ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH-PERFORMANCE POWER SYSTEMS

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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). 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.

During this quarter, initial char combustion tests were performed at the CETF using a Foster Wheeler commercial burner. These preliminary tests were encouraging and will be used to support the development of an innovative char burner for the HIPPS program.

The CETF design effort continued through this quarter with the completion of the following systems:

1. Char Storage and Transport System
2. Reheat Burner

The char storage system is required for the HIPPS program because the ball mill needs to be de-coupled from the burner. This de-coupling of the mill and the burner allows greater flexibility in changing char particle size distribution – one of the main test variables under the HIPPS program. The reheat burner is employed to prevent condensation of the flue gas in the baghouse.

TABLE OF CONTENTS

PAGE NO.

LIST OF FIGURES

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 that 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.

Initial char combustion tests were performed during this quarter at the Combustion and Environmental Test Facility in Dansville, NY. These tests demonstrated that char combustion could be sustained without co-firing natural gas. The preliminary tests were performed with a conventional commercial burner used typically for anthracite coal. Further tests are planned with a burner specifically designed for char.

A two-phase cold model is being designed to support the overall design of the actual HIPPS burner to be tested at the CETF. The cold model will represent a ½ scale version of the HIPPS char burner. In a commercial plant, overall burner pressure drop is an important design constraint since ID and FD fan power requirements influence plant efficiency. Two–phase cold model tests will be run to confirm estimated burner pressure drop, and to support the final hydrodynamic design of the "hot" burner.

The design of the char storage system , and the reheat burner were completed during this quarter. The char storage system will be used to de-couple the operation of the ball mill and the burner, and therefore, afford additional flexibility in altering char particle size distribution. The particle size distribution of the char is an essential variable in the overall combustion program. For instance, if initial test results demonstrate low carbon conversion efficiencies, the mill conditions will need to be varied to produce a finer char feedstock for the burner. The char feed system has been designed for two-phase pneumatic transport.

The reheat burner as identified on the overall CETF schematic (Figure 4.), was designed for the purpose of preventing flue gas condensation in the baghouse. The baghouse is located outdoors, and serves as the final particulate collection device before the flue gas enters the stack. The burner has a

capacity of approximately 3 MMBtu/hr. and is fired with natural gas.

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.

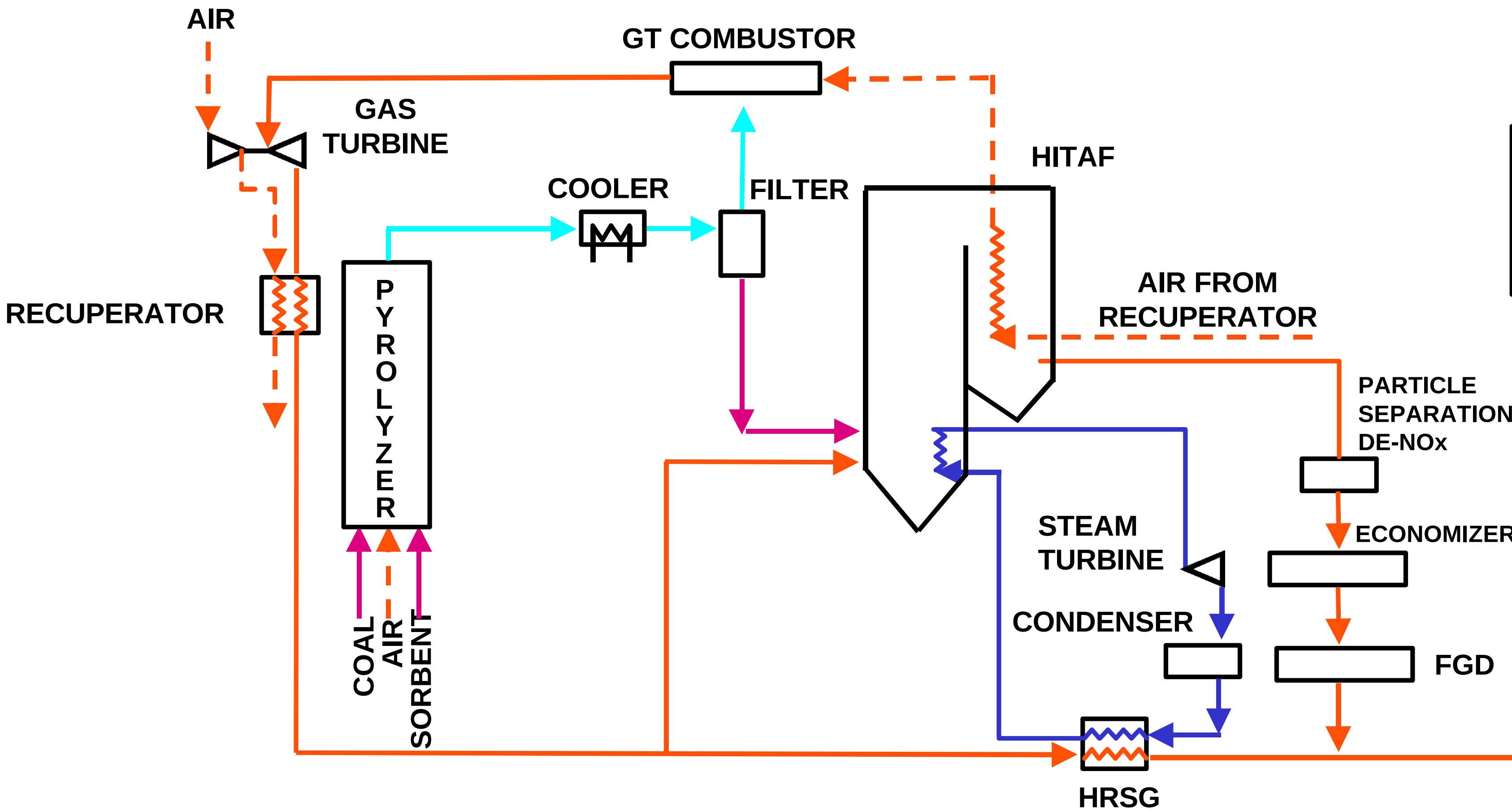

Figure 1 All Coal Fired HIPPS

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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.

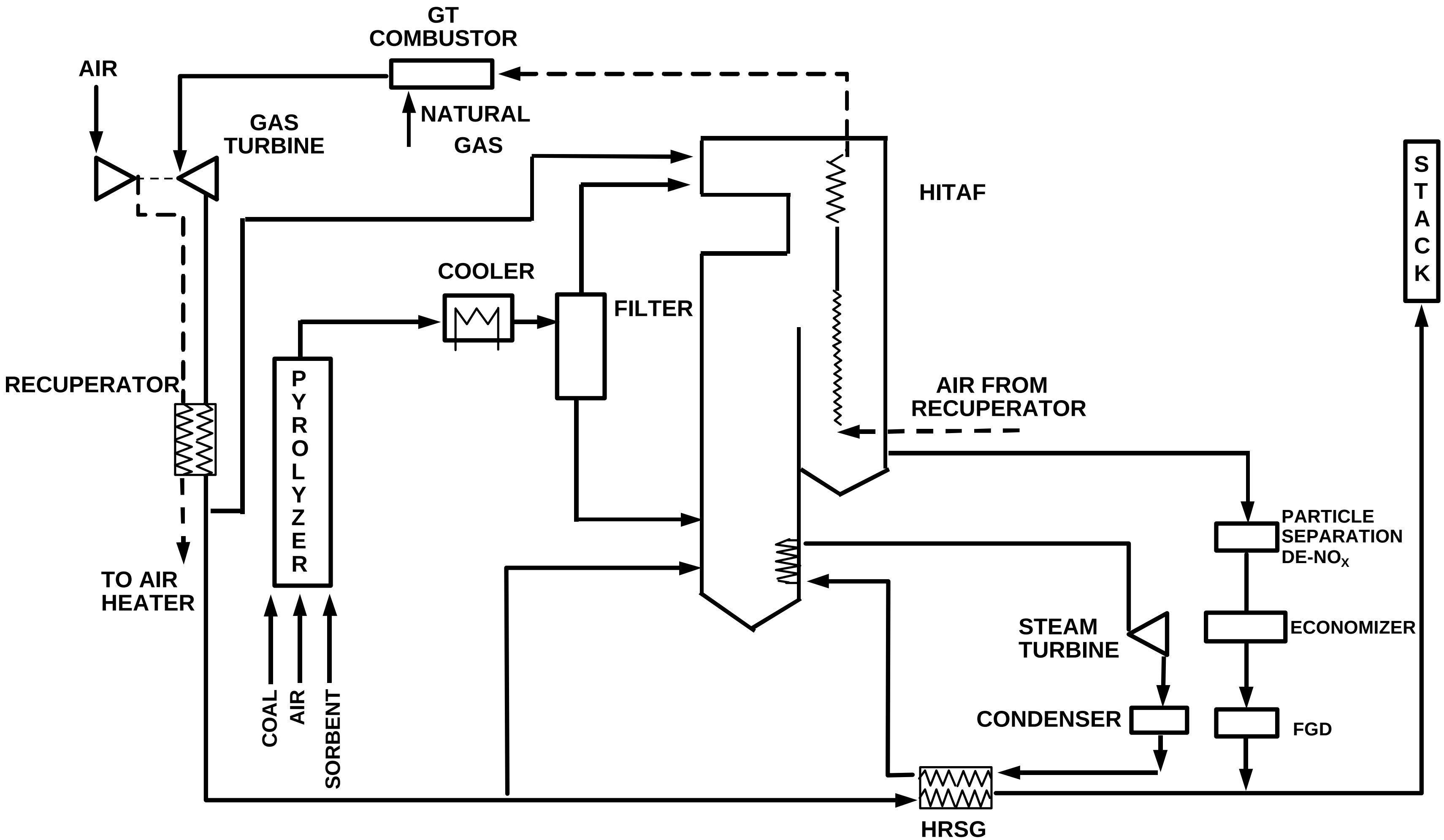

Figure 2   35-Percent Natural Gas HIPPS

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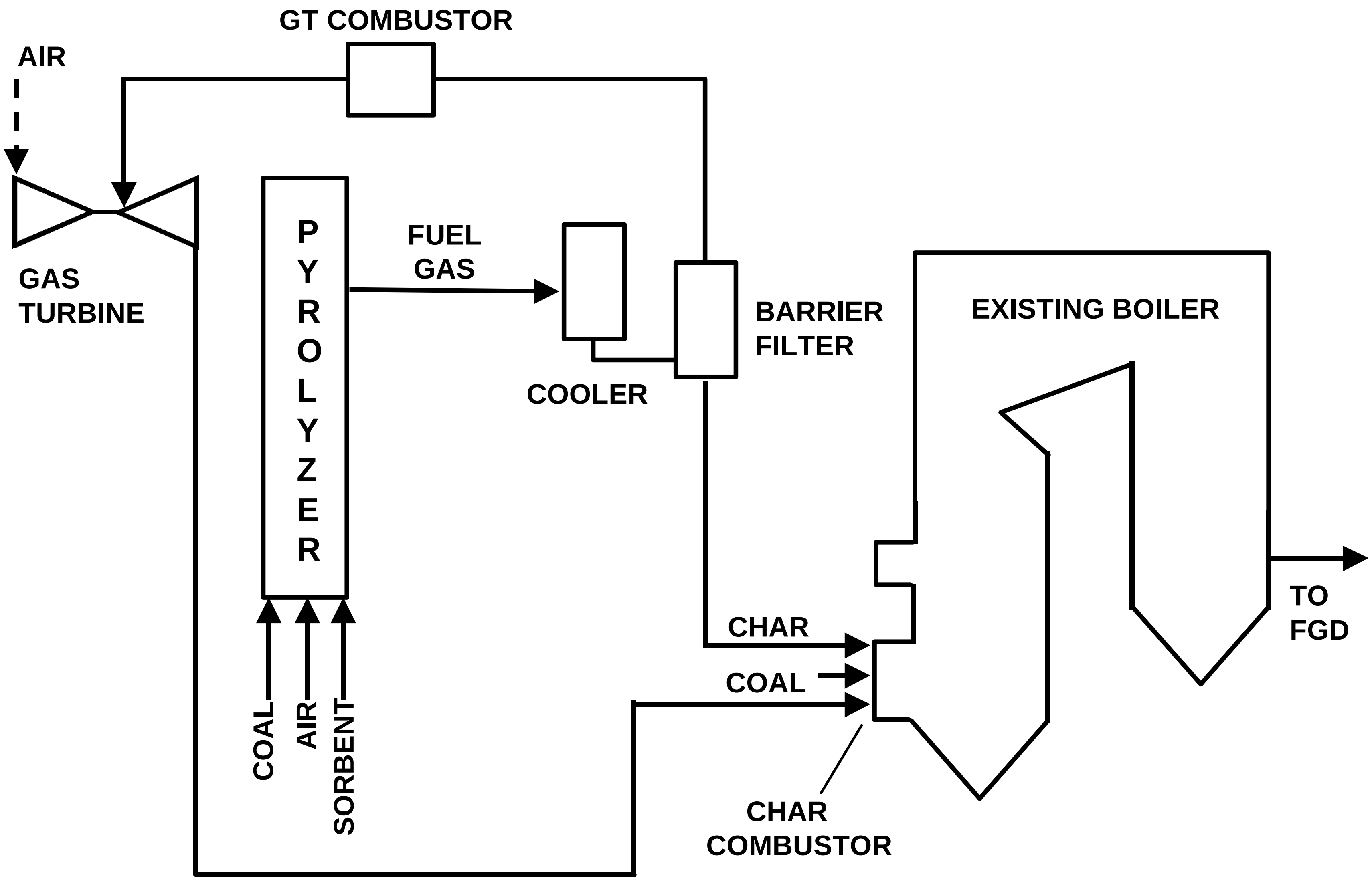
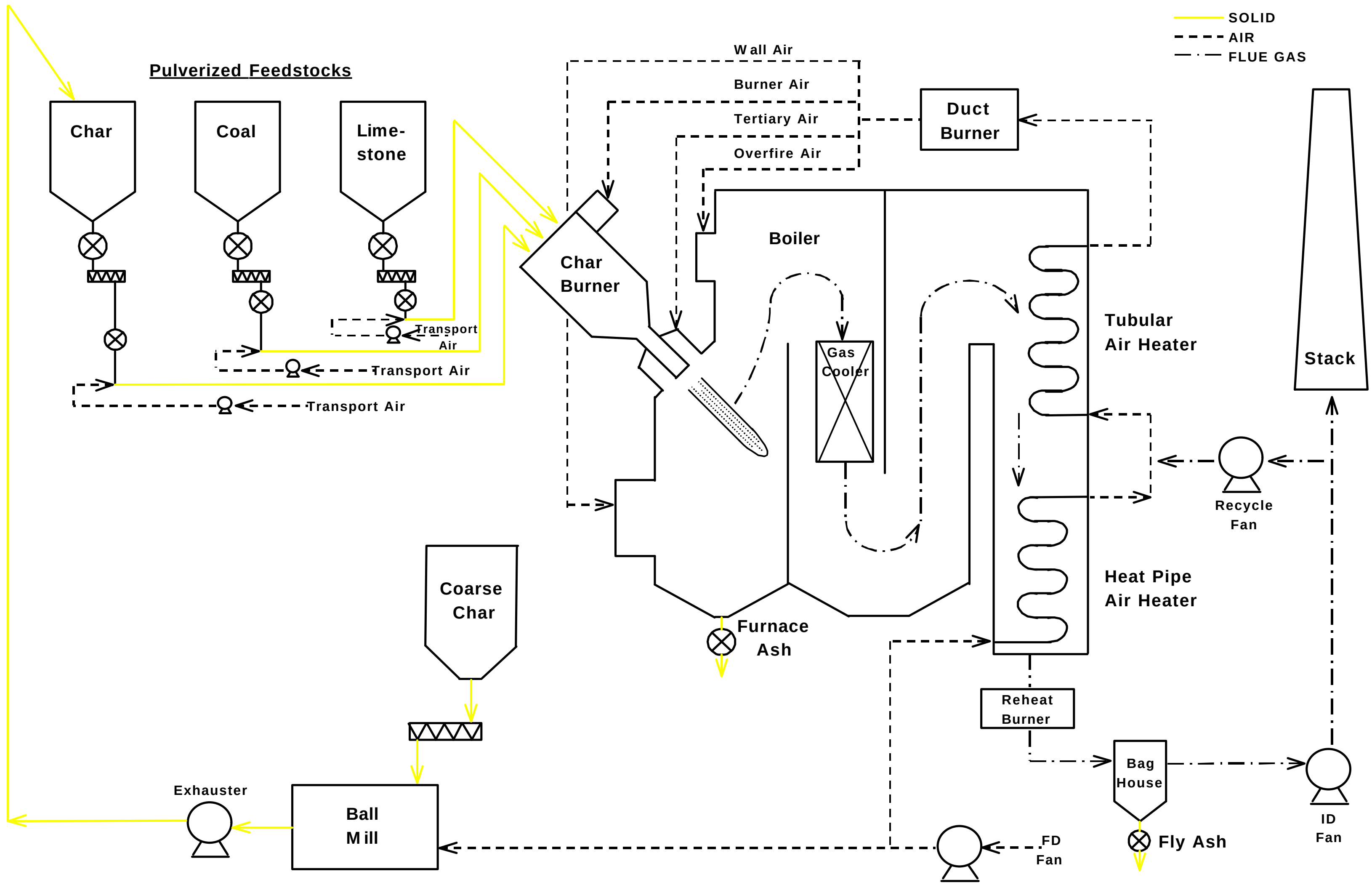


Figure 3 Simplified HIPPS Repowering Process Flow Diagram



Combustion & Environmental Test Facility (CETF) HIPPS Burner Program

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 Model Test

A HIPPS char combustor will 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 HIPPS fuel injector is planned at the Two-Phase Cold Flow Test Facility in Livingston. Based on fan performance and the Cold Flow Test Facility plan area availability, it was decided that a one-half scale CETF char injector model would be fabricated for two-phase flow testing. Preliminary discussions on the two-phase testing focused on pressure drop, primary air and pumice thermal mixing, and erosion of the model's inside paint layers. Data on pressure and temperature data in the model will be obtained, from which performance predictions can be made. Test flow rates will be based on modeling momentum and velocity similarity with the firing test conditions at the Combustion and Environmental Test Facility (CETF).

The major parameters that will be varied during the two-phase testing include primary air flow, primary air temperature, tertiary air flow, pumice flow rate, burner model vane position (extended or retracted), and placement of tertiary air swirler. Primary air temperatures and flows will be varied in order to model the changes in the inlet and outlet burner temperatures due to mixing of the hot primary air and the cooler char that occur in the actual burner. Solids flow and primary air flows will also be varied for different operating conditions. The char and sorbent will be modeled as pumice entering the burner as one stream.

Sizing calculations of the full scale CETF injector were made based on Foster Wheeler Energy Corporation (FWEC)Engineering Design Standards and combustion equipment design experience. Mass and energy balance calculations were made at different locations of the injector in order to size inlet and outlet areas of the injector, tertiary air tube, and tertiary air swirler. Conceptual design of the CETF HIPPS burner was made from these calculations and is shown in Figures 5., 6., 7.. A one-half scale cold flow test model will be developed from this full-scale CETF design concept.

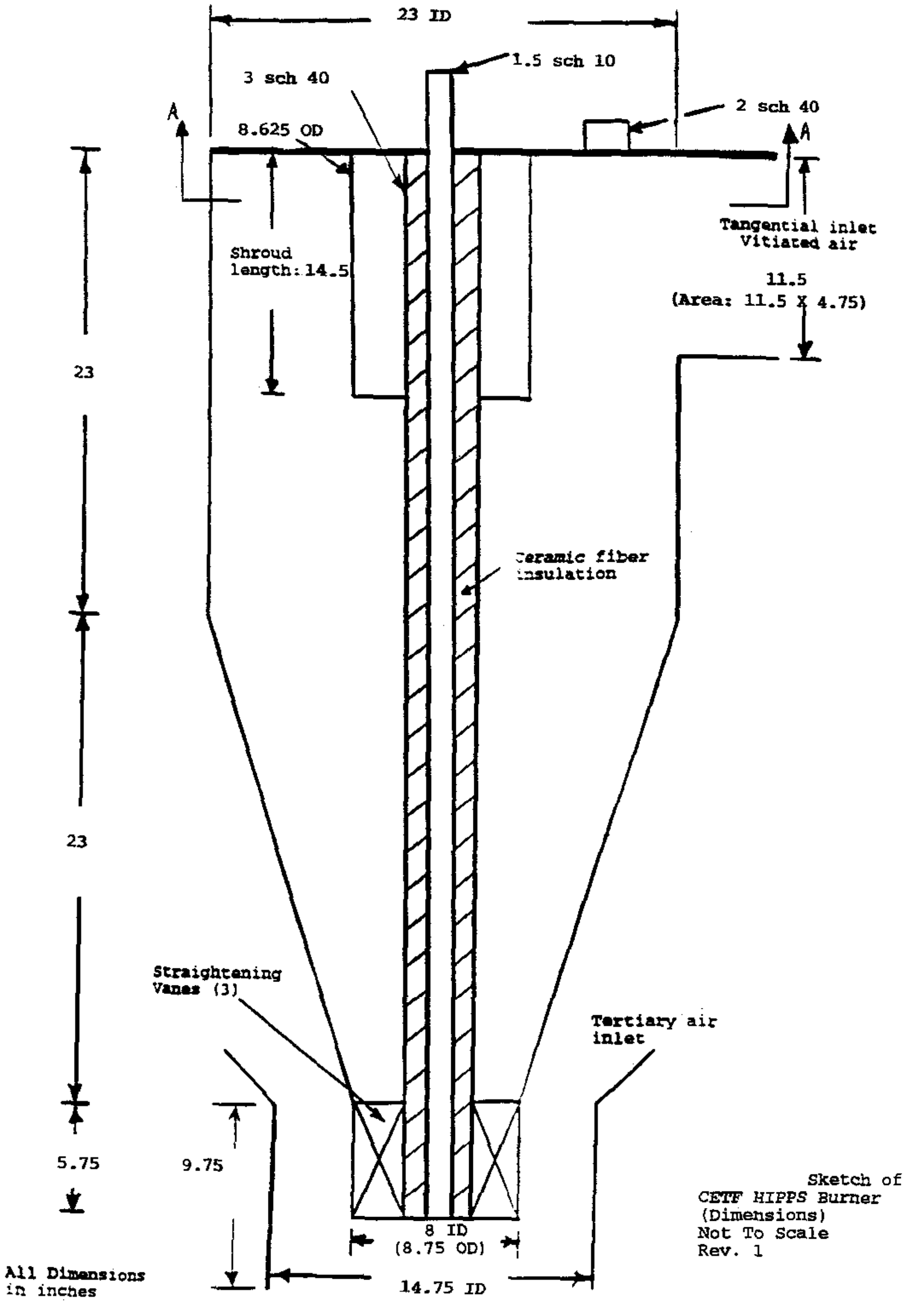
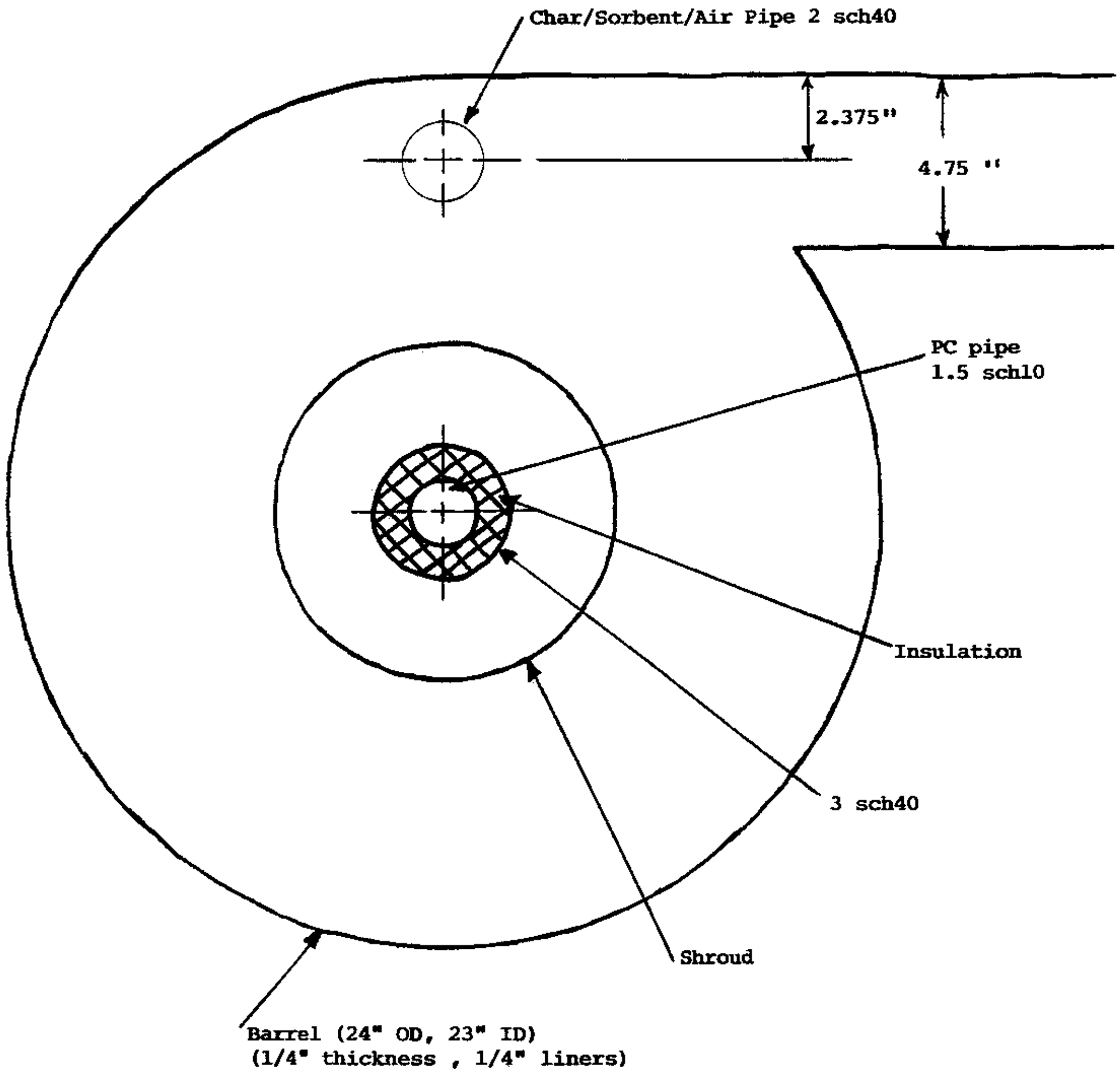

23 ID
1.5 sch 10
3 sch 40
2 sch 40
A
8.625 OD
A
Shroud
length: 14.5
Tangential inlet
Vitiated air
11.5
(Area: 11.5 X 4.75)
23
Ceramic fiber
insulation
23
Straightening
Vanes (3)
Tertiary air
inlet
5.75
9.75
8 ID
(8.75 OD)
14.75 ID
Sketch of
CETF HIPPS Burner
(Dimensions)
Not To Scale
Rev. 1
All Dimensions
in inches

Figure 5



Sketch of CETF HIPPS Burner (Section A-A)

Figure 6

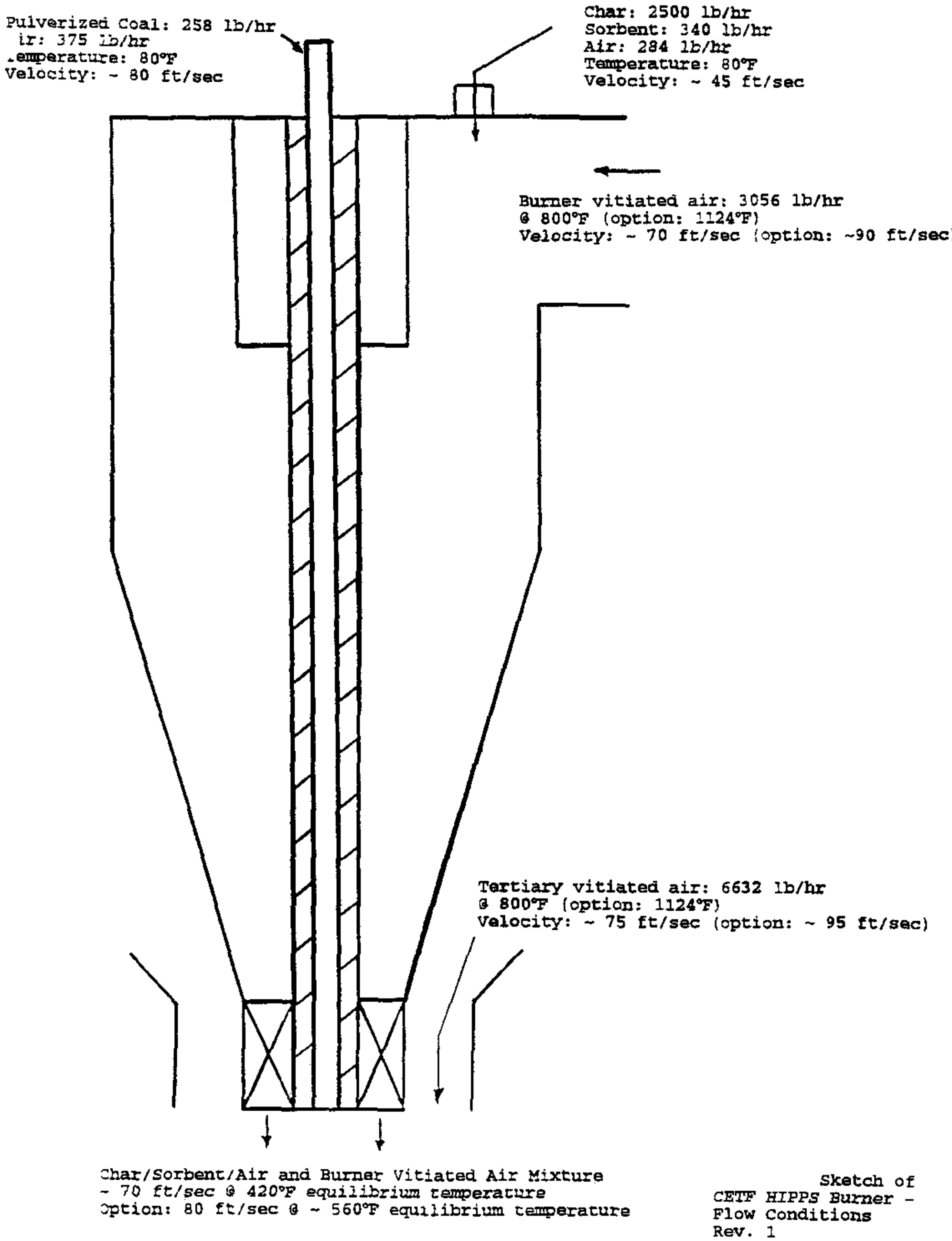

Pulverized Coal: 258 lb/hr
ir: 375 lb/hr
.emperature: 80°F
Velocity: ~ 80 ft/sec
Char: 2500 lb/hr
Sorbent: 340 lb/hr
Air: 284 lb/hr
Temperature: 80°F
Velocity: ~ 45 ft/sec
Burner vitiated air: 3056 lb/hr
@ 800°F (option: 1124°F)
Velocity: ~ 70 ft/sec (option: ~90 ft/sec)
Tertiary vitiated air: 6632 lb/hr
@ 800°F (option: 1124°F)
Velocity: ~ 75 ft/sec (option: ~ 95 ft/sec)
Char/Sorbent/Air and Burner Vitiated Air Mixture
~ 70 ft/sec @ 420°F equilibrium temperature
Option: 80 ft/sec @ ~ 560°F equilibrium temperature
Sketch of
CETF HIPPS Burner -
Flow Conditions
Rev. 1

Figure 7

Task 3 - Subsystem Test Unit Design

Subtask 3.2 - Char Combustion Subsystem Design

For the char combustor testing at the Combustion and Environmental Test Facility (CETF) in Dansville, NY, an indirect firing method has been designed. This method is designed with a silo coupled to a feed system for storage and pneumatic transport of the fuel to the burner. The storage silo will have the provision to be filled either from the ball mill exhauster located at the CETF, or by means of pneumatic transport off a truck. If fuel is delivered that doesn't meet the fineness requirement for the test matrix, it can be fed into the ball mill located on site, crushed to the required fineness, and pneumatically transported from the mill to the storage silo via the exhauster and a 12" transport pipe. If fuel is delivered by truck with the required fineness, there is a provision for the truck to attach to a 4" transport pipe and pneumatically transport fuel into the silo.

The storage silo was designed with a usable storage capacity of approximately 1800 ft^3, with a 12' diameter and approximately a 28' eave height (Figure 8.). With the char density of approximately 22 lb/ft^3, the storage in the silo is roughly 40,000 lbs of fuel. The silo was designed with a 60º hopper and a 6' diameter discharge. There will be four (4) level probes in the silo, and the cone will have ten (10) 1" half-coupling openings for nitrogen blanketing of the fuel. Beneath the silo is a bin activator section, which holds 36 ft^3, has a 6" diameter exit, and has a vibrating motor to assist fuel exiting the silo. The char silo will be equipped with a bin vent filter with 530 ft^2 of cloth area and have a pulsing mechanism that will activate at any time when fuel is entering or exiting the silo.

The silo will be equipped with four (4) explosion vents, 30" X 60", located around the circumference at the upper 6' of the silo, that provide 50 ft^2 of venting area. Calculations for sizing of these vents were based on a dust classification of ST-1 and fuel with a K_{st} = 151, representing a worse case scenario for fuel in the silo. The roof of the silo will have four (4) fog nozzles mounted for the injection of CO_2, or water, in case of a silo fire or fuel smoldering. This system will be activated on either a high reading on a CO monitor located in the freeboard of the silo or on registering temperature rise in any two (2) of six (6) RTD's located at two elevations of three (3) RTD's each in the silo.

An explosion vent has also been designed on the 12" transport line that runs from the mill exhauster to the char silo. This will provide explosion protection for the equipment located upstream of the char silo in the event of a char silo explosion. There exists the potential for flame propagation up the 12" transport pipe from the silo, building pressure as it goes. The vent will be installed on a "Y" off the pipe 20º from horizontal, oriented with the "Y" pointing upstream so the flame will "see" the vent and so no fuel will plug the line. The vent will be installed 15' – 20' from the silo giving the flame time to "see" the vent.

An 8" discharge chute has been designed for removal of smoldering fuel from the silo. It will be located at the lowest possible point on the bin activator section. This chute will be equipped with a nitrogen port and a water spray ring at the tip for inerting and cooling purposes. The intent is to discharge smoldering fuel, if possible, into a water filled dumpster to prevent a fire and/or explosion in the silo.

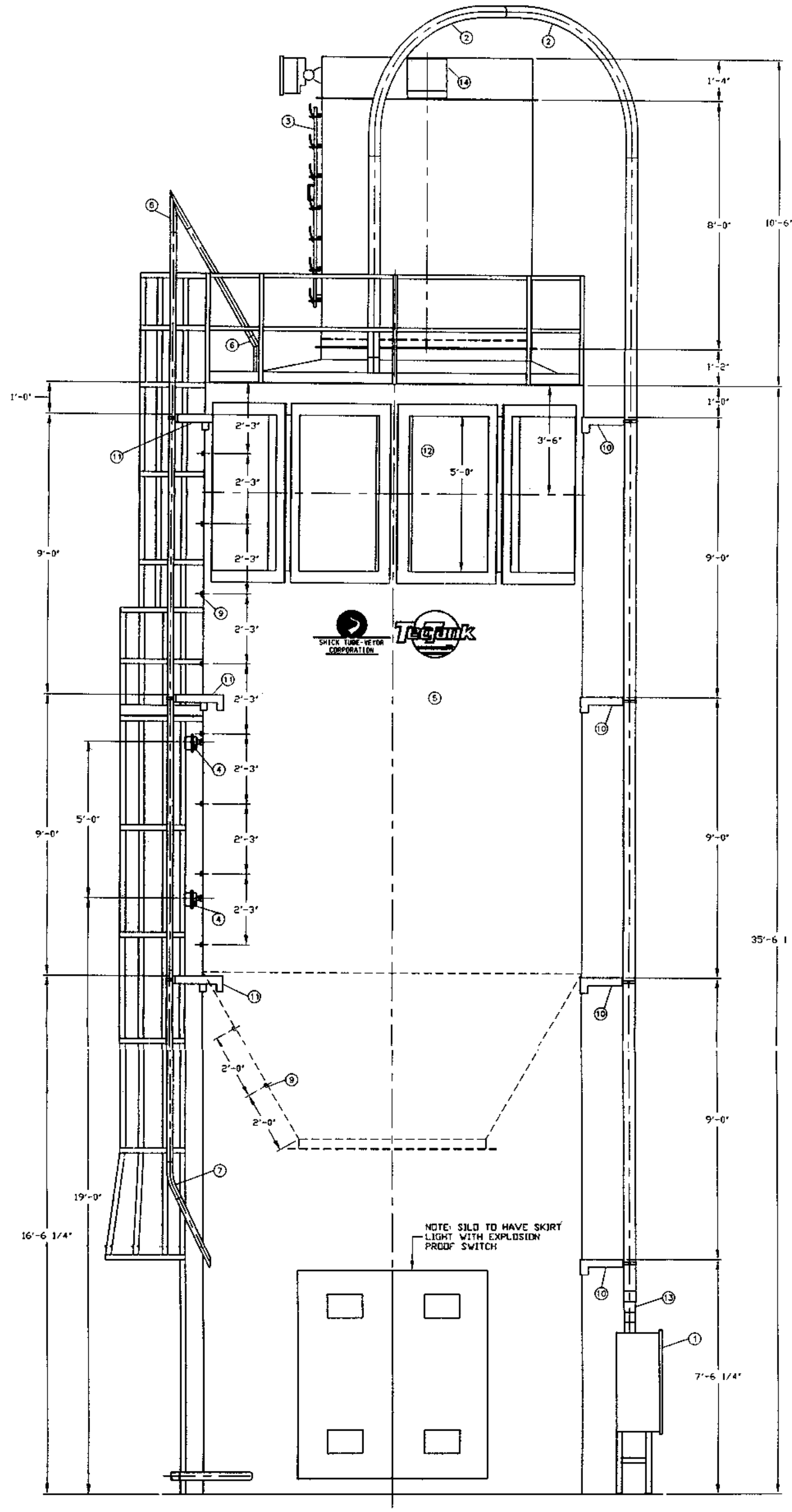


Figure 8 Char Storage Silo

Located beneath the bin activator will be the feed system for pneumatically transporting char to the burner. The system was designed with two rotary valves, a weighfeeder, and a positive displacement blower (Figure 9.) The transport line will be 2" Schedule 40, carbon steel piping and the blower was designed to provide 110 inlet CFM of air to transport the char to the burner. The size of the transport pipe was determined to reduce the risk of particles settling in the transport pipe as well as to keep pressure drop of the transport line within the limits of the blower. The system was designed for a pressure drop of approximately 6 psi and a transport velocity of 79 fps with 30' of vertical and 40' of horizontal piping and a nominal char flow rate of 2,500 lb/hr. The pressure drop was determined using Particulate Solids Research Institute's (PSRI) Kanno and Saito correlation for dilute phase conveying. The particle terminal velocity was calculated using a correlation from PSRI, and was found to be 49 fps. This assures little or no settling will occur in the transport pipe.

One of the rotary valves will be located between the weighfeeder and the transport line. The purpose of this device will be to provide a pressure seal between the transport line and the weighfeeder. The weighfeeder will be used to indicate the amount of fuel being fed to the burner while the second rotary valve, located between the feeder and the bin activator, will be used to meter the char onto the weighfeeder and provide a positive seal above the weighfeeder. The lower rotary valve will run at a constant speed and has been sized to handle the maximum flow from the weighfeeder of 4,000 lb/hr. The weighfeeder is capable of variable speed, but the upper rotary valve will be metering the char flow. A control loop in the control system will compare the setpoint asked for by the operator with the output of the weighfeeder and vary the upper rotary valve speed accordingly.

The boiler located at the Combustion and Environmental Test Facility (CETF) in Dansville, NY was designed for a fuel heat input of 75 MMBtu/hr. Under normal operating conditions the temperatures in the baghouse are above the dew point and the baghouse operates fine. Under some turndown experiments, problems occurred in the baghouse where the temperatures fell below the dew point, condensation formed on the bags, and high pressure drop across the baghouse became an operational concern.

The char burner designed for testing at the CETF has a fuel heat input of 30 MMBtu/hr. Under normal operating conditions for this burner, temperatures in the baghouse are expected to fall below the dew point. To ensure that problems with the baghouse don't occur during the HIPPS burner testing, a flue gas reheat burner was designed.

To provide the appropriate amount of heating for the flue gas, whose flow rate can range up to approximately 65,000 lb/hr, a 3.0 MMBtu/hr natural gas burner has been purchased to be installed in the flue gas duct upstream of the baghouse. The burner package includes an air blower to provide it's own combustion air (Figure 10.) Under normal char burner operating conditions, the reheat burner is designed to fire at 2.4 MMBtu/hr to heat 42,000 lb/hr of flue gas from 300ºF to 450ºF.

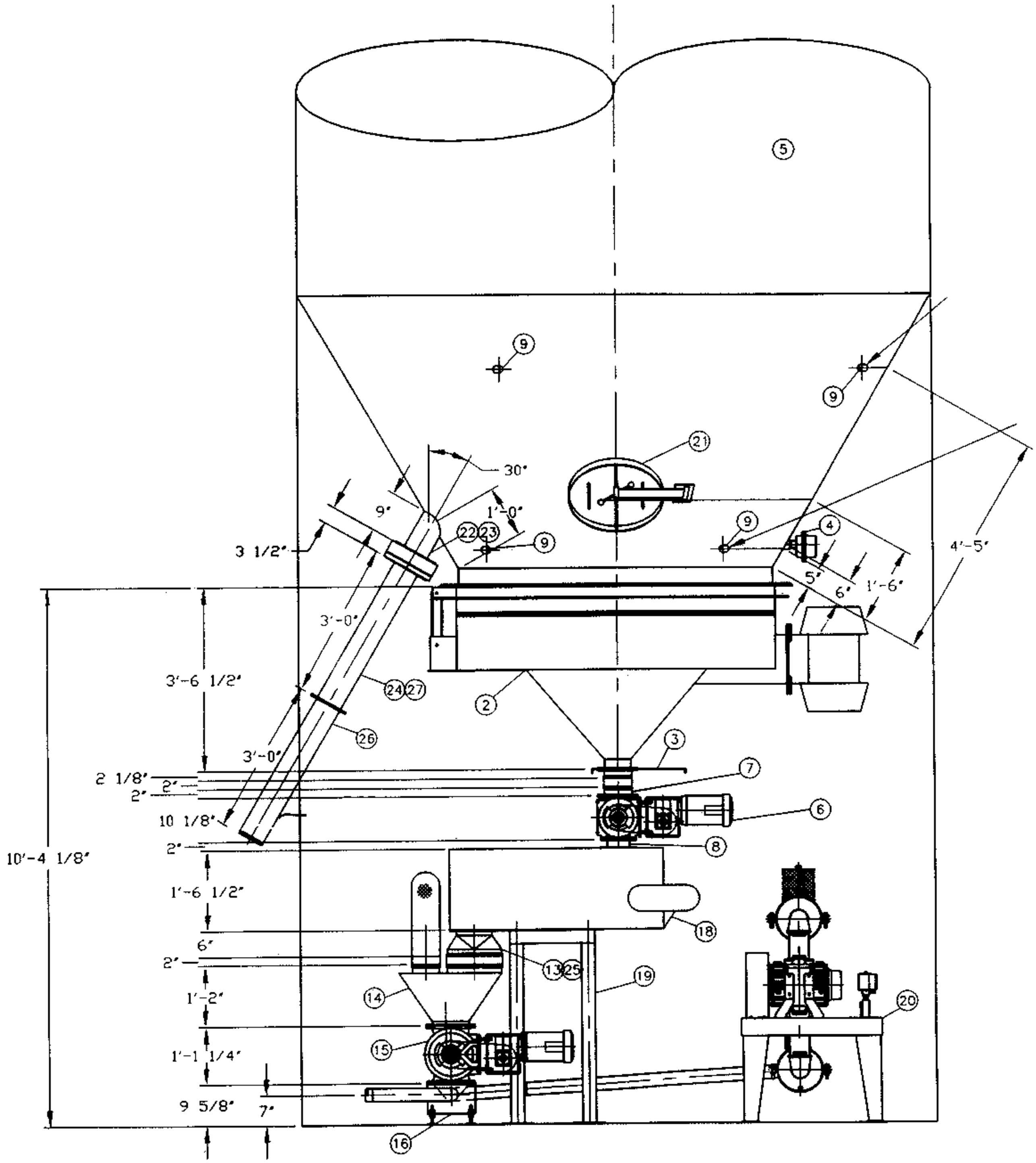


Figure 9 Char Storage Silo Feed System

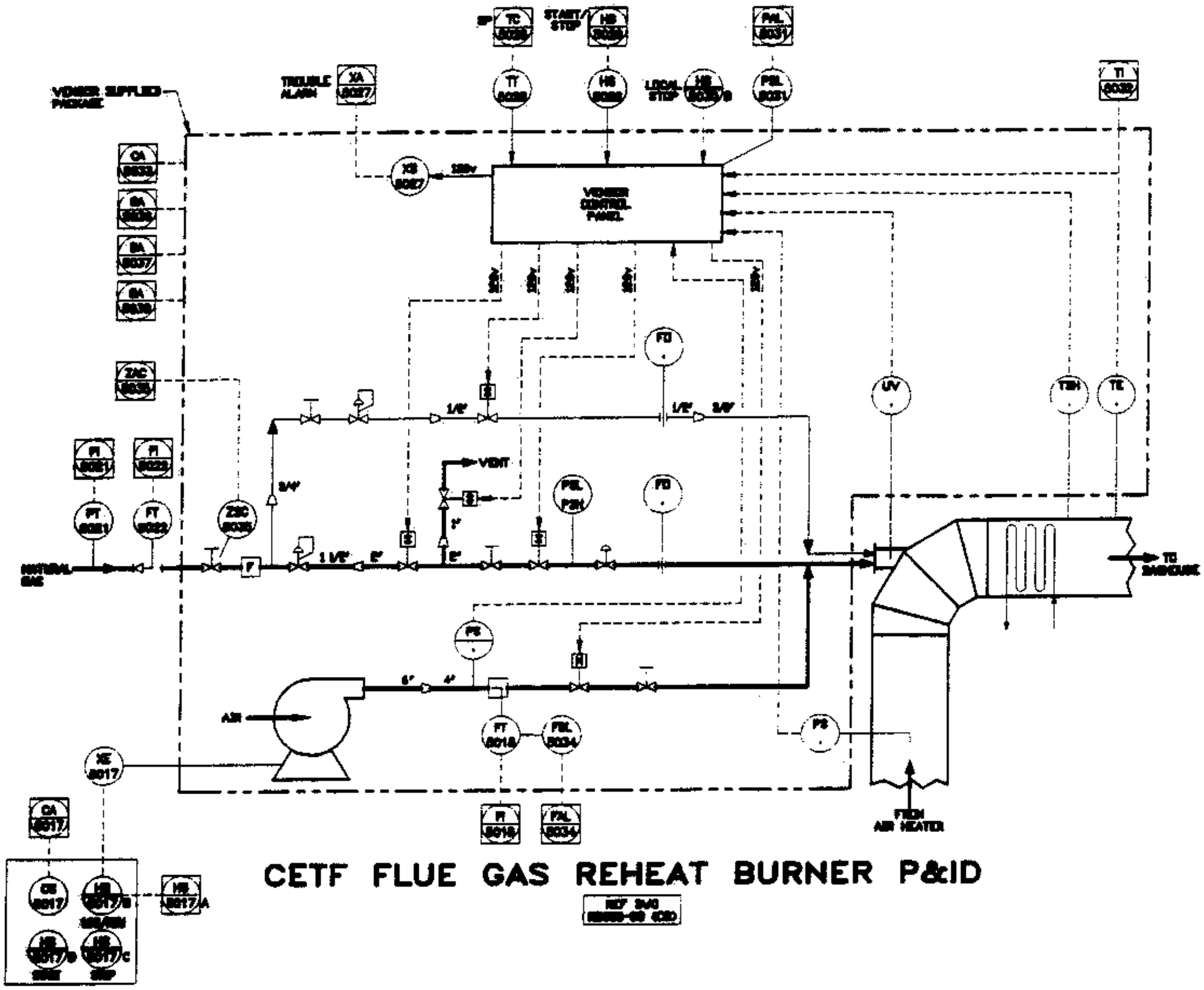


Figure 10

Task 4 - Subsystem Test Unit Construction

No work was performed under this task for this quarter.

Task 5 - Subsystem Test Unit Testing

Subtask 5.1 – Initial Char Firing in Commercial Burner Configuration

During the 4th quarter of 1997, the coal char which has been selected to simulate the pyrolyzer char (devolatilized bituminous Pittsburgh # 8 coal) was fired for two days (11/21,11/24/97) at the CETF.

This test firing demonstration was done with one commercially designed Foster Wheeler Energy Corporation's (FWEC) double cyclone burner. This burner is mounted at the arch of a furnace firing vertically downward. The test firing was conducted at conditions similar to industrial and utility steam generator combustion systems firing pulverized low volatile solid fuels. The initial char test firing was intended to confirm char ignition and combustion with a commercial FWEC arch-firing burner under conditions similar to those expected in the HIPPS experimental test campaign.. The flow rate of char feed to this single burner ranged from 4,100 to 5,500 pounds per hour.

These tests were successfully conducted on equipment which replicate in scale commercial installations. The initial co-fired fuel tests also revealed the potential environmental benefits available. An additional level of confidence in the burner design approach to the HIPPS burner has also been obtained.