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DEVELOPMENT AND TESTING OF A COMMERCIAL-SCALE COAL-FIRED COMBUSTION SYSTEM - PHASE III

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By
A.F. Litka and R.W. Breault

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Prepared for
PETC Project Manager: Mr. Douglas Gyorke
Pittsburgh Energy Technology Center
U.S. Department of Energy
P.O. Box 10940
Pittsburgh, Pennsylvania 15236-0940

Prepared by
Tecogen Inc.
45 First Avenue
P.O. Box 9046
Waltham, Massachusetts 02254-9046

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1. INTRODUCTION

Coal is the most plentiful energy resource in the United States, and in 1987 it provided approximately one third of the quads of total energy consumed in the United States. Its use, however, has been largely restricted to utility power generation since World War II for environmental and economic reasons.

Within the commercial sector, oil and natural gas are the predominant fuels used to meet the space-heating needs of schools, office buildings, apartment complexes, and other similar structures. In general, these buildings require firing rates of 1 to 10 million Btu/hr. The objective of this program is to demonstrate the technical and economic viability of a coal-fired combustion system for this sector.

The development program includes all aspects of the process, from fuel selection and preparation to pollution control and waste disposal. In attempting to restore coal to small users such as residential and commercial space heating, it is important to recognize that fuel form is an important consideration because of its impact on handling and emissions. Ease of handling is an important criterion at the small sizes since complex equipment will add greatly to the overall system costs. Furthermore, manpower is not available to perform manual functions or keep complex equipment working. Emission levels, if not currently regulated, can be expected to be regulated at low levels in the future. The levels considered acceptable will be reduced over time, following the current environmental trends. Preparation and use of a coal-water slurry fuel can aid in meeting these criteria. Coal-water slurry eliminates the need to use dry pulverized coal with its attendant handling and dusting problems as well as its explosive potential. In addition, coal-water slurry is amenable to coal washing since coal cleaning technologies are generally water-based processes requiring fine grinding of the coal. For these reasons, the program objective will be met through the development of a coal-water slurry fired system.

Although the coal-water slurry fuel in commercial practice will be manufactured by coal companies or fuel suppliers at regional facilities and transported to the user much as is done today with oil, the program includes the construction of a slurry production facility. In this way, all aspects of the fuel's use -- from coal selection to combustion properties -- can be evaluated and an economic evaluation of the process can be carried out.

The commercial-scale coal-water slurry (CWS)-fired space heating system will be a scale-up of a CWS-fired residential warm-air heating system developed by Tecogen under contract to the Department of Energy, Pittsburgh Energy Technology Center. This system included a patented nonslagging combustor known as IRIS, for Inertial Reactor with Internal Separation. This combustion technology, which has demonstrated high combustion efficiency using CWS fuels at input rates of 100,000 Btu/hr, will be scaled to operate at 2 to 5 million Btu/hr. Along with the necessary fuel storage and delivery, heat recovery, and control equipment, the system will include pollution control devices to meet targeted values of NO_x, SO_2, and particulate emissions. In general, the system will be designed to match the reliability, safety, turndown, and ignition performance of gas or oil-fired systems. Table 1.1 summarizes the performance goals of the system.

The successful development and future marketability of the heating system requires a strong, dedicated team with expertise in a broad range of areas including coal-water slurry preparation, coal combustion, pollution control, component manufacture, and systems integration. Such a team has been assembled and includes the following organizations: Tecogen, Donlee Technologies, AMAX Coal, and Southern Illinois University.

Tecogen is the prime contractor and is responsible for overall program management, combustor development, and integration of the subsystem components and installation of the system at the field test site. AMAX has extensive experience in coal-water slurry preparation and serves as the principal coal supplier. Donlee Technologies is responsible for the boiler/heat exchanger design and manufacture. Donlee has over 70 years' experience in the commercial boiler business and is a potential commercializer of the technology. Southern Illinois University is the host for the field test portion of the program. The heating system will provide space heating at the SIU Coal Research Center.

The development program has been divided into 3 stages covering a time span of 39 months. During the first stage, which covers 14 months, the program will focus on component development. The second stage, which covers a 10-month period, will focus on proof-of-concept testing. The final stage covers a 15-month period and will focus on testing all the components as an integrated system in an actual installation. Figure 1.1 gives the work breakdown structure for the program.

This report documents the work carried out in the second quarter of the program. Activities focused on the detailed design of the major system components.

During the first quarter, work concentrated on the definition of the overall system configuration and the determination of the key parameters to be considered in the combustor design. A preliminary heat balance was developed to define the overall process and to size system components and piping. Coal properties were evaluated and predictions made for the CWS properties capable of being achieved with the selected coals.

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TABLE 1.1

PERFORMANCE GOALS

- Thermal Input – 4 million Btu/hr
- Thermal Efficiency – >80%
- Combustion Efficiency – >99%
- Emissions – 1.2 lb SO_2/MMBtu
  0.3 lb NO_x/MMBtu
  0.03 lb Part./MMBtu
- Turndown – 3:1
- Ignition – Fully automatic startup with system purge and ignition verification
- Reliability/Safety – Comparable to oil-fired commercial boilers
- Ash Removal – Dust free and automatic or semi-automatic
- Routine Maintenance – Less than one manhour per day and an additional two manhours per week
- Service Life – >20 years

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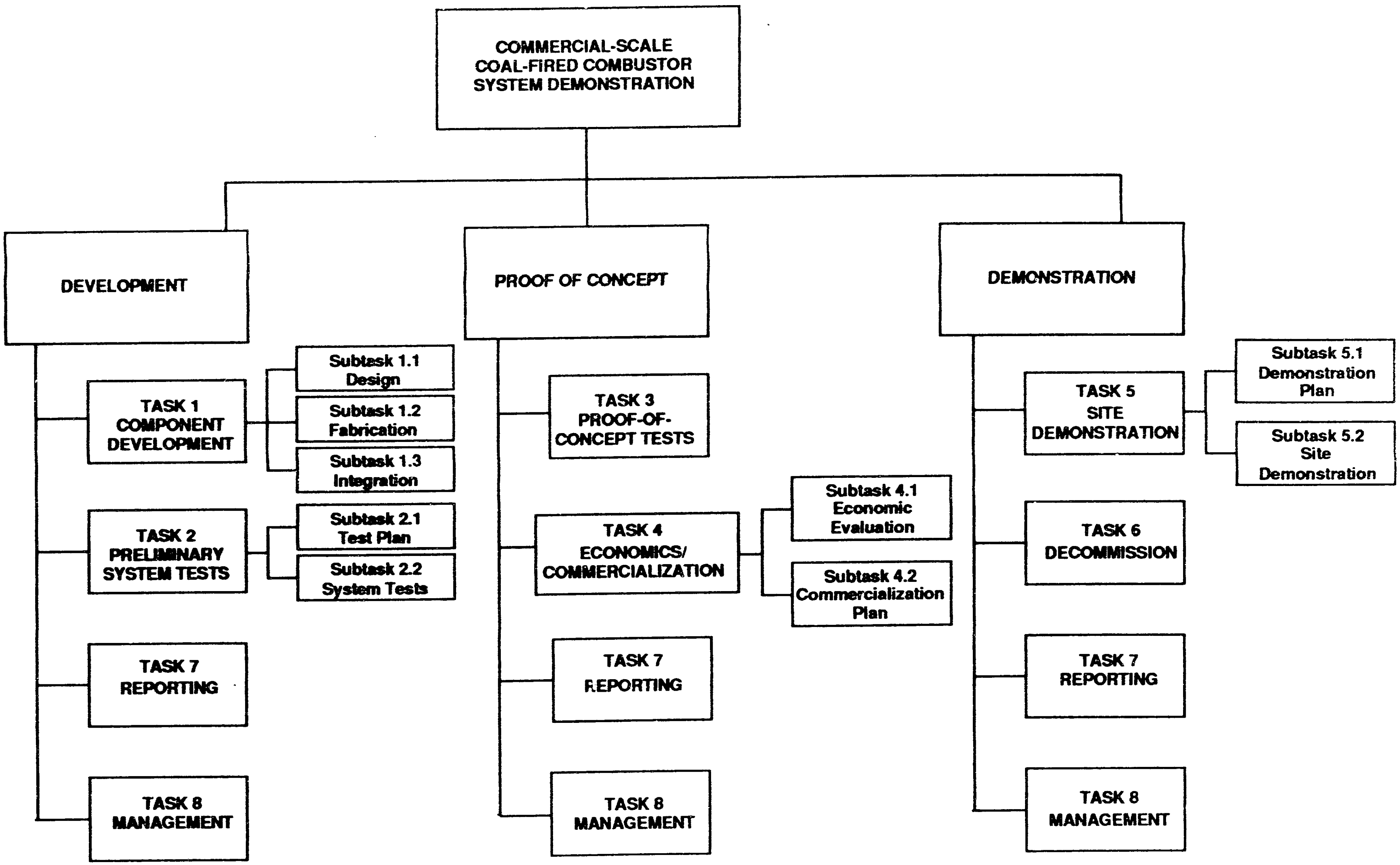

Figure 1.1 Work Breakdown Structure for Entire Project

Combustor scaling laws were developed to allow for an extension of the data base that has been established with the residential combustor and to provide guidelines for the scale-up of this combustor technology to larger sizes. In particular, particle separation, reaction rate kinetics, pressure drop, and residence times were evaluated.

2. PROJECT STATUS

2.1 TASK 1.1 - COMPONENT DESIGN

Combustor

Based on the combustor scaling parameters developed during the previous reporting period, a nominal 24-inch-diameter combustor has been selected for the commercial system. This combustor diameter closely matches the diameter determined through straight geometric scaling with equal heat release rates, and provides comparable particle retention with acceptable pressure drop and gas velocities. A sketch showing the key combustor dimensions is shown in Figure 2.1; detailed design of the combustor is under way. The combustor will be a double-jacketed water-cooled unit with a refractory liner. A graph of the predicted combustor outlet temperature versus refractory wall thickness is given in Figure 2.2.

The combustor will be connected to a transition chamber that will provide the connection to the boiler as well as collect large ash agglomerates. The transition box will also be a double-jacketed water-cooled unit with a refractory liner. The outlet temperature from the transition box (boiler inlet temperature) is plotted versus combustor outlet temperature for various refractory thicknesses in Figure 2.3. Based on these heat loss predictions, the combustor will be designed with a two-inch refractory thickness and the transition box will have a three-inch thickness. This combination will provide a boiler inlet temperature of between 2200 and 2300°F.

Boiler

A York-Shipley fire-tube heat-recovery boiler will be utilized. A schematic showing the boiler configuration is given in Figure 2.4. This three-pass boiler configuration has been utilized on various "dirty" gas applications. In particular, York-Shipley has provided over 50 units for operation with fluidized bed combustors burning wood, coal, and other alternative fuels.

Boiler performance data were generated for three standard boiler sizes (400, 500, and 625 ft^2), at the predicted flue gas flow leaving the combustor. The initial boiler selection was based on a boiler inlet temperature of 2300°F. A summary of this evaluation is given in Table 2.1. The 400-ft^2 boiler, which has a smaller drum diameter than the 500 ft^2 and 625 ft^2 models (4.5 ft versus 5.5 ft) and correspondingly lower tube free flow area and higher gas velocities, results in higher overall heat recovery. The velocities and pressure drops are considered acceptable.

A complete mapping was made of the 400-ft^2 boiler performance at full, two-thirds, and one-third thermal input and for different boiler operating conditions (50 psig, 15 psig, and 180°F hot water), and the results are summarized in Table 2.2. Since combustor exit temperature at this time can only be estimated

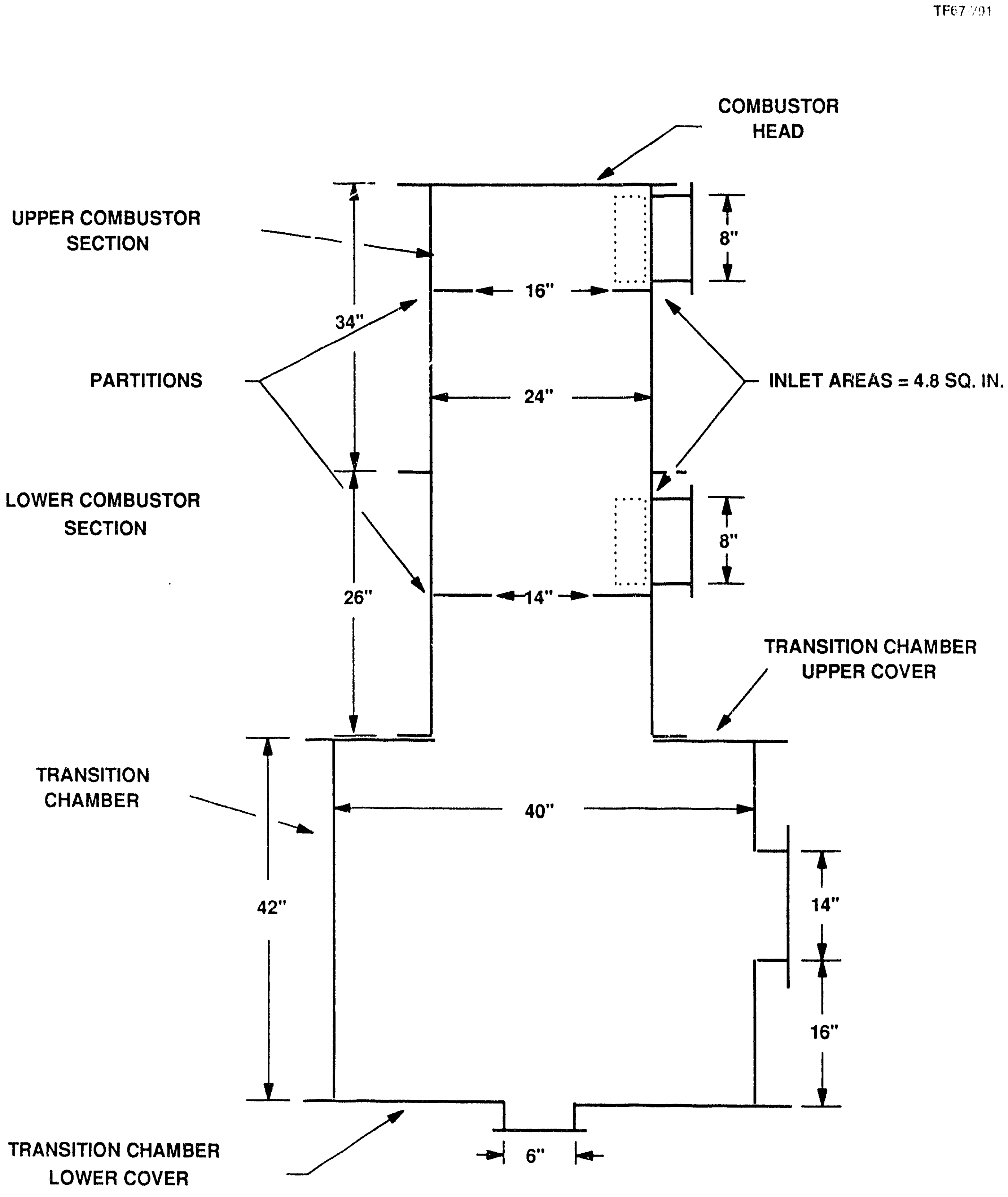

Figure 2.1 Combustor/Transition Chamber Configuration

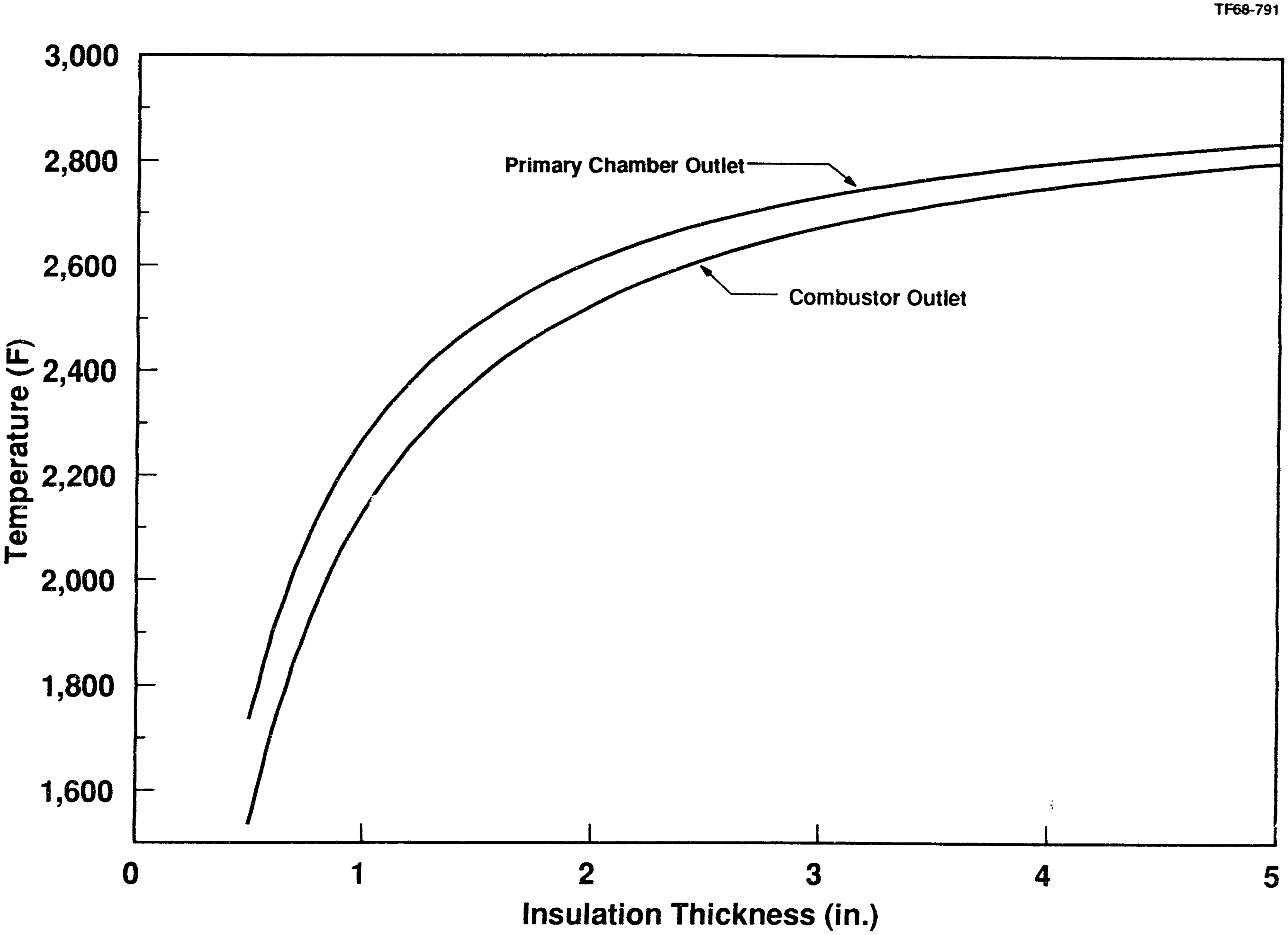

Figure 2.2 Combustor Outlet Temperature versus Insulation Thickness

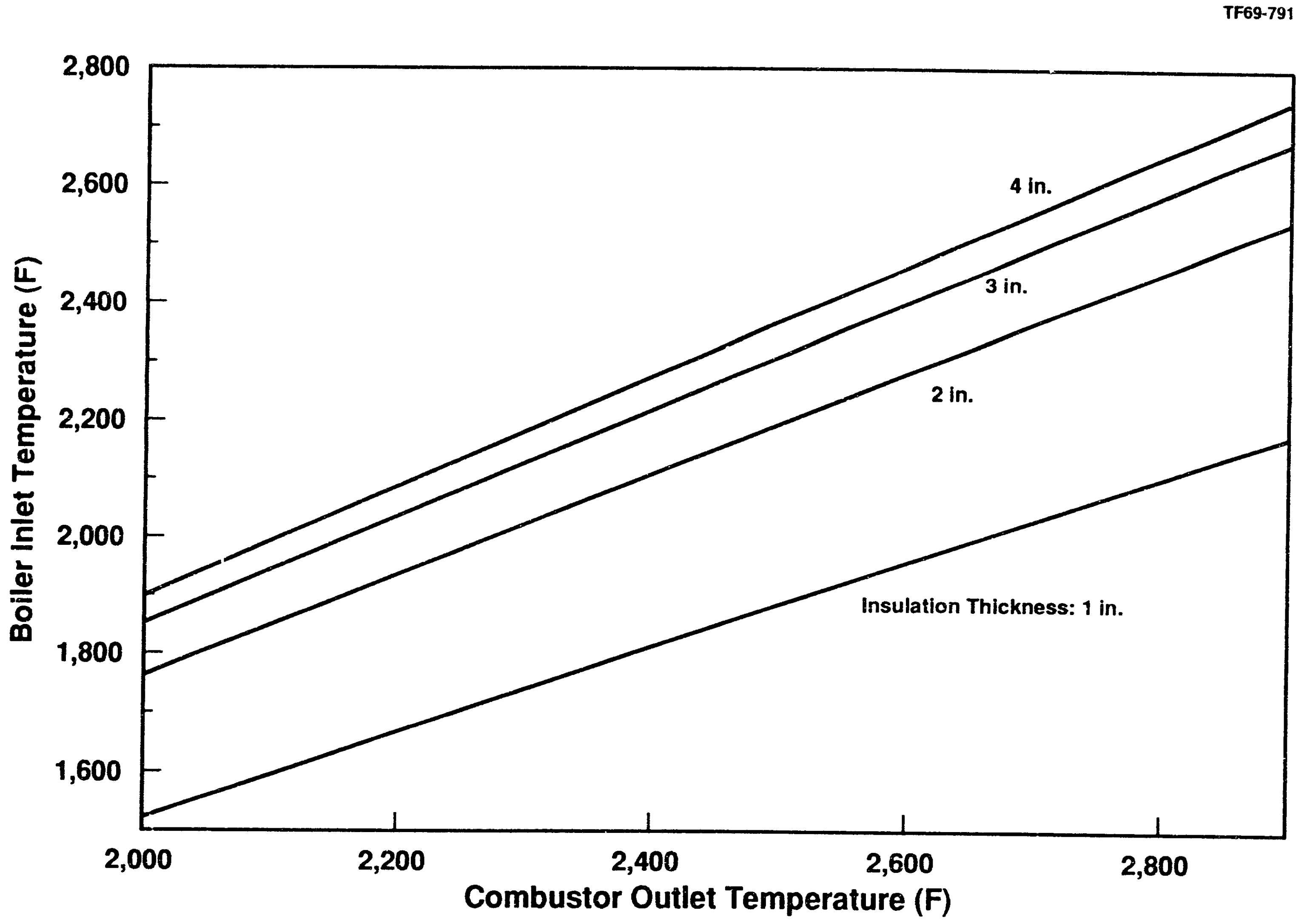

Figure 2.3 Boiler Inlet Temperature versus Combustor Outlet Temperature and Insulation Thickness

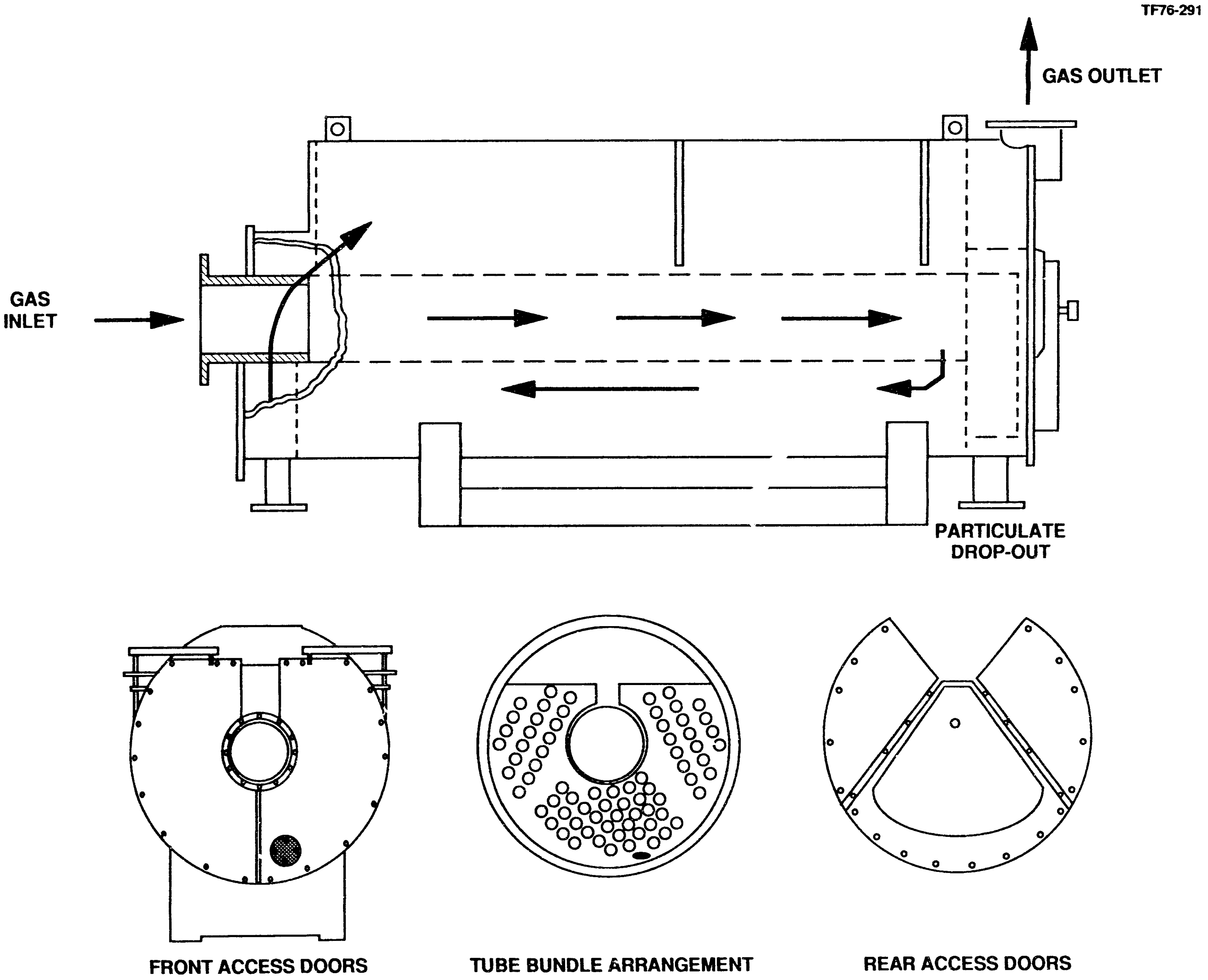

Figure 2.4 York-Shipley Fire-Tube Heat-Recovery Boiler Configuration

TABLE 2.1

BOILER SELECTION SUMMARY

Boiler Size	400 ft^2	500 ft^2	625 ft^2
Flue Gas Inlet Temp, °F	2300	2300	2300
1st Pass Outlet Temp, °F	2011	2054	2004
2nd Pass Outlet Temp, °F	750	830	693
3rd Pass Outlet Temp, °F	443	494	414
1st Pass Velocity, ft/sec	36.8	25.6	25.6
2nd Pass Velocity, ft/sec	87.5	52.5	51.4
3rd Pass Velocity, ft/sec	58.0	52.5	51.4
Pressure Drop, in. wc	4.3	3.8	3.8

TABLE 2.2
PERFORMANCE DATA FOR 400-FT^2 BOILER

Description	50 Psig			15 Psig			Hot water		
Flue gas flow #/hr	4225	2816.67	1408.33	4225	2816.67	1408.33	4225	2816.67	1408.33
Flue gas inlet temp. F	2000	2000	2000	2000	2000	2000	2000	2000	2000
I pass outlet temp. F	1782	1740	1639	1771	1726	1617	1754	1704	1582
II pass outlet temp. F	700	646	561	664	605	520	608	554	458
III pass outlet temp. F	428	401	363	385	356.5	318	321.5	294	252
1 pass inlet velocity ft/s	32.8	21.8	10.94	32.8	21.8	10.94	32.8	21.8	10.94
2 pass inlet velocity ft/s	79.4	51.9	24.77	78.97	51.6	24.51	78.4	51.1	24.1
3 pass inlet velocity ft/s	55.6	35.31	16.3	53.83	34	15.63	51.2	32.37	14.65
Pressure drop inwc	3.38	1.49	0.37	3.36	1.48	0.36	3.33	1.47	0.36

Description	50 Psig			15 Psig			Hot water		
Flue gas flow #/hr	4225	2816.67	1408.33	4225	2816.67	1408.33	4225	2816.67	1408.33
Flue gas inlet temp. F	2300	2300	2300	2300	2300	2300	2300	2300	2300
I pass outlet temp. F	2011	1949	1798	1997	1932	1771	1977	1903	1728
II pass outlet temp. F	750	686	585	710	646	543	655	587	479
III pass outlet temp. F	443	412	370	399.5	368	324	336	303	257
1 pass inlet velocity ft/s	36.81	24.5	12.27	36.81	24.5	12.27	36.81	24.5	12.27
2 pass inlet velocity ft/s	87.46	56.85	26.64	86.97	56.5	26.3	86.2	55.8	25.82
3 pass inlet velocity ft/s	57.95	36.58	16.68	56	35.3	16.1	53.4	33.43	14.99
Pressure drop inwc	3.44	1.51	0.37	3.41	1.5	0.37	3.38	1.49	0.36

Description	50 Psig			15 Psig			Hot water		
Flue gas flow #/hr	4225	2816.67	1408.33	4225	2816.67	1408.33	4225	2816.67	1408.33
Flue gas inlet temp. F	2600	2600	2600	2600	2600	2600	2600	2600	2600
I pass outlet temp. F	2229	2142	1933	2213	2120	1900	2187	2087	1848
II pass outlet temp. F	798	721	603	757	679	560	699	619	496
III pass outlet temp. F	458	422	374	413.8	377.5	328	349.6	312	261
1 pass inlet velocity ft/s	40.81	27.2	13.6	40.81	27.2	13.6	40.81	27.2	13.6
2 pass inlet velocity ft/s	95.18	61.4	28.23	94.61	60.88	27.84	93.69	60.1	27.23
3 pass inlet velocity ft/s	60.24	37.7	16.97	58.28	36.36	16.28	55.5	34.45	15.25
Pressure drop inwc	3.49	1.53	0.37	3.47	1.52	0.37	3.43	1.5	0.37

based on combustor performance scaling and heat transfer analysis, performance data were generated for a range of inlet temperatures (2000, 2300, and 2600°F). For all cases, the 400-ft^2 boiler provides sufficient heat extraction to meet the overall system thermal efficiency goal of 80 percent.

A hot-water heating system has been selected for the demonstration program. Figure 2.5 gives a schematic of the system. As shown, boiler water will be used for cooling the combustor and will be returned to the boiler at an elevated temperature. To prevent steam generation, the system will be operated under a pressure of approximately 10 psig through the use of an expansion tank and static leg.

Slurry Atomizers

A slurry test loop was set up to assess the performance of two commercially available atomizers. Figures 2.6 and 2.7 illustrate the two atomizers. The first is a Delavan Delta Swirl-Air Nozzle and the second is a Bete XA Series External Mix Flat Fan Air Atomizing Nozzle. Both nozzles achieved good atomization of the slurry. The Delavan nozzle produced a hollow cone with an included angle of approximately 90 degrees, and the Bete nozzle produced a flat fan with an included angle of approximately 50 degrees. The spray pattern for the Delavan nozzle is suited for downward firing, and the Bete nozzle is suited for side wall or tangential firing, as illustrated in Figure 2.8.

Process Controls

A control strategy has been developed for the system. The control system will be made up of discrete single loop controllers with a programmable sequencer for overall system control and ladder logic sequencing. A schematic of the process control and instrumentation is given in Figure 2.9. Following is a list of the control system elements:

Independent Variable	Manipulated Variable	Dependent Variable
Boiler Water Temp. (variable thermal input)	Fuel Flow	Combustion Air Flow Sorbent Feed Atomizer Air Flow
Thermal Input (fixed thermal input)	Fuel Flow	Combustion Air Flow Sorbent Feed Atomizer Air Flow
Boiler Water Temperature (fixed thermal input)	Thermal Load	
Boiler Water Level	Makeup Water	
Draft Pressure	ID Fan Damper	
Baghouse Pressure Drop	Pulse Air Frequency	

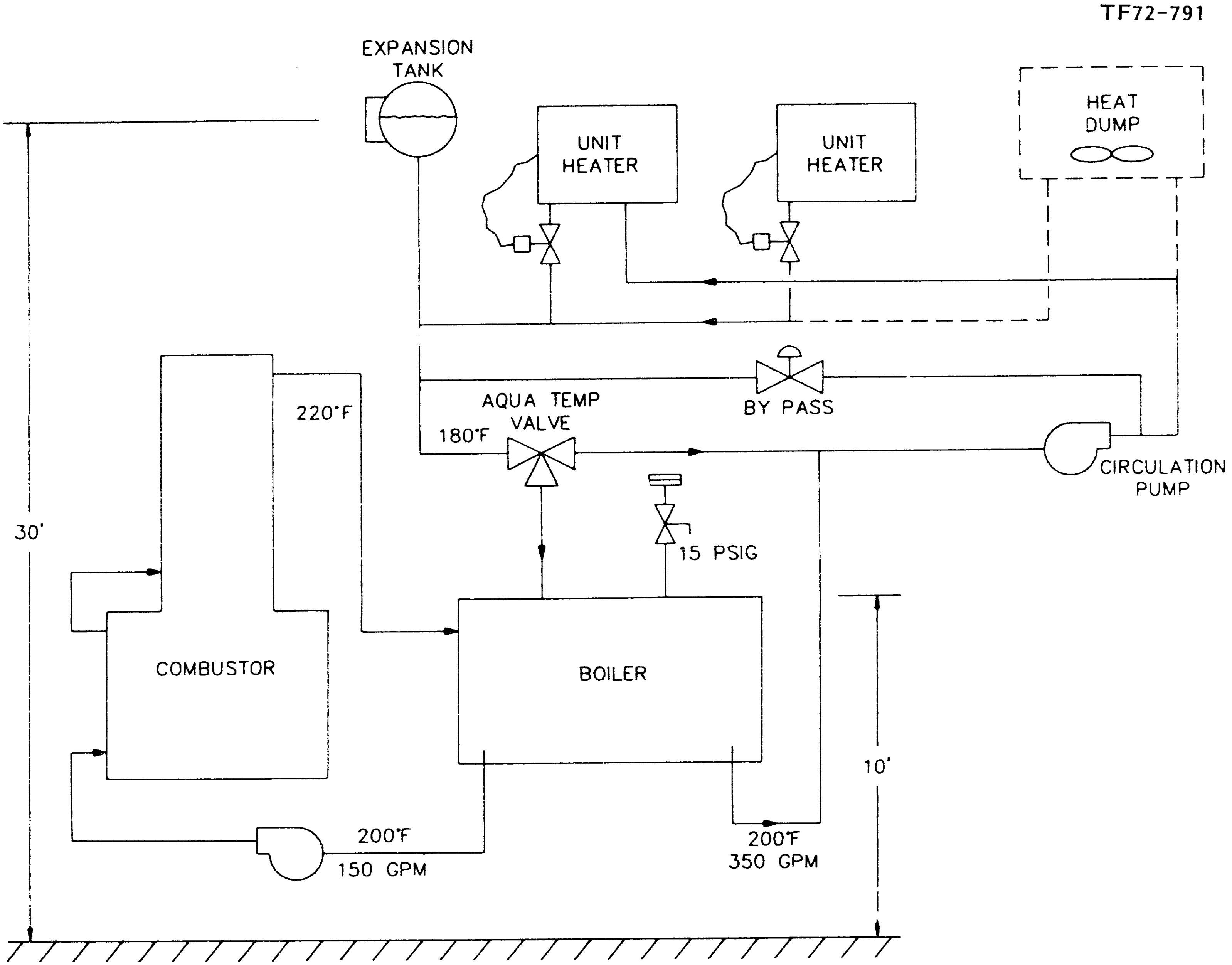

Figure 2.5 Hot Water Flow Diagram

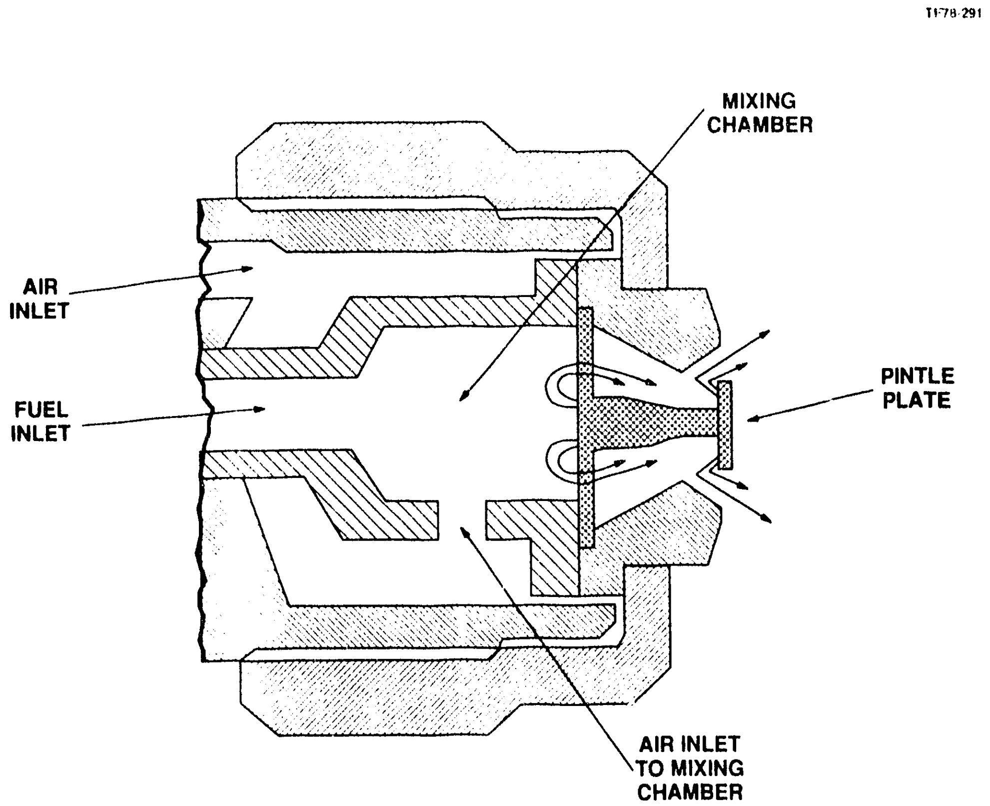

Figure 2.6 Delavan Delta Swirl-Air Atomizing Nozzle

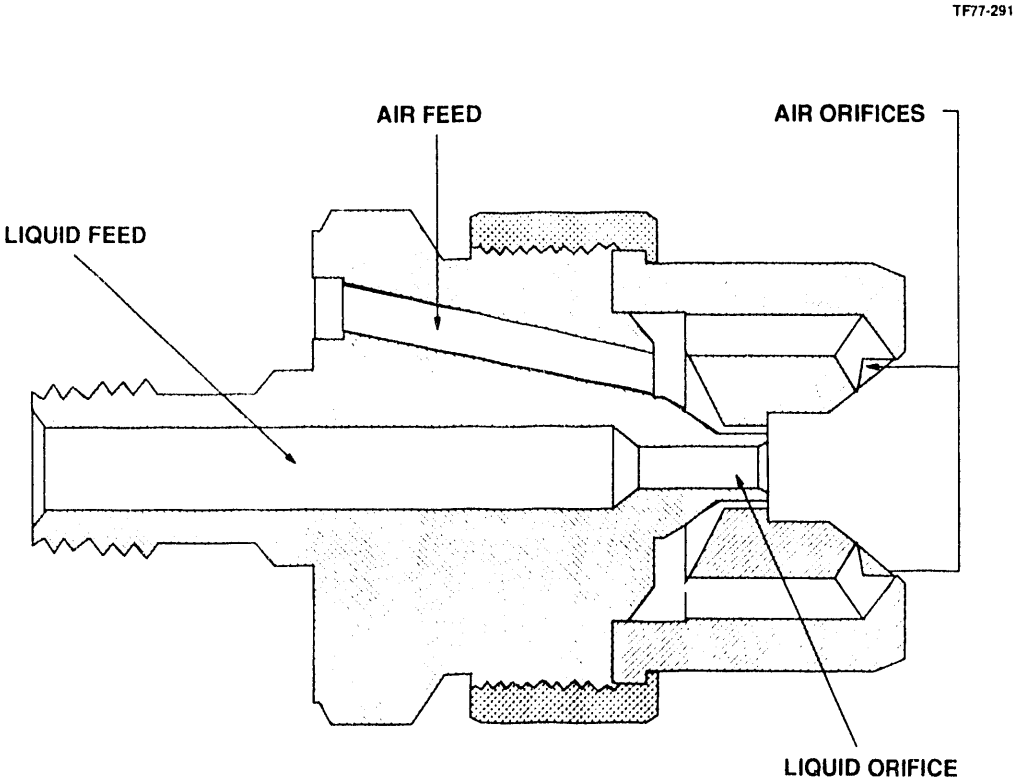

Figure 2.7 Bete XA Series External Mix Flat Fan Nozzle

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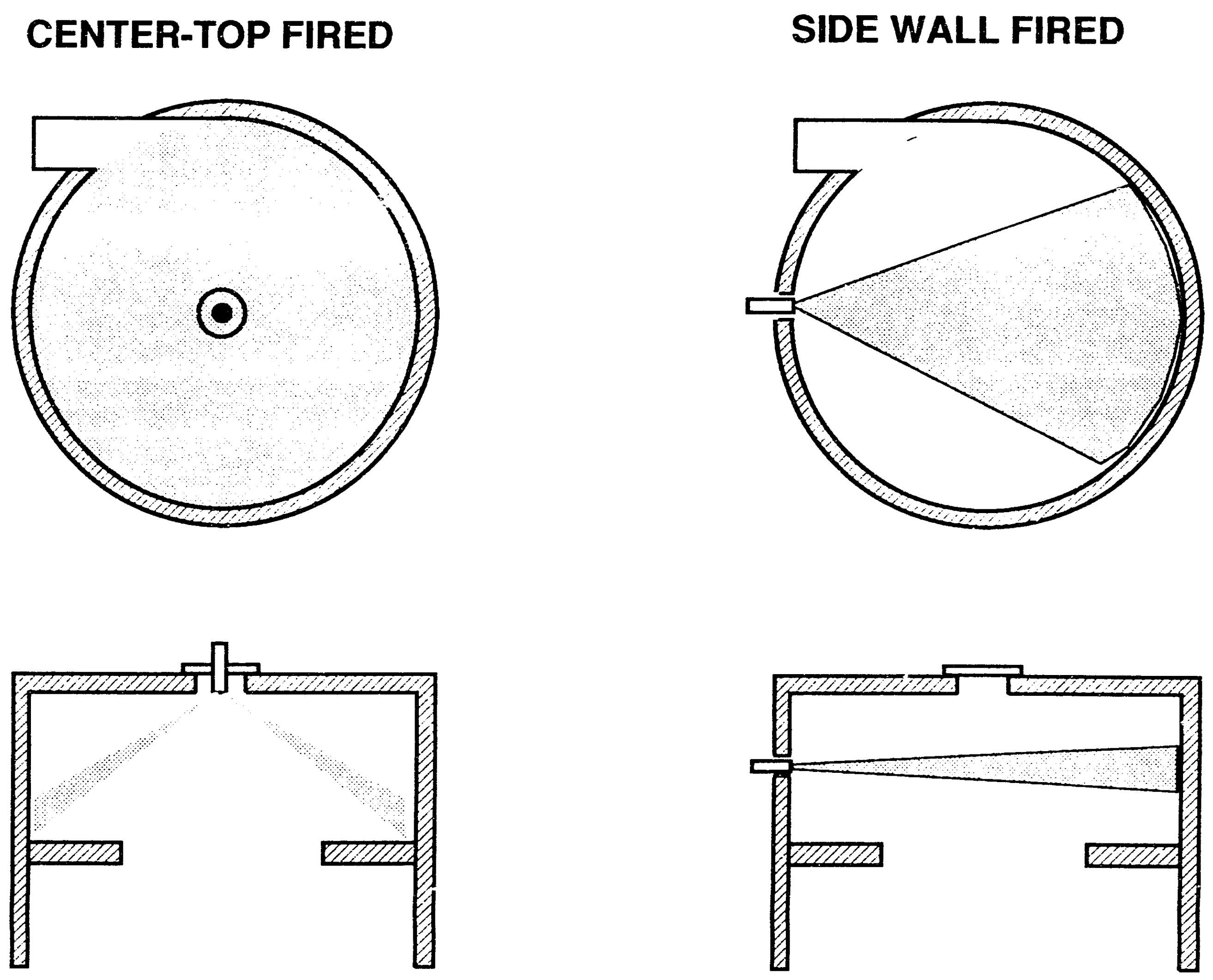

Figure 2.8 Slurry Injection Configurations

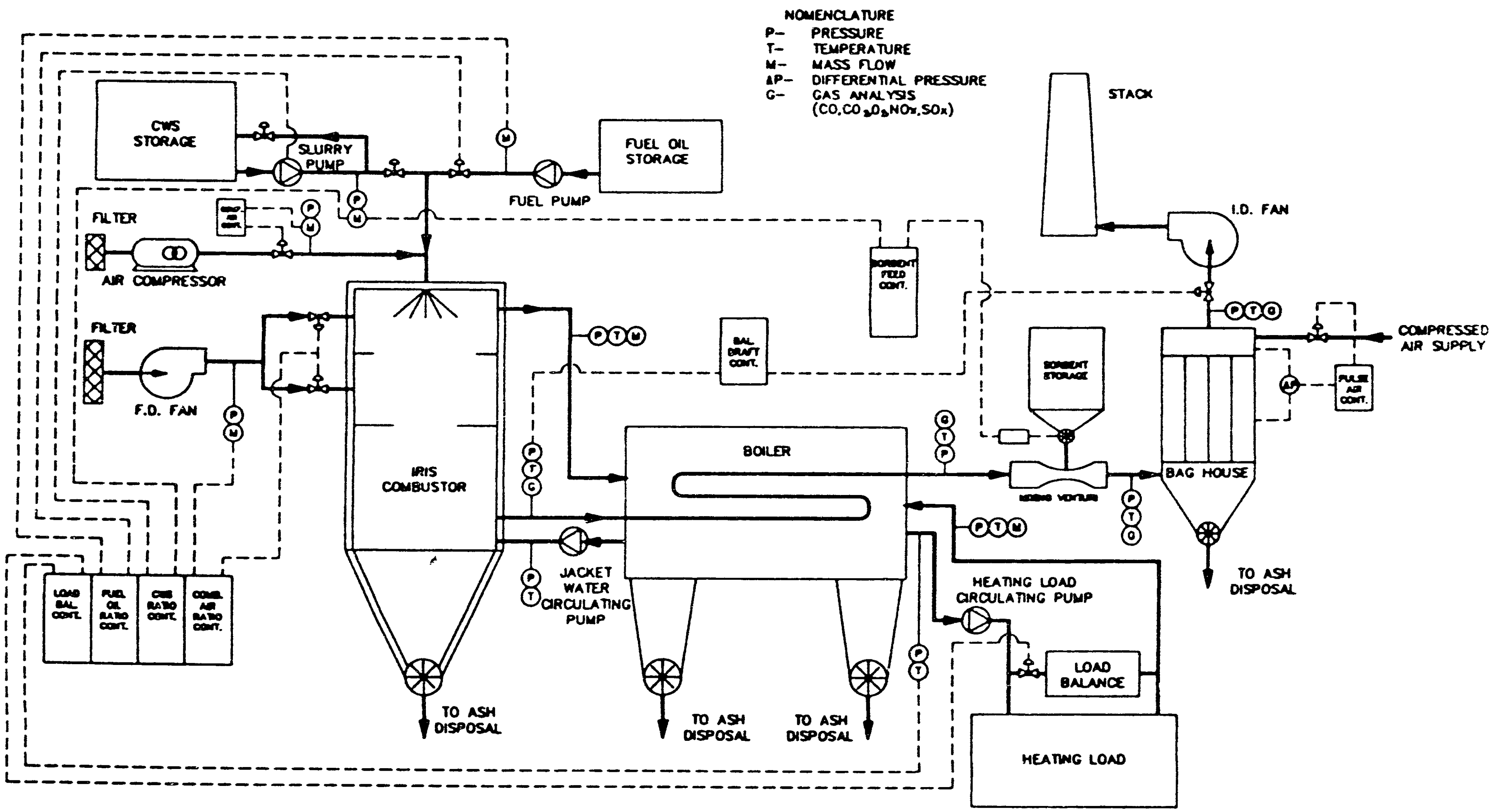

Figure 2.9 Process Control and Instrumentation Diagram

The control system will be arranged so that the combustion system can be operated in either a variable or fixed input mode. In the variable input mode, combustor thermal input will be adjusted within the turndown capability of the unit to the heating requirements of the system, as is typically done in space heating systems. In the fixed input mode the combustor input will be fixed and the thermal energy in excess of that required by the space heating system, if any, will be dumped through a load balance radiator or cooling tower. This feature will allow greater flexibility in the test operations and will allow for system operation during periods when space heat is not required.

2.2 TASK 1.2 - COMPONENT FABRICATION

Component Design Testing

Several hot combustion tests were performed to evaluate combustor component design and scale-up parameters. The air inlet of the Tecogen industrial-scale combustor was modified to obtain higher inlet velocities as determined in the combustor scale-up analysis. An adjustable damper was installed so that the inlet slot width could be varied from 3/16 to 3 inches.

Initial tests with oil revealed that with top-center firing adequately high wall temperatures could not be achieved in the primary chamber with the higher air inlet velocities. Modifications were made to permit side wall injection of fuel oil adjacent to the air inlet. This change allowed a higher concentration of oil to be burned close to the wall and increased the wall temperature from 800 to 1600°F.

Slurry injection tests were carried out with both the Delavan Swirl-Air Nozzle and the Bete External Mix Flat Fan Nozzle. With the Delavan nozzle top-center firing, it appeared that the majority of the slurry was projected past the partition and entered the lower section. Modification to the nozzle is required to increase the spray angle, or the length of the primary zone must be increased to get a larger portion of the slurry into the upper section.

The Bete nozzle was used in a side wall injection configuration. With this arrangement slurry could be seen impacting the side wall just beyond the air inlet and being sheared off into droplets by the high-velocity combustion air. It appeared that particle retention in the primary zone was not sufficient, and improvements are necessary to produce a mass of burning particles that provide the heat for slurry droplet vaporization and adequate reaction rates.

3. PLANNED ACTIVITIES

During the next reporting period, detailed design of the combustor and transition chamber will be completed and fabrication of these components will be initiated. Additional combustor testing will be carried out to evaluate component designs. In particular, cold flow testing will be conducted to assess the particle retention capability of the primary combustor zone configuration.

4. SUMMARY

During the second quarter of the program, work concentrated on detailed design of the main system components. Detailed design of the combustor, transition chamber, and boiler were initiated, and construction of these components will begin during the next reporting period. A hot water distribution system has been configured along with a process control system.

Several component design tests were carried out to evaluate the performance of system components and subsystem arrangements. Atomizers, slurry pumps, ignitors, fuel oil components, etc., were evaluated.

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