Design and Development of a Pulverized Char Combustor for the High Performance Power System

Mark R. Torpey (mark_torpey@fwc.com; 973-535-2232)
Jan Friedrich (jan_friedrich@fwc.com; 908-713-2242)
Richard J. Graham (richard_graham@fwc.com; 973-535-2204)
Aleksandr Kravets (alex_kravets@fwc.com; 973-535-2350)
Anthony Mosca (CETF@fwc.com; 716-335-0213)
Andrew Seltzer (andrew_seltzer@fwc.com; 973-535-2542)

Foster Wheeler Development Corporation
12 Peach Tree Hill Road
Livingston, N.J. 07039

Abstract

A high performance power system (HIPPS) with a thermal to electric conversion efficiency of more than 47% is being developed by Foster Wheeler Development Corporation (FWDC) under the sponsorship of the United States Department of Energy, Federal Energy Technology Center (USDOE-FETC). This coal-fired combined cycle system utilizes a partial gasification process to generate both a coal derived low-Btu fuel gas for direct firing in a gas turbine, and a combustible solid char serving as the feedstock for a pulverized char fired boiler. The combustion behavior of the char is critical to the overall performance of the HIPPS technology, and FWDC's Combustion and Environmental Test Facility (CETF) in Dansville, N.Y., has been modified to meet the test requirements for the development of an advanced burner.

This paper describes the general arrangement of the test facility, the instrumentation used for process control and diagnosis, the burner design, and the experimental test matrix for the burner development program. The HIPPS char burner (35 MMBtu/hr.) to be tested at the facility represents a one half scale design of a commercial unit. The experimental tests at this scale should provide sufficient information for commercial design. The overall objective of the char burner test program is to establish a design with minimal NOx generation, high carbon conversion efficiencies, and stable flame characteristics.

Introduction

A High Performance Power System (HIPPS) is being developed under the sponsorship of the United States Department of Energy, Federal Energy Technology Center (FETC). This system is a coal fired combined cycle that uses a High Temperature Advanced Furnace (HITAF) that transfers heat to both air and steam working fluids. The Foster Wheeler design uses a pyrolyzation process to convert a pulverized coal feedstock into two components, a low-Btu fuel gas and solid char. Figure 1 illustrates the HIPPS process flow schematic as defined for a commercial plant. The fuel gas exhaust from the reactor is directly connected to the gas turbine and is burned with the air from the compressor. The generated char provides the feedstock for the HITAF. Systems of this type are capable of over 47 percent efficiency (HHV).

Foster Wheeler Development Corporation is leading a team of companies in the development of this power generation system. The team member companies are Bechtel Corporation, Foster Wheeler Energy Corporation, University of Tennessee Space Institute, and Westinghouse Electric Corporation. In Phase 1 of the HIPPS project, a conceptual design of a 300 MW commercial plant was developed. Economic analysis of this plant relative to a PC boiler of equivalent size indicates that the HIPPS plant will have a 15 percent lower cost of electricity. Phase 2 of the project is now in progress and includes both experimental pilot scale testing of a coal-fired Pyrolyzer and a char combustor. Several test runs have been completed for the Pyrolyzer subsystem at Foster Wheeler Development Corporation's (FWDC) test facility in Livingston, N.J. Testing of the char combustor will commence in October 1998 at Foster Wheeler Energy Corporation's (FWEC) facility in Dansville, N.Y. The Phase 2 work is being done to support the design of a prototype plant in Phase 3 of the overall project. Utility participation will be solicited in Phase 3 of the overall program to demonstrate the technology at the commercial level.

A simplified version of the greenfields HIPPS arrangement can be applied to existing boilers. Figure 2 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 pulverized char and coal. The existing boiler and steam turbine infrastructure remain intact; however, additional equipment is required on the front end of the plant. 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 [1]. This repowering technology is based upon a totally coal fired scheme, however, there are a number of commercial units applying a similar arrangement, more commonly referred to as “hot windbox repowering”, exclusively firing natural gas [2].

In both the greenfields plant and the repowering application, the development of a char combustor with stable flame characteristics, high carbon conversion, and low NOx generation is critical. A char burner has been designed and will be tested at the CETF in Dansville, N.Y. to support the HIPPS program. This paper addresses the CETF pilot plant arrangement, the burner design, and the test plan for the development of a suitable burner for char combustion.

Facility Description

1. Material Processing

The arrangement of the CETF to support the HIPPS program is outlined in Figure 3. The char feedstock is delivered via truck to the site in one ton supersacks. The char is produced from Pittsburgh #8 coal that has been preheated to liberate most of the volatile matter. Table 1 and Table 2 identify the proximate and ultimate analyses, respectively, for both the char and the original Pittsburgh #8 coal. The compositions defined in these tables represents average values for both the char and coal.

Table 1. Proximate Analysis

	Pittsburgh #8 Coal	Pittsburgh #8 Char
Fixed Carbon	47.25	77.85
Volatile Matter	37.76	1.55
Ash	13.76	20.20
Moisture	1.23	0.40
Total	100.00	100.00

Table 2. Ultimate Analysis

	Pittsburgh #8 Coal	Pittsburgh #8 Char
Carbon	70.51	77.13
Hydrogen	4.92	0.0
Oxygen	4.42	0.03
Nitrogen	1.24	1.05
Sulfur	3.92	1.19
Ash	13.76	20.20
Moisture	1.23	0.40
Total	100.00	100.00

The char is removed from the supersacks and loaded into the coarse char silo utilizing a front-end loader. The char is gravity fed onto a weighbelt feeder, and conveyed into a rotating ball mill for processing. The relationship between the air flowrate and the fuel flowrate dictate the particle size distribution of the char exiting the mill. The inventory of char in the mill is held constant at all times during processing, and the forced draft fan and exhauster operate in conjunction to establish a pressure of -2.0 in. H_20 within the mill. The processed char is pneumatically conveyed through the exhauster and into an outdoor silo with a maximum char storage capacity of 40,000 lbs. Figure 4 compares the particle size distribution of the char entering the ball mill with the size distribution exiting the mill; the fine particle size exiting the mill is expected to promote excellent burner performance. One of the objectives of the HIPPS test program is to define the ideal char size distribution for optimum burner operation, and as such, the particle size distribution of the char exiting the mill is one of the main test variables. In most pulverized coal fired boilers, the mills are directly connected to the burners, and independent control of the boiler and feedstock processing is not afforded. For the HIPPS program, it was essential to de-couple the char processing from the char firing to maintain flexibility within the test program. This arrangement is commonly referred to as an “indirectly fired” system.

2. Feedsystem Design

The pulverized char is metered through a rotary valve and on to a weighbelt feeder. The weighbelt feeder is used only to monitor the char flowrate, while the upper rotary valve is adjusted to control char flow. The lower rotary valve operates at its maximum rate, and serves only as a pressure seal between the char storage hopper and the pneumatic transport line. The pulverized char is conveyed with air through a 2” transport line to the burner, at a solids-to-gas weight ratio of approximately 5:1. Similar feed systems are utilized for concurrent feeding of limestone and coal.

The pulverized coal feed system is designed to provide a source of support fuel for the char feedstock. The absence of volatile matter in the char raises concerns with regard to stable combustion; however, recent studies have been encouraging [3]. Nonetheless, to be used as necessary, the support fuel (Pittsburgh #8 coal) will be pneumatically conveyed with air through a 1-1/2” transport line at a solids-to-gas weight ratio of 1:1, to maintain suitable flame characteristics for an evenly distributed heat flux within the boiler. The system is designed to provide a maximum coal flowrate of 300 lbs./hr. By comparison, the maximum char flowrate to the burner is designed for a nominal 3000 lbs./hr. Stable operation of the burner without support fuel is an essential objective of the overall test program.

Although tests were performed to evaluate the performance of the pyrolyzer subsystem, at Foster Wheeler’s pilot plant facility in Livingston, N.J., the char collected during this test program was of insufficient quantity to support the requirements of the larger scale burner tests at the CETF, in Dansville, N.Y. The maximum pyrolyzer char generation rate at the Livingston, N.J. pilot plant site was nominally 250 lbs./hr., while the test program at the CETF requires a char flowrate of approximately 3000 lbs./hr. (25 MMBtu/hr). In order to provide the quantity of char necessary for the burner test program, a source for commercially produced char was solicited. As mentioned previously, the char was produced from Pittsburgh #8 coal; however, unlike the small quantity of char produced in the HIPPS pyrolyzer, this synthetically processed char was devoid of calcium oxide and calcium sulfide. Limestone was fed concurrently with coal to minimize the risk of agglomeration in the pyrolyzer at the pilot plant in Livingston, N.J. This technical issue will be further addressed at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. Nonetheless, the limestone feedsystem at the CETF was installed to provide a means of adding calcium carbonate in the burner, which immediately calcines in the boiler to calcium oxide, to better simulate the char produced in the partial gasification reactor. The limestone is air pneumatically conveyed at a solids-to-gas weight ratio of 1:1 through a 1-1/2” transport line, and is mixed with the char in the burner.

3. Boiler Design

The design of the boiler at the CETF has been modified to support the needs of the HIPPS project. Since the char is low in volatile matter, it was determined that an arch-fired boiler arrangement would provide the optimum design. The arch-fired boiler, as opposed to the more common wall-fired system, is typically used when burning low volatile anthracite coal. This deficiency in volatile matter makes the fuel harder to burn. In the arch-fired arrangement the flame is directed downward into the boiler to provide for increased particle residence time and improved carbon conversion efficiencies. Combustion air is introduced to the boiler in five different locations as follows:

1. Feedstock transport air (FTA) to convey the material to the burner.
2. Wall air (WA) to provide combustion air to the lower section of the boiler.
3. Burner air (BA) to convey the feedstocks through the burner.
4. Tertiary air (TA) to provide a swirling component to the burner flame.
5. Overfire air (OFA) to enhance combustion staging for NOx control.

Airflow distribution is one of the main variables of the HIPPS test plan. Total air flow is adjusted to maintain a specific oxygen level at the boiler exit. It should be noted that the forced draft and induced draft fans are operated concurrently to maintain the boiler pressure at -0.7 in. H_2O. The boiler is outfitted with a water seal to provide for withdrawal of bottom ash and to maintain stable operating conditions.

The flue gas is conveyed out of the boiler and through a series of back-end heat exchangers. These exchangers include a water cooled gas cooler, a tubular air heater, and the heat pipe air heater. Following the bank-end heat exchangers, the flue gas continues through a baghouse, for removal of fine particulate, before final discharge through the stack. In the HIPPS commercial design, the exhaust air from the gas turbine provides the oxidant for char combustion; at CETF a flue gas recycle system will be utilized to simulate this condition. In the HIPPS commercial design, the oxygen concentration of the vitiated air exiting the gas turbine is approximately 15 percent, by weight. The flue gas and air mix at CETF will be controlled to maintain representative gas turbine exhaust conditions.

Char Burner Design

The elevation and plan views of the char burner designed for the HIPPS test program at the CETF are illustrated in Figure 5. Char is pneumatically conveyed to the burner and discharged through a 3" Sch. 40 pipe into the top cover plate of the burner. The burner air is admitted through a 4-3/4" by 11-1/2" rectangular inlet duct tangential with the upper cylindrical portion of the burner. The burner geometry is similar to that of a standard cyclone. As the burner air enters the barrel, it is initially mixed with the char entering through the top plate. The upper cylindrical portion of the burner has an inner diameter of 23" and an overall length of 1'-11". The burner cone converges from the 23" cylindrical inner diameter to mate with an 8" Sch. 40 pipe in a total axial length of 1"-11". Limestone is also pneumatically conveyed into the top plate of the burner, and is introduced 180 degrees counterclockwise of the char injection point. As part of the overall test program, the burner air is to be heated to different temperatures to simulate the full range of conditions for the commercial design gas turbine exhaust stream. As previously mentioned, the commercial HIPPS plant utilizes the exhaust from the gas turbine for combustion of the char. The limestone and the char are mixed with the heated burner air (approximately 800 ^{o} F) in an effort to preheat these feedstocks prior to combustion within the boiler. For the low volatile char, this preheat is deemed necessary to promote complete combustion. Thermocouples are added to the straightening vanes in the 8" sch. 40 char discharge pipe to measure the resultant temperature of the two phase (air-char-limestone) mixture. These straightening vanes are outfitted with a set of "push/pull" rods providing for variable vane positioning.

Pulverized coal, to be used as necessary, to maintain stable burner combustion, is introduced through a 304 SS tube with an outer diameter of 2-1/4" and a wall thickness of 1/4". This central tube extends all the way through the burner and admits the coal support fuel directly into the boiler. Under operating conditions, this central core of Pittsburgh #8 coal will be surrounded by the char. The outer diameter of the coal injection pipe is covered with multiple layers of Fiberfrax ceramic fiber paper to insulate the coal from the preheated burner air. This insulation is applied to prevent the coal from becoming too hot, and coking up the central injection tube.

The final HIPPS char burner component is the tertiary air swirler illustrated in figure 6. These swirler vanes are positioned around the 8" Sch. 40 burner discharge pipe and are flush with the interior arch wall of the boiler. The inner diameter of the vane support ring measures approximately 8-7/8", allowing for an 1/8" annular clearance with the outside diameter of the 8" Sch. 40 pipe. In a similar design to the "push/pull" rods for the straightening vanes, the position of the swirler vanes for the HIPPS char burner is also adjustable. Many commercial pulverized coal fired boilers utilize tertiary air swirl to enhance burner performance, and as such, the HIPPS char burner will demonstrate its application for the combustion of char.

Burner Test Plan

The fifteen variables, identified in Table 3, 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 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) methods will be 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 major criteria for each test are combustion stability (determined by both visual observation and flame scanner measurements taken throughout the furnace), NOx emission, and carbon conversion (analyzed by loss of ignition (LOI) tests of actual bottom ash and flyash samples). The “optimal” burner design will be selected as the combination of burner and furnace flow rates producing the best combustion and flame stability and the lowest NOx generation . In the first phase of experimental testing, an “optimum” burner design will be selected by exploring the effects of the “burner” variables (variables 1-8 of Table 3). Table 4. presents the test matrix for phase 1 of the overall burner test program. In the second phase, the boundaries of the “optimum” burner design will be investigated by varying the HIPPS system parameters (variables 9 –15 of Table 3). Testing and interpretation of results will be guided by the HIPPS burner CFD analyses and two-phase tests that have already been performed.

Table 3. 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, middle, bottom)	1	1st set 100, 100, 20	2nd set 50, 50, 30	3rd 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	^{o}F	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 4. 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

Summary

The development of an efficient char burner is critical to both the greenfields and repowering HIPPS technologies. The low volatile content of the char presents significant challenges in the design of a suitable burner. Foster Wheeler's test facility in Dansville, N.Y. has been modified to meet the requirements of the HIPPS burner development program. In particular, the simulation of the gas turbine exhaust stream has been accomplished with the use of a flue gas recycle fan to maintain reduced oxygen levels (15 wt. %), and a gas fired duct burner to raise the temperature of the burner air to approximately 800 ^{o}F. Previous commercial experience in burning low volatile anthracite coals throughout the world has prompted the use of the arch fired configuration at the CETF. Arch firing provides for a longer particle residence time in the boiler since the flame is directed downward, and should serve to enhance overall carbon conversion efficiency. The test facility has been designed for indirect firing, where char milling is been de-coupled with char firing. Since the char particle size distribution is one of the HIPPS program test variables, the indirect system affords greater testing flexibility.

An innovative char burner has been designed for initial testing at the CETF. Pulverized char and burner air are mixed within the burner to preheat the fuel prior to combustion within the boiler. This preheating process is deemed necessary because of the low volatile content of the char. The burner has been outfitted with a central coal injection nozzle to provide a means of support fuel, if necessary, to maintain stable combustion. Swirling of the tertiary air stream is utilized to promote flame stability, and overfire air is added to minimize the generation of NOx.

Based upon preliminary numerical burner/boiler modeling and a series of two phase "cold" model tests, fifteen variables have been identified as important to investigate during the HIPPS experimental program at the CETF. In order to achieve comprehensive results with a minimum number of tests, a statistical design of experiments (SDOE) methodology has been employed. Burner performance will be quantified by evaluating three criteria – combustion stability, NOx emission levels, and overall carbon conversion.

Future Work

Once the char combustion tests at the CETF have been completed, additional research will focus on the development of a larger scale pyrolyzer system at the Wilsonville, Alabama, Power Systems Development Facility (PSDF). The pyrolyzer system tested at Foster Wheeler's pilot plant facility in Livingston, N.J. represents a one-tenth scale version of the system at the PSDF. The char generation rate of the pyrolyzer at the PSDF is an exact match for the char utilization rate at the CETF. Although the PSDF is not outfitted with a char burner system, a portion of the char generated in the pyrolyzer during this experimental program will be collected and shipped to the CETF for future combustion tests. The PSDF includes a topping combustor and a gas turbine, and as such, affords the HIPPS program an opportunity to demonstrate integrated operation.

Bibliography

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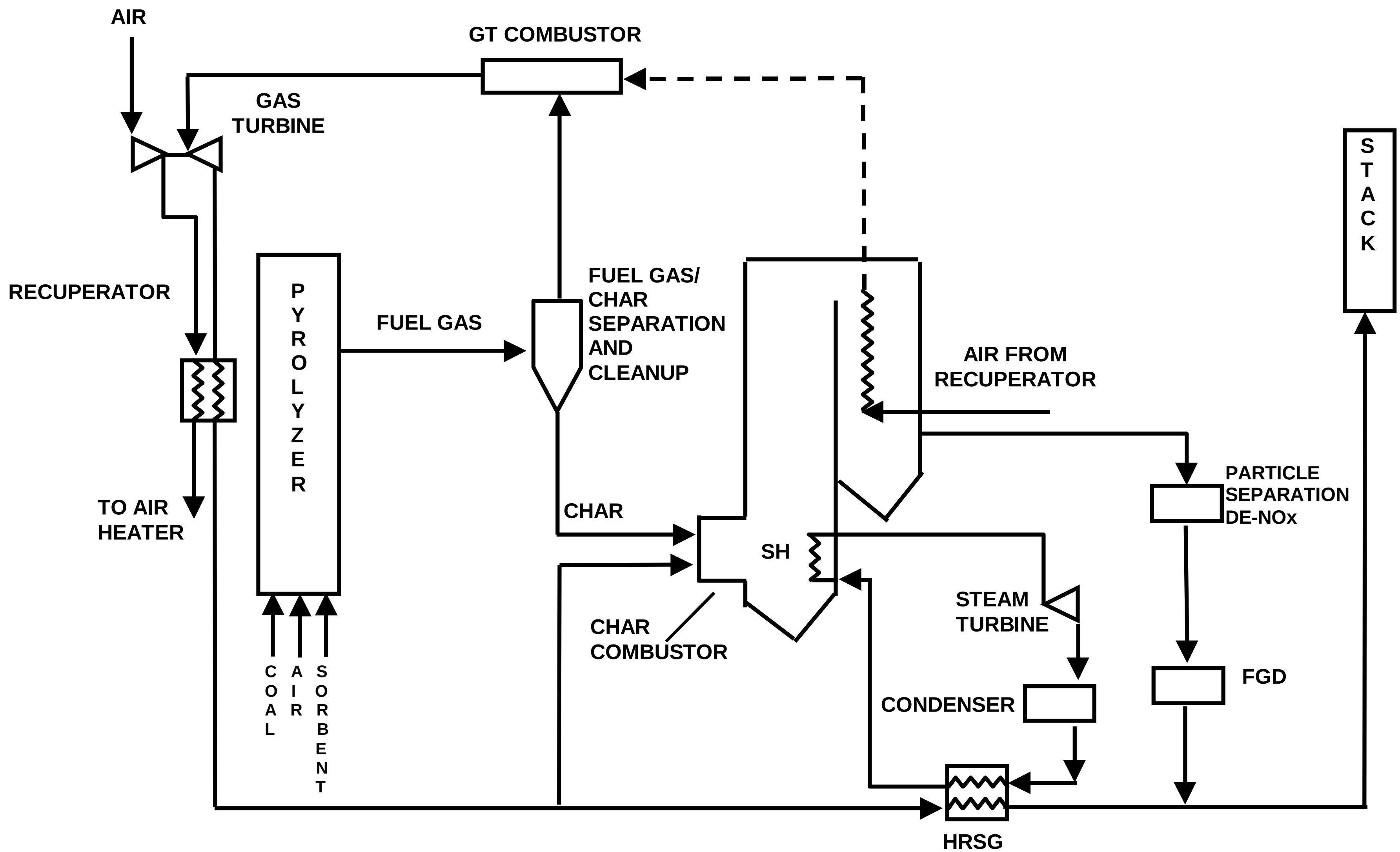
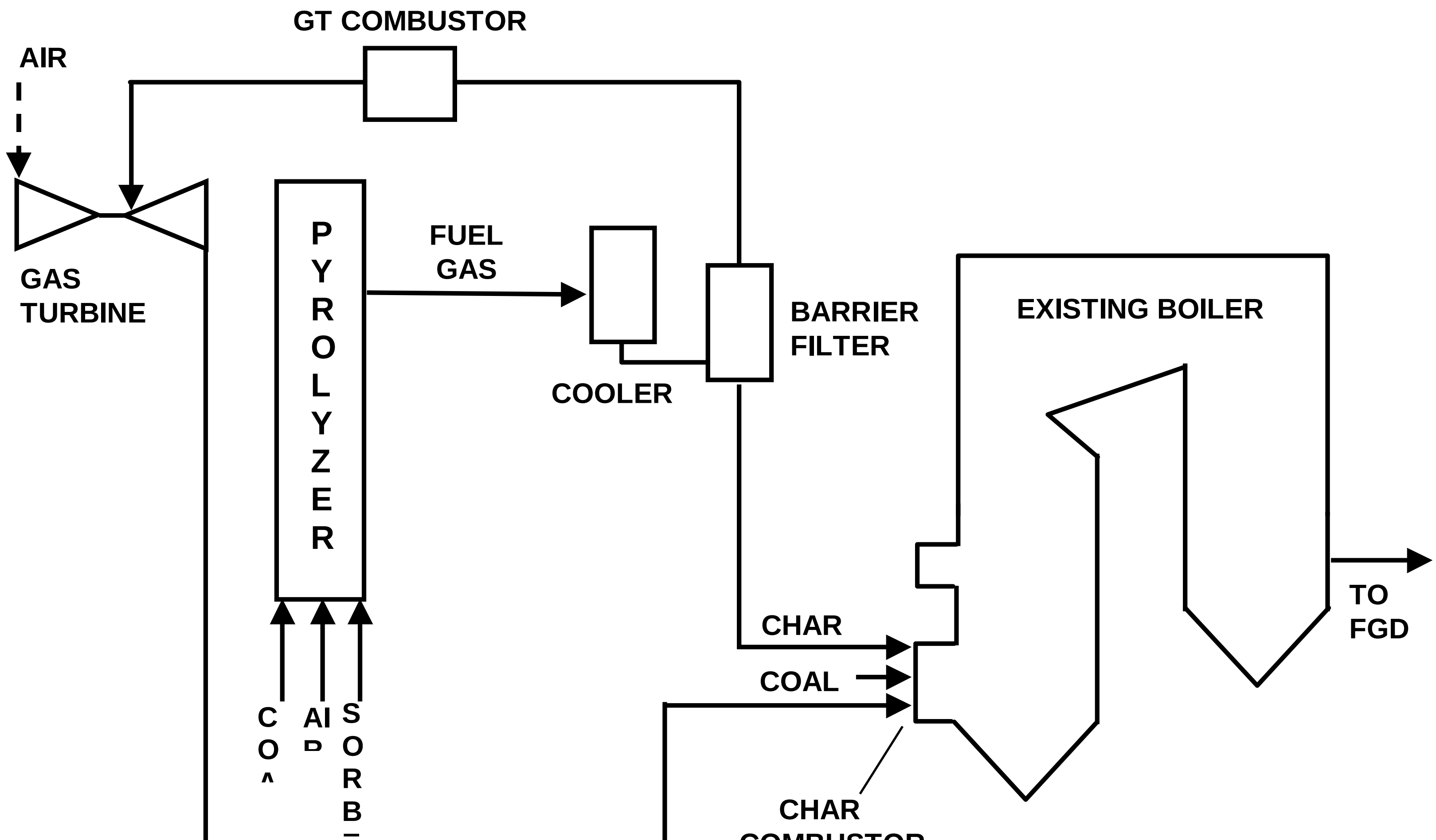
Figure 1



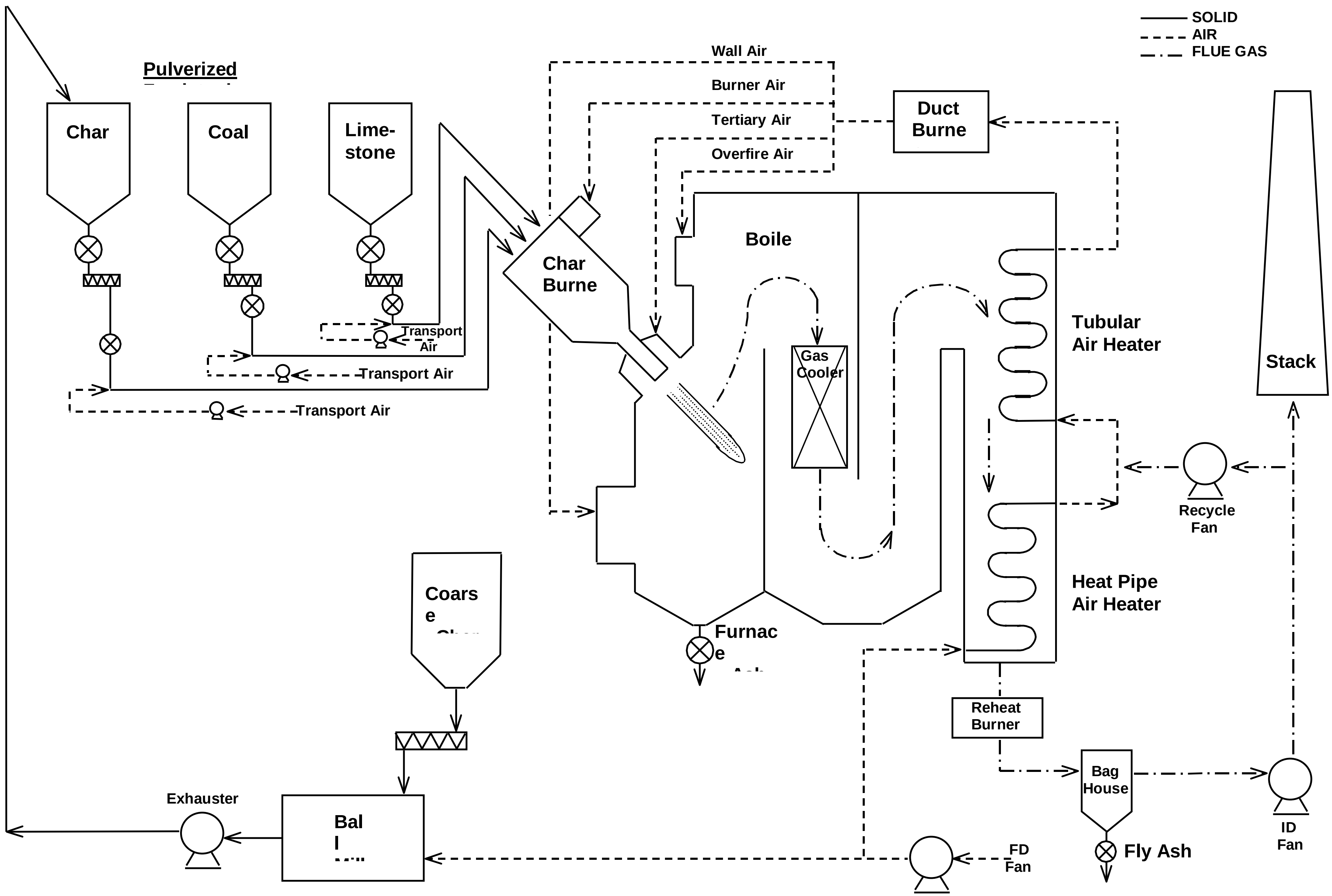
Greenfields HIPPS Process Flow Diagram

Figure 2



Simplified HIPPS Repowering Process Flow Diagram

Figure 3



Combustion & Environmental Test Facility (CETF) HIPPS Burner Program

Figure 4

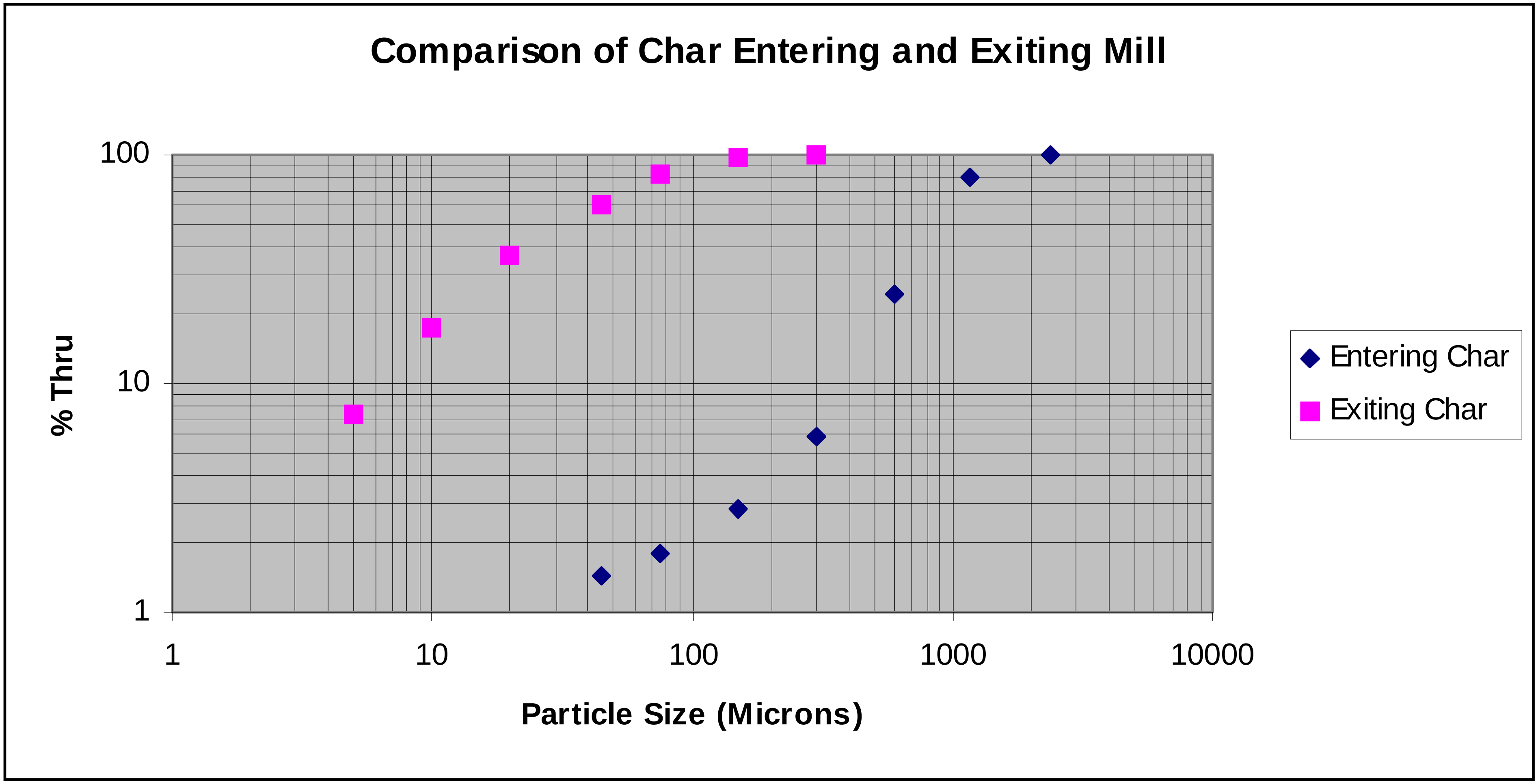
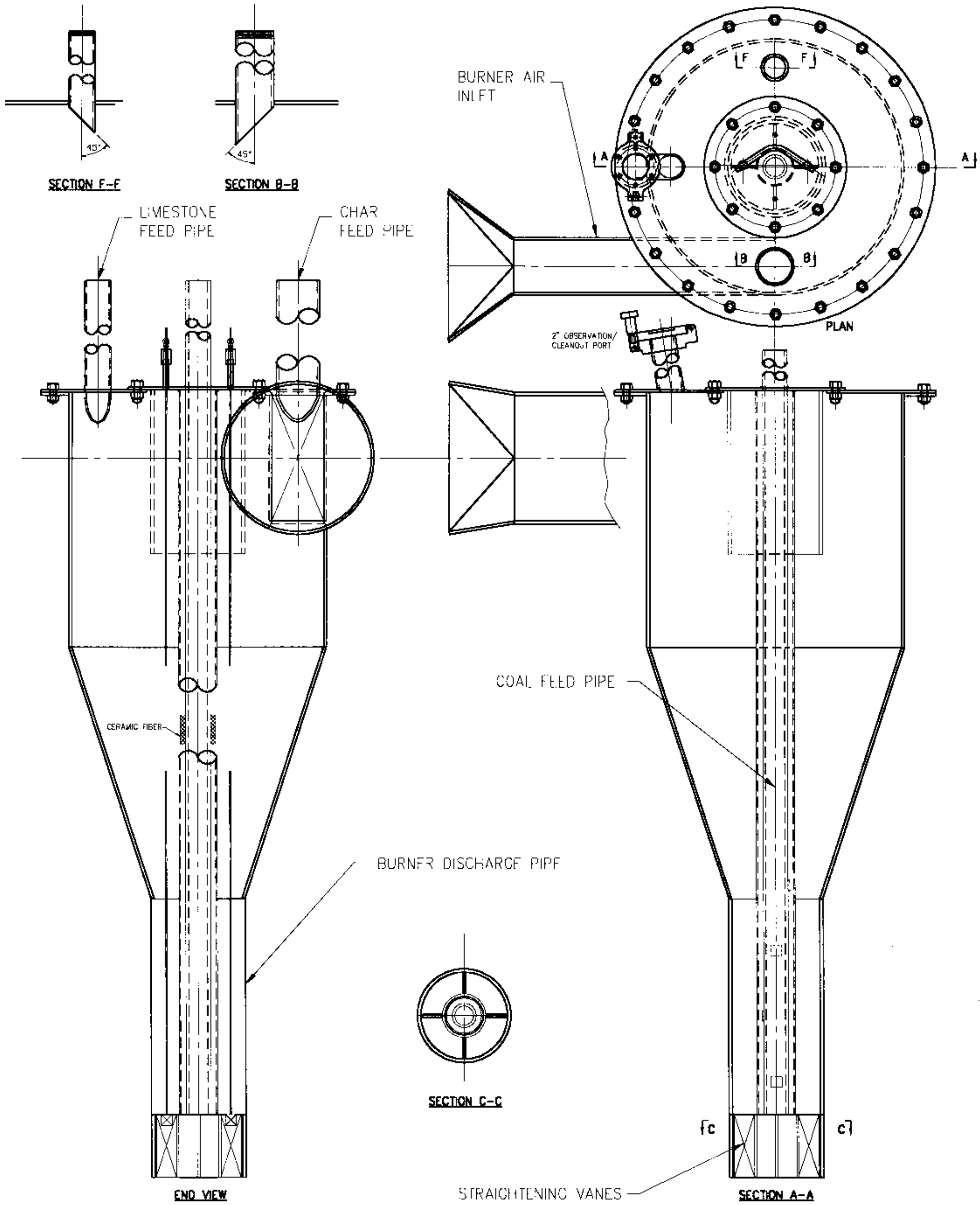
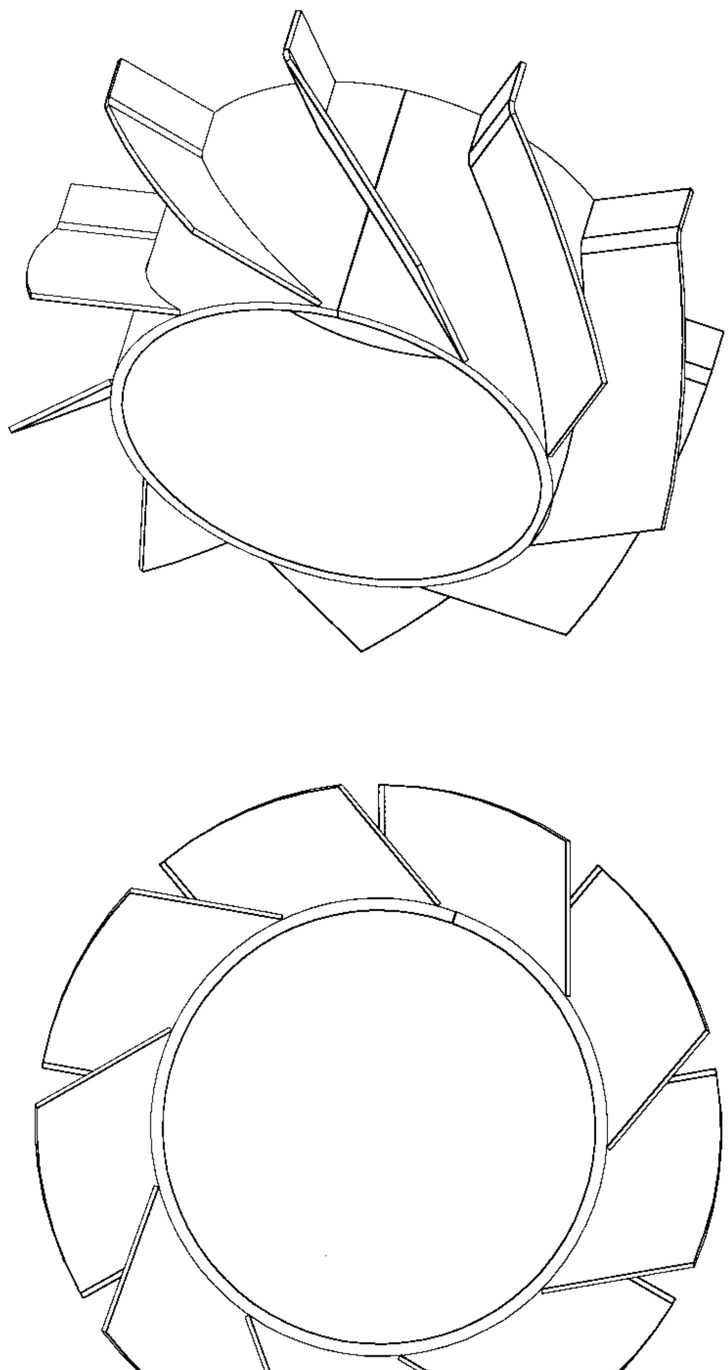

Comparison of Char Entering and Exiting Mill
100
10
1
% Thru
1
10
100
1000
10000
Particle Size (Microns)
Entering Char
Exiting Char

Figure 5



HIPPS Char Burner

Figure 6



Tertiary Air Swirler Fan