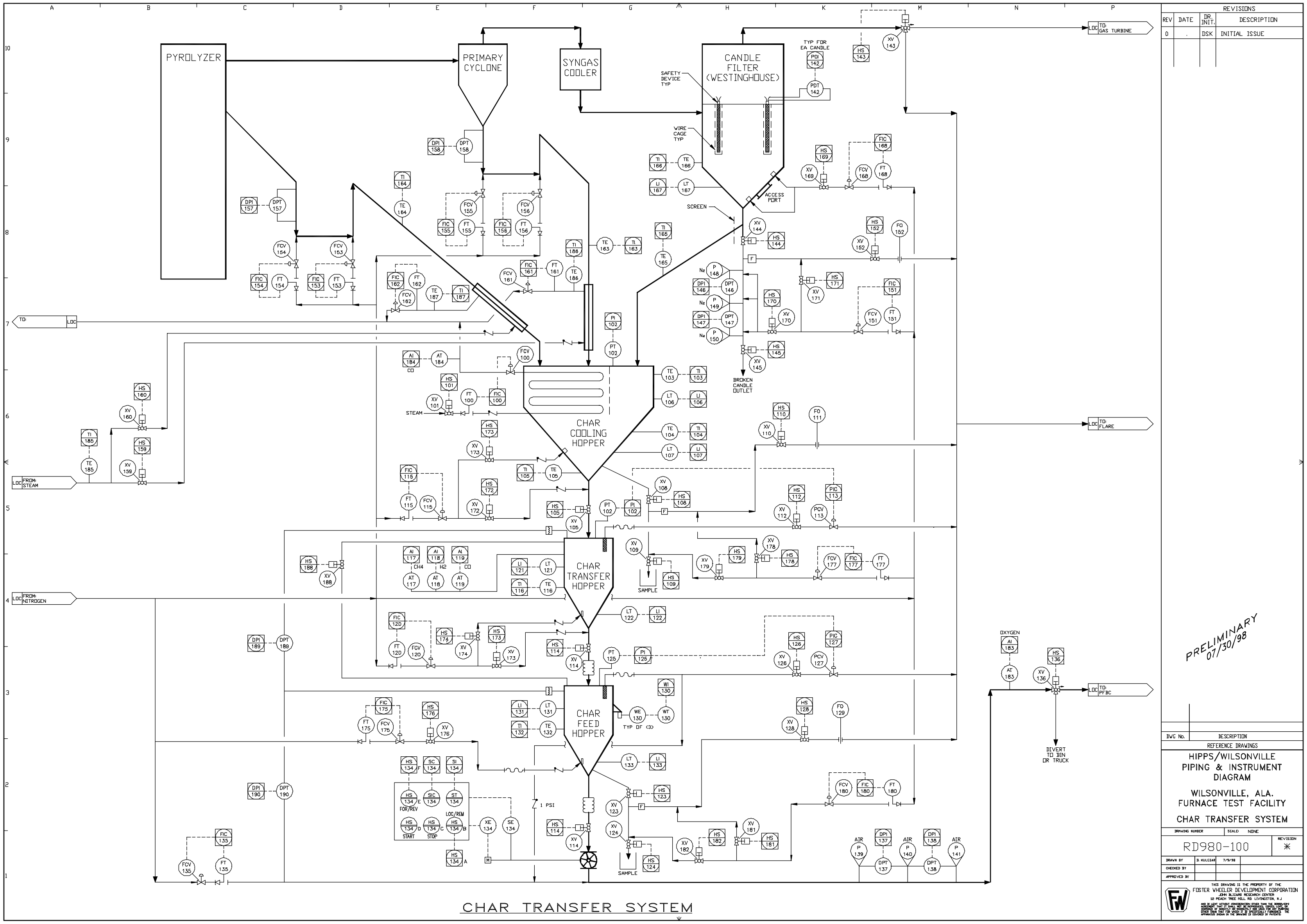

PYROLYZER
PRIMARY CYCLONE
SYNGAS COOLER
CANDLE FILTER (WESTINGHOUSE)
CHAR COOLING HOPPER
CHAR TRANSFER HOPPER
CHAR FEED HOPPER
FROM STEAM
FROM NITROGEN
TO: GAS TURBINE
TO: FLARE
TO: PFBC
DIVERT TO BIN OR TRUCK
BROKEN CANDLE OUTLET
PRELIMINARY 07/30/98
HIPPS/WILSONVILLE PIPING & INSTRUMENT DIAGRAM
WILSONVILLE, ALA. FURNACE TEST FACILITY
CHAR TRANSFER SYSTEM
RD980-100
CHAR TRANSFER SYSTEM

Figure 5

Task 4 - Subsystem Test Unit Construction

Subtask 4.2 - Char Combustion System Test Unit Construction

The construction effort at the Combustion and Environmental test facility (CETF) was completed during this quarter with the installation of the char burner and the on-line mass spectrometer. A schematic of the facility is shown in Figure 6.

The installation of the char burner proceeded as planned. A new penetration through the boiler waterwall was opened in order to accommodate the discharge nozzle and swirler vanes. A picture of the installed burner is provided in Figures 7 and 8.

The on-line mass spectrometer has been installed, and will be used to monitor the composition of three separate streams at the facility. The sample points are included in the process air line downstream of the duct burner, downstream of the gas cooler, and at the inlet to the recycle fan. A photograph of the installed system is shown in Figure 9.

Task 5 - Subsystem Test Unit Testing

Subtask 5.2 – Char Combustion System Testing

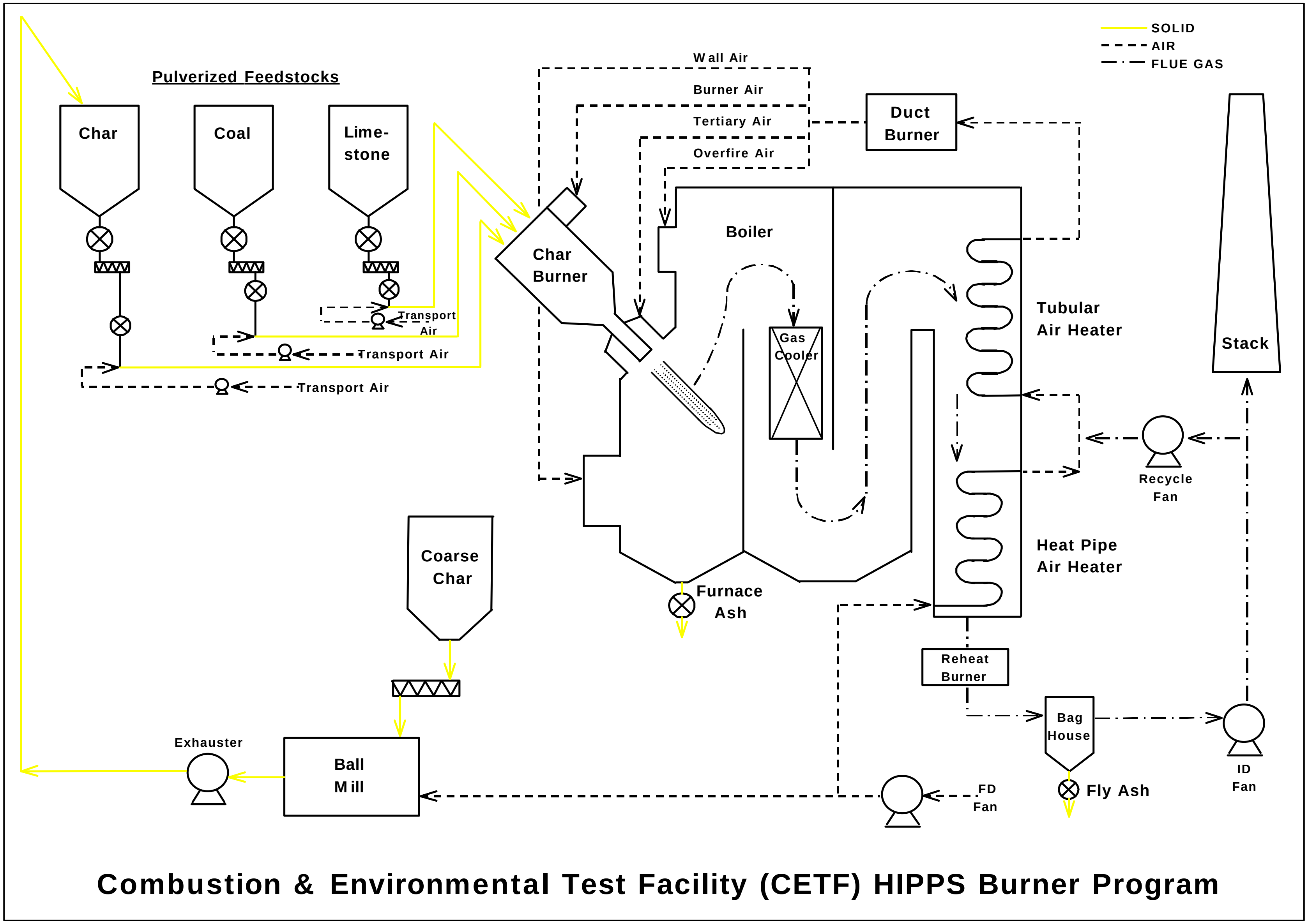
With the construction tasks completed at the CETF, initial system shakedown commenced during this period. All of the analog instruments were calibrated – this includes:

1. Thermocouples (both RTD and Type J,K)
2. Pressure Transmitters
3. Flow Transmitters (Pitot, Vortex, and Turbine)
4. Modulating Control Valve Position Feedback

All discrete input devices were also calibrated – these include:

1. Temperature Switches
2. Pressure Switches
3. Level Switches

The second phase of system shakedown will continue into next quarter with the validation of safety interlocks, and the integrated operation of motors, fans, burners, and compressors.



SOLID
AIR
FLUE GAS
Pulverized Feedstocks
Char
Coal
Lime-
stone
Wall Air
Burner Air
Tertiary Air
Overfire Air
Duct
Burner
Char
Burner
Boiler
Gas
Cooler
Tubular
Air Heater
Stack
Transport
Air
Transport Air
Transport Air
Recycle
Fan
Heat Pipe
Air Heater
Coarse
Char
Furnace
Ash
Reheat
Burner
Bag
House
Exhauster
Ball
Mill
FD
Fan
Fly Ash
ID
Fan
Combustion & Environmental Test Facility (CETF) HIPPS Burner Program

Figure 6

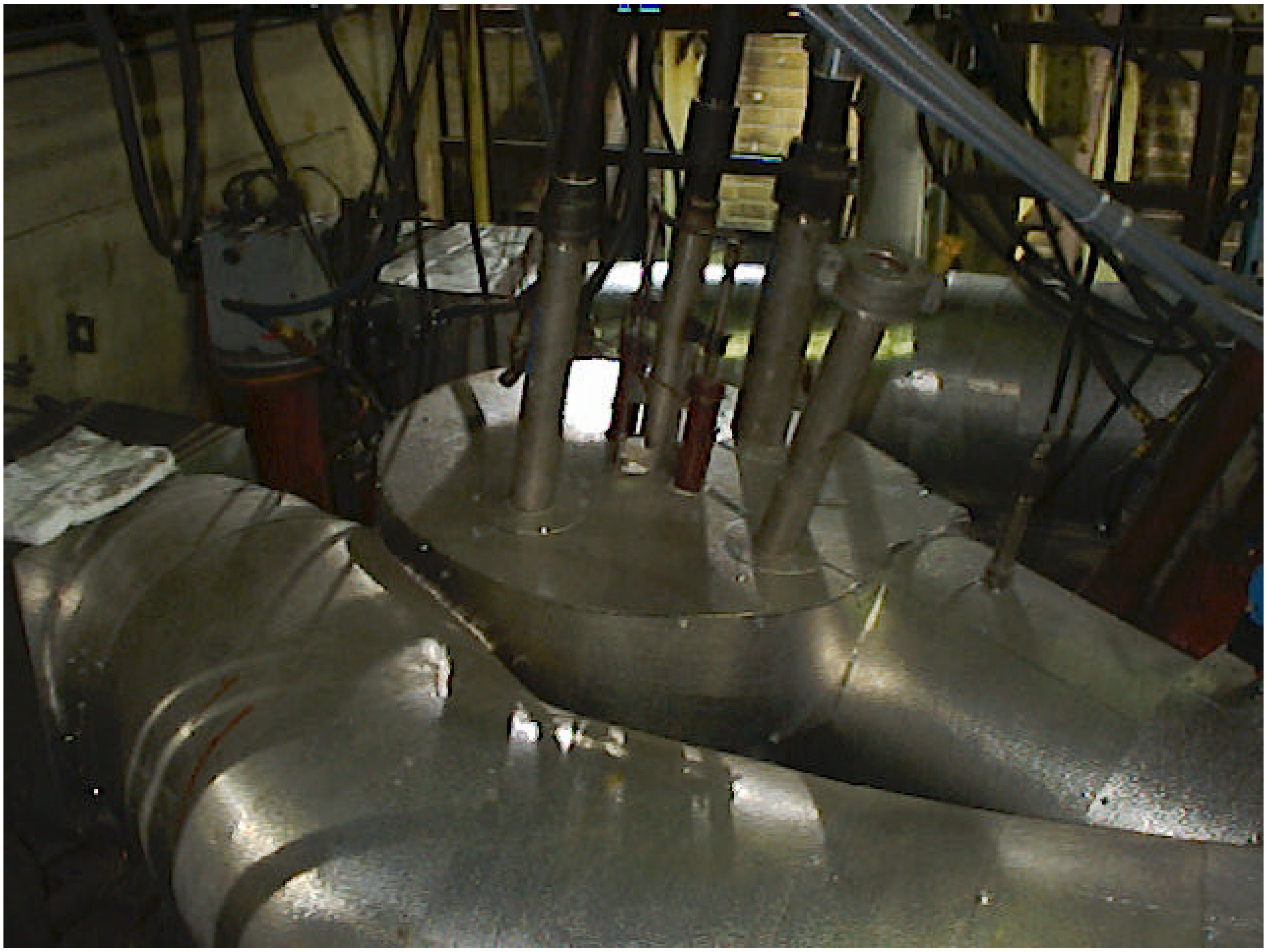


Figure 7 Char Burner (North View)

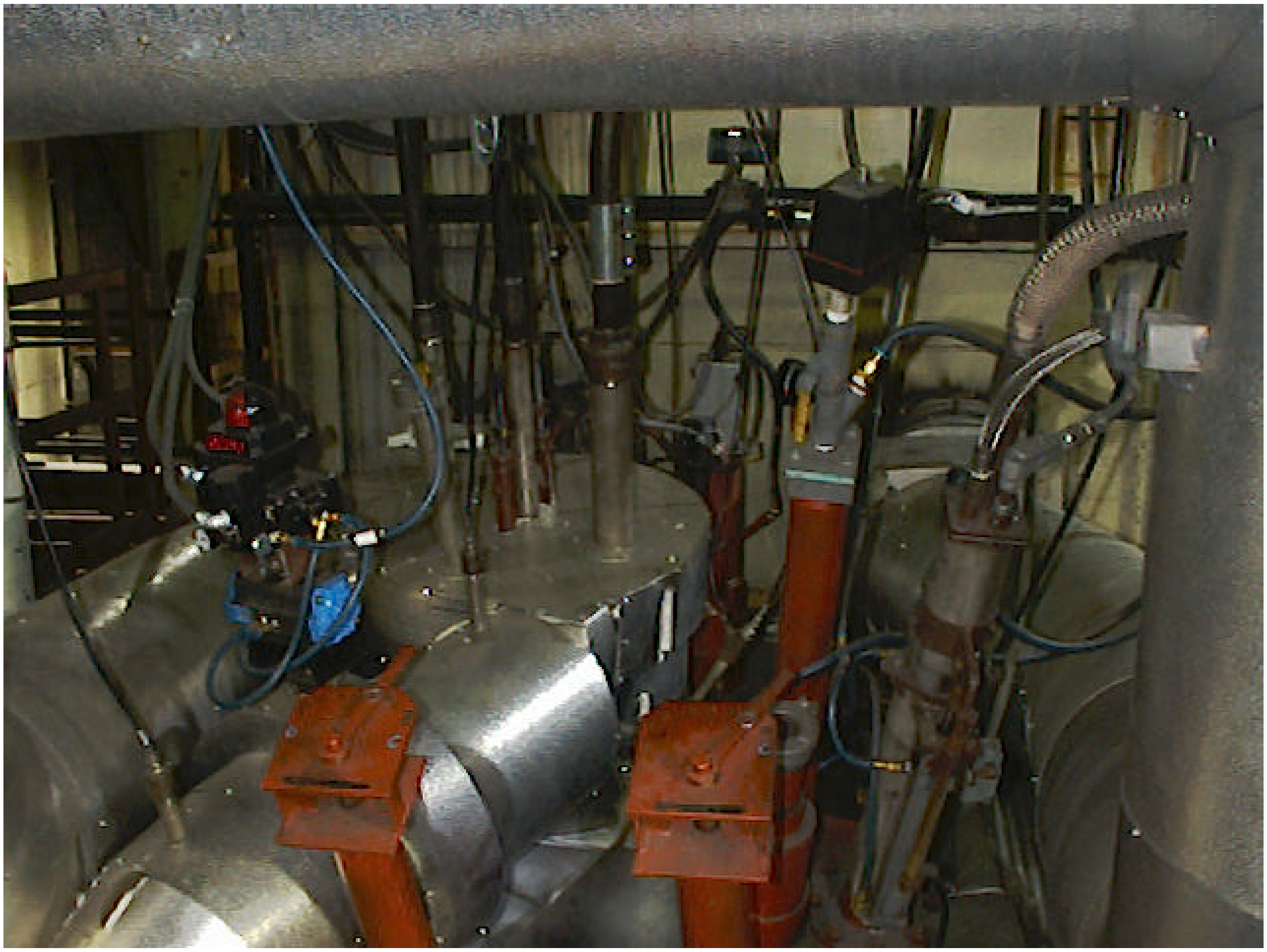


Figure 8 Char Burner (West View)

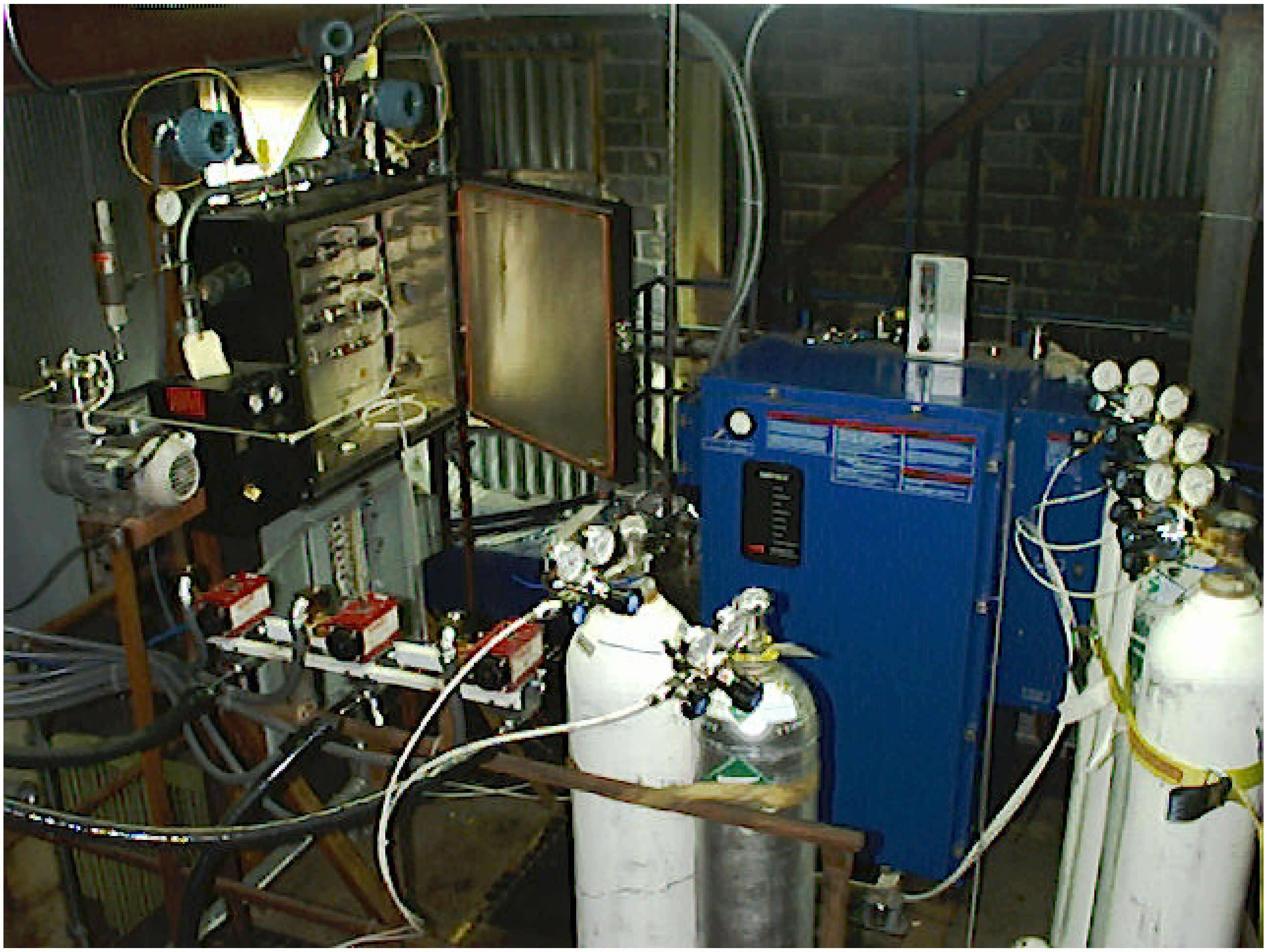


Figure 9 Mass Spectrometer System