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Final Report

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Work Performed Under Contract No.: DE-AC21-88MC25069

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Manufacturing and Technology
Conversion International, Inc.
Columbia, Maryland

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Morgantown, West Virginia 26507-0880

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EXECUTIVE SUMMARY

The development and commercialization of fluidized bed combustion technology has matured to the point where it successfully competes for the large industrial boiler market and is soon expected to enter the utility market as a generation option, especially for add-on, replacement and/or retrofit applications. In other market sectors < 50,000 PPH steam, there has been, until recently, considerable uncertainty over the availability of a scaled down technology that could be cost and performance competitive with oil and gas. The overall objective of this program, sponsored by the U.S. Department of Energy (Contract No. DE-AC21-88MC25069), was to establish the feasibility that the MTCI pulsed atmospheric fluidized-bed combustion (PAFBC) technology could esolve many of the scale-down technology issues that were considered to be constraining for commercial, institutional, and industrial applications. The PAFBC system actually surpassed the performance of the larger conventional bubbling and circulating fluid-bed combustion units and presented an opportunity to provide smaller systems at a reasonable price and in an environmentally acceptable manner.

The overall objective was implemented with two tasks. The specific objective of Task I was to establish preliminary feasibility by the use of theoretical and state-of-the-art information. The specific objective of Task 2 was to build and experimentally verify the feasibility of the technology at the laboratory-scale and to establish the potential operability and performance parameters of the PAFBC for different types of coal.

The preliminary feasibility analysis indicated that a coal-based technology that provides competitive levels of capital and O&M costs, performance, and reliability at the 1000 to 10,000 PPH steam can displace as much as 2.5 quads of gas and oil within the residential, commercial, and light industrial sectors. In the industrial sector, systems from 10,000 to 50,000 PPH steam can displace another 1.1 quads of energy per year. Discussions with commercial boiler vendors (i.e., Dixon Boiler Works and Hercules Power Equipment, both of Los Angeles, California and York-Shipley of York, Pennsylvania) indicated that a boiler size of 300 HP (12,500 PPH) would be a good choice for initial commercial entry. That size is in great demand, with a large inventory of boilers in the marketplace. In addition, the boiler owner is better able to absorb the capital cost differential between an oil/gas-fired and alternate fuel-fired unit to take advantage of the fuel differential.

A cost analysis was performed to estimate the capital cost of a 1000 lb/hr PAFBC steam generator based on the configuration investigated in Task 2. A convective section and baghouse were included and the cost for a one-of-a kind system (not the mass produced version) was estimated to be about $65,000. A packaged PAFBC boiler, however, is anticipated to meet the target capital cost goal of $45,000 - $50,000 and compete favorably with a natural gas- or oil-fired system. The projected steam cost is about $7/1000 lb. Since the steam cost is very sensitive to capacity factor, applications/markets with high capacity factors (>60%) provide the best targets for the initial entry of this advanced coal-fired technology. Also, due to economy of scale - smaller surface area per unit volume and lower marginal investment in subcomponent cost with increase in unit size - PAFBC boilers in the 10,000 to 50,000 PPH steam range would provide a keener competitive edge for replacing oil- and gas-fired units.

In order to verify the technical feasibility of the MTCI Pulsed Atmospheric Fluidized Bed Combustor (PAFBC) technology, a laboratory-scale system (1.5 MMBtu/hr coal-firing rate) was designed, built and tested. In this development effort, important aspects of the operational and performance parameters of the system were established experimentally. A considerable amount of the effort was invested in the initial task of constructing an AFBC that would represent a reasonable baseline against which the performance of the PAFBC could be compared.

A summary comparison of the performance and emissions data from the MTCI 2′ x 2′ facility (AFBC and PAFBC modes) with those from conventional BFBC (taller freeboard and recycle operation) and circulating fluidized bed combustion (CFBC) units is given in Table ES-1. The comparison is for typical high-volatile bituminous coals and sorbents of average reactivity. The values indicated for BFBC and CFBC were based on published information. The AFBC unit that was designed to act as a baseline for the comparison was indeed representative of the larger units even at the smaller scale for which it was designed. The PAFBC mode exhibited superior performance in relation to the AFBC mode. The higher combustion efficiency translates into reduced coal consumption and lower system operating cost; the improvement in sulfur capture implies less sorbent requirement and waste generation and in turn lower operating cost; lower NO_x and CO emissions mean ease of site permitting; and greater steam-generation rate translates into less heat exchange surface area and reduced capital cost. Also, the PAFBC performance generally (i) surpasses those of conventional BFBC, (ii) is comparable to CFBC in combustion and NO_x emissions, and (iii) is better than CFBC in sulfur capture and CO emissions even at the scaled-down size used for the experimental feasibility tests.

TABLE ES-1: PERFORMANCE CHARACTERISTICS

	AFBC	PAFBC	BFBC*	CFBC*
Combustion Efficiency (%)	89-93	92-97	90-97	93-99
SO_2 Capture (%)	70-85	90-98	70-85	75-95
NO_x Emissions (ppm)	115-620	110-265	400-500	100-300
CO Emissions (ppm)	400-1600	180-800	400-1200	500-1500
Steam Rate (lb/hr)	500-700	800-820		
TEST PARAMETERS				
Bed Temperature	1500-1600°F			
Ca/S Ratio	2.5 - 2.7			
Coal	Bituminous (high volatile)			

*Based on literature data.

These factors indicated that the PAFBC could be an attractive option at any scale. The fact that it is impractical and expensive to scale-down CFBC to the 1,000 - 50,000 PPH steam equivalent range makes the PAFBC a clear contender for the small-scale boiler market sector.

After the completion of more than 200 hours of operation, the PAFBC system was partially dismantled to assess the integrity of the unit and conduct materials evaluation. The diffuser section connected to the pulse combustor tailpipe had separated due to the fracture of the holding/support rods. The failure is attributed to thermal stress. Incorporation of water-cooled support rods is expected to solve this problem. An examination of the furnace internals and the pulse combustor indicated that the refractory linings had minor surface cracks but erosion was not evident. In conclusion, the PAFBC system seemed to be generally in good condition.

The performance of the laboratory-scale system exceeded the expectations of both MTCI and DOE. The integration of a pulse combustor with a fluidized bed combustor has produced the following benefits:

- The oscillating flow field imposed by the introduction of pulse combustor exit gas into the fluid bed helps stabilize fluidization dynamics, reduce particle entrainment, improve interphase heat and mass transfer, enhance sulfur capture and reduce solid waste volume.

- The fines burned in the pulse combustor generate pressure boost for fluidization and/or air staging thereby reducing air moving equipment requirements and cost.

- The furnace height requirement is lowered due to pulse combustor integration, freeboard expansion and in-furnace solids disengagement. The pulse combustor integration decreases carbon loading in the freeboard. The freeboard expansion helps decrease gas velocity, increase gas residence time and decrease solids elutriation. The in-furnace solids disengagement improves combustion and sulfur capture performance and decreases particle carryover with flue gas.

- The heat exchange surface area requirement is greatly reduced by efficient heat transfer both in the fluidized dense bed and the pulse combustor tailpipe.

- The high combustion intensity (2 to 5 MMBtu/hr/ft^3) and fast response of the pulse combustor facilitate rapid system start-up and load-following.

- The draft tube configuration employed at the end of the pulse combustor tailpipe provides fines recirculation and increased particle residence time in the bed for enhanced combustion and sulfur capture.

- It is possible to incorporate multiple air staging in the freeboard to achieve even lower NO_x emissions.

- The system affords the potential for co-incineration of wastes of various types - hospital waste, hazardous waste, coal pond waste, coal tailings etc. - in an efficient, environmentally acceptable and economical manner.

Due to the advantages cited above, a number of end-users such as Baltimore Thermal Energy Corporation, Island Creek Corporation, and Cleveland Thermal Energy Corporation have expressed great interest in this technology and have offered participation in field testing and further development of the PAFBC system.

TABLE OF CONTENTS

TABLE OF CONTENTS
(CONT'D)

LIST OF FIGURES

LIST OF FIGURES
(CONT'D)

LIST OF FIGURES
(CONT'D)

LIST OF FIGURES
(CONT'D)

LIST OF TABLES

LIST OF TABLES
(CONT'D)

SECTION 1.0

INTRODUCTION

1.1 BACKGROUND

Many technologies have been developed and/or demonstrated for utilizing high-sulfur fuels in general and coals in particular. The technologies include fuel beneficiation, flue gas desulfurization (FGD), fluidized bed combustion (FBC), and gasification-cum-purification. From the performance, emissions, and economics standpoint, FBC technology has emerged as the leading candidate for utilizing high sulfur fuels. Many FBC designs are available and are at various stages of commercialization. FBCs can be classified in terms of operating pressure (atmospheric or pressurized) and fluidization mode (bubbling or circulating). All these FBC designs possess the following major attributes:

- in-situ sulfur capture,
- low NO_x emissions due to lower operating temperature,
- no slagging or fouling of heat-transfer surfaces,
- high heat transfer rates to heat exchange surfaces,
- near uniform temperature in combustion zone, and
- fuel flexibility.

The features cited above have made it possible for FBC technology to compete successfully for the large industrial boiler market (50,000 - 300,000 lb/hr steam). Large-scale (70 to 150 MW_e) field demonstration projects are in progress to enable FBC commercialization in the utility sector. The potential of FBC technology, and specifically, atmospheric fluidized bed combustion (AFBC) for small-scale (< 50,000 lb/hr steam equivalent) applications has, however, not been explored seriously until recently.[1]

An AFBC-based technology appears to have a great potential for oil and gas replacement in small-scale installations of less than 50,000 PPH steam equivalent. These smaller units can meet the needs of process heat, hot water, steam, and space heating in the residential, commercial, and industrial sectors. Currently, oil- and natural gas-fired equipment is used almost exclusively for these applications. However, due to the large difference between the prices of these fuels and coal, a coal-fueled AFBC technology engineered for small-scale applications has the potential of becoming very competitive under economic conditions in which the price differential overcomes the initial capital cost of the coal-based system. A successful coal-fueled AFBC system can not only be more economical, but can also reduce the nation's dependence on foreign oil and open up new markets for domestic coal and the coal-fueled fluid-bed technologies.

The current oil- and gas-fired boilers and process heaters have proven records of performance, cost, reliability, and maintainability. The AFBC technology has the potential to provide similar levels of reliability and maintainability when scaled-down (10,000 to 50,000 PPH steam equivalent) from the larger scale units that are now part of a mature and competitive technology. The scale-down of the existing AFBC technology, however, poses some problems with regard to cost, performance, start-up, load-following, and design compactness.

As pointed out earlier, the AFBC systems can be classified into bubbling-bed (BFBC) and circulating-bed (CFBC) FBC systems. In BFBC, it is critical to control the extent of fines (elutriable particles) in the coal and sorbent feed in order to limit particle carryover and its adverse effect on combustion and sulfur capture performance, emissions, and the size of solids collection equipment. Additionally, the higher Ca/S feed ratios typically required in BFBC applications tend to increase sorbent and waste disposal costs. Furthermore, the turndown capability of the BFBC is rather limited. As regards the CFBC, it exhibits higher combustion efficiency and sorbent utilization, lower NO_x emissions due to multiple air staging, and greater fuel flexibility and turndown as compared to BFBC. However, the CFBC system requires a lengthened combustor to accommodate sufficient heat exchange surface. This makes it both impractical and expensive to scale-down CFBC to sizes significantly smaller than 100,000 PPH steam equivalent.

Fluid beds tend to have large thermal inertia. Start-up of large fluid-bed systems require a considerable amount of time and auxiliary subsystems to preheat the beds in a controlled manner. Such configurations and operational characteristics are more appropriate for base-loaded systems and are not satisfactory for small-scale applications due to cost and operational inadequacy. Concepts which provide for a simple compact design for fast start-up with low-cost hardware that also have simple operational characteristics are a must for those end-use sector applications. Thermal inertia of fluid beds also affects load following to some extent and this has also been a serious shortcoming for scale-down to small end-use applications. System designs must provide fast response to load changes, particularly through auxiliary firing subsystems and methods of bed heating. Such a design should not require additional hardware and control systems if the system capital cost is to be maintained sufficiently low to compete favorably with the existing oil and gas equipment.

In addition to the attributes discussed above, new design concepts that are aimed at the target market and end-use sectors must provide an opportunity for high throughput and above-average pollution control requirements characteristic of the end-use applications contemplated. Higher throughput for a given combustor size will make a contribution to the reduction in capital cost per Btu/hr of fuel fired. This must be achieved, however, without compromising the pollution control performance of equipment intended to meet stringent requirements in some of these end-use applications. New concepts are therefore required that will enhance the combustion and sulfur removal reaction rates in the fluid bed beyond those found in conventional fluid-bed combustors without an increase in NO_x emissions or equipment size. These designs should also provide sufficient effluent pressure to allow the separation of particulate matter from the combustor effluent prior to exhausting it to the atmosphere without the need for complex mechanical systems. Other important attributes for these small systems should be reliability and ease of operation.

Simply scaling-down existing large AFBC systems to the size range suitable for small end-use sectors of interest will result in complex and expensive systems that will not be competitive with presently available oil- and gas-fired equipment. New innovative approaches are needed to reduce cost and enhance performance. Specifically, the new system should possess the following attributes:

- high combustion efficiency;
- high SO_2 capture capacity;
- low NO_x emissions;
- reliability, maintainability and safety of operations equivalent to oil- and gas-fired packaged systems;
- cost competitiveness with gas- and oil-fired systems;
- simple and inexpensive controls;
- rapid start-up and load-following capability;
- clean, aesthetic, and compact design; and
- minimal operator attention.

The MTCI Pulsed Atmospheric Fluidized Bed Combustion (PAFBC) system meets the above requirements and has the potential to develop into a technology which meets the needs of small commercial and industrial installations as well as larger units. The PAFBC system is a result of a "marriage" between pulse combustor technology and an atmospheric bubbling-bed type fluidized-bed combustor (BFBC). Incorporation of pulse combustion overcomes all of the aforementioned problems and enhances combustion efficiency, SO_2 capture capacity, and heat transfer efficiency of the fluidized bed. These benefits of pulse combustion result in smaller size PAFBC units of high throughput rates, superior environmental performance, and lower costs when compared to conventional AFBC units. Since the fundamental basis for the PAFBC concept resides in MTCI's advanced pulse combustion technology, a description of the pulse combustion technology is included in some detail in Section 1.3.

1.2 PAFBC CONCEPT AND SYSTEM

The objectives of this new process and apparatus are to:

- burn coal in an efficient, cost-effective, safe, reliable, and environmentally acceptable manner;
- replace oil- and gas-fired equipment in the residential, commercial and industrial sectors of the economy; and

- expand coal utilization and reduce the nation's dependence on foreign oil.

The MTCI PAFBC system integrates a pulse combustor with an atmospheric bubbling-bed type fluidized bed combustor (BFBC) as shown in Figure 1-1. In this modular configuration, the pulse combustor burns the fines (typically less than 30 sieve or 600 microns) and the fluidized bed combusts the coarse particles. Since each of these combustion steps is very efficient, the process reduces the elutriation of unburned carbon, provides a higher combustion efficiency, and results in a more compact system requiring lower freeboard height as compared to a conventional BFBC. The fines burned in the pulse combustor generate pressure boost and robust fluidization flow, thereby reducing air-moving equipment requirements and cost. The oscillating flow field imposed on the bed helps stabilize fluidization dynamics, improves interphase heat and mass transfer, enhances sulfur capture and reduces solid waste volume. The heat release rate of the pulse combustor is high and is utilized for initial start-up as well as controlling fluidization air flow rate to the bed. The MTCI pulse combustor is capable of fast response so that the load-following capability of the total system is quite rapid. The pulse combustor has no moving parts as it employs an aerodynamic valve (fluidic diode) and achieves higher levels of reliability and availability. The heat transfer coefficient in the pulse combustor tailpipe is comparable to that in the dense fluidized bed, thereby significantly reducing the total cost of heat transfer surface.

1.3 PULSE COMBUSTION

Pulse combustion is an extremely effective method for increasing heat transfer and combustion efficiency via acoustic enhancement. Particles burning in an intense acoustic field have been shown to combust more rapidly and transfer heat 150 to 250 percent more effectively than conventional methods do. As a cost-effective method for supplying the intense acoustic field within an FBC, the pulse combustor can provide phenomenal improvements in combustion and heat transfer efficiencies - beyond even the exceptional efficiencies already available in the FBC technology.

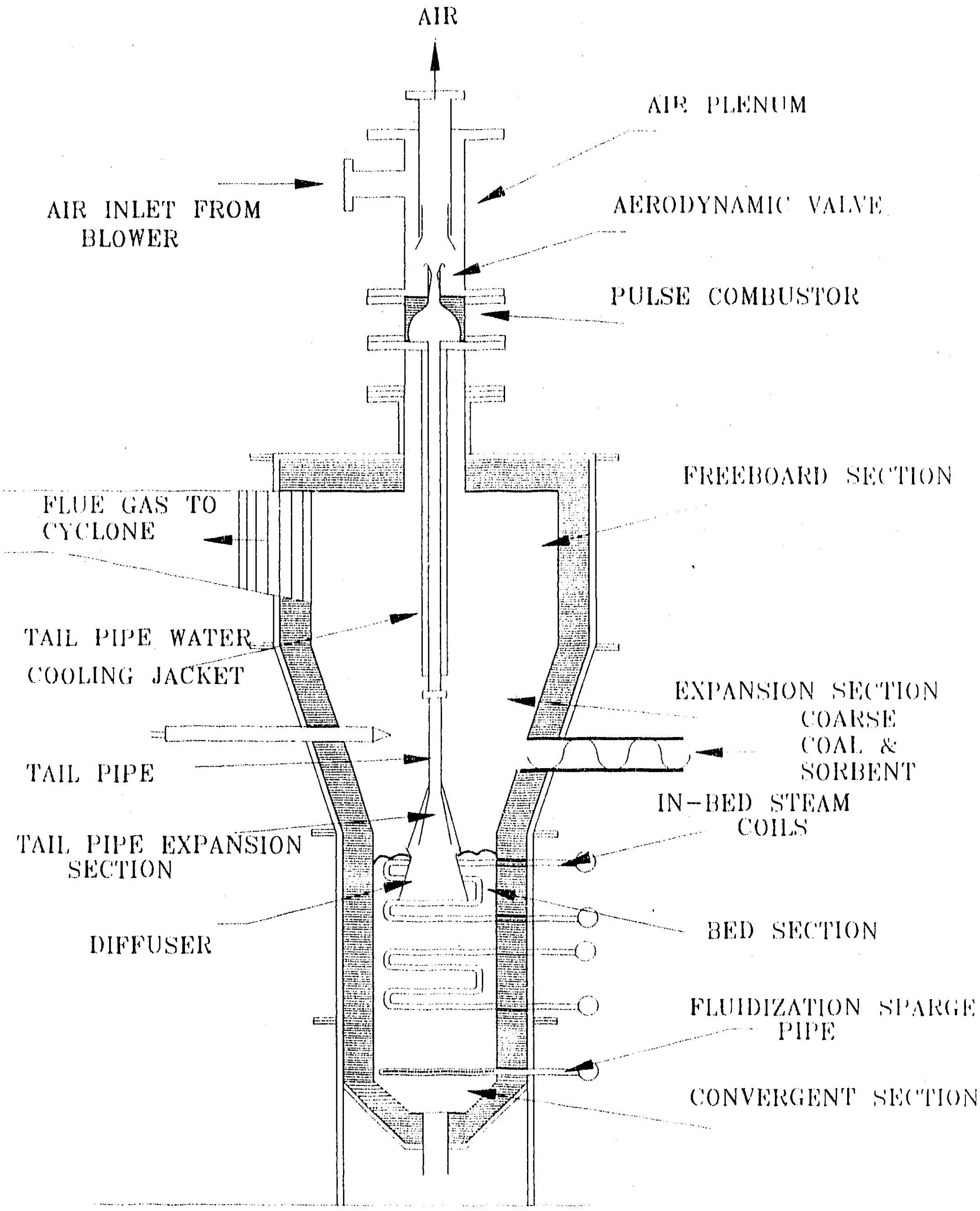


FIGURE 1-1: THE MTCI PULSED ATMOSPHERIC FLUIDIZED BED COMBUSTOR

The pulse combustor is a compact, auxiliary burner with no moving parts (**Figure 1-2**) consisting of:

- Flow diode
- Combustion chamber
- Resonance tube

Fuel and air enter the combustion chamber (**Figure 1-3**). An ignition source (not shown) detonates the explosive mixture during start-up. The sudden increase in volume, triggered by the rapid increase in temperature and evolution of combustion products, pressurizes the chamber. As the hot gas expands, the flow diode permits preferential flow in the direction of the resonance tube.

Gases exiting the hot combustion chamber in the resonance tube possess significant momentum. A vacuum is created in the combustion chamber due to the inertia of the gases within the resonance tube. The inertia of the gases in the resonance tube permits only a small fraction of exhaust gases to return to the combustion chamber; the balance of the gas exits the resonance tube. Since the chamber pressure is below atmospheric pressure, air and fuel are drawn into the chamber where autoignition takes place. Again, the flow diode constrains reverse flow, and the cycle begins anew. Once the first cycle is initiated, engine operation is self-perpetuating.

The flow diode utilized in many other pulse combustion concepts is a mechanical "flapper valve." The flapper valve is actually a check valve permitting flow from inlet to chamber, and constraining reverse flow by a mechanical seating arrangement. This served quite well for the purpose intended. MTCI's pulse combustor technology is designed for a much longer service life utilizing an aerodynamic valve without moving parts as an effective alternative to the flapper valve.

During the exhaust stroke, the boundary layer builds in the reverse direction. Turbulent eddies choke off much of the reverse flow. Moreover, the exhaust gases are of a much higher temperature than the inlet gases. Therefore, the viscosity of the gases is much higher and the reverse

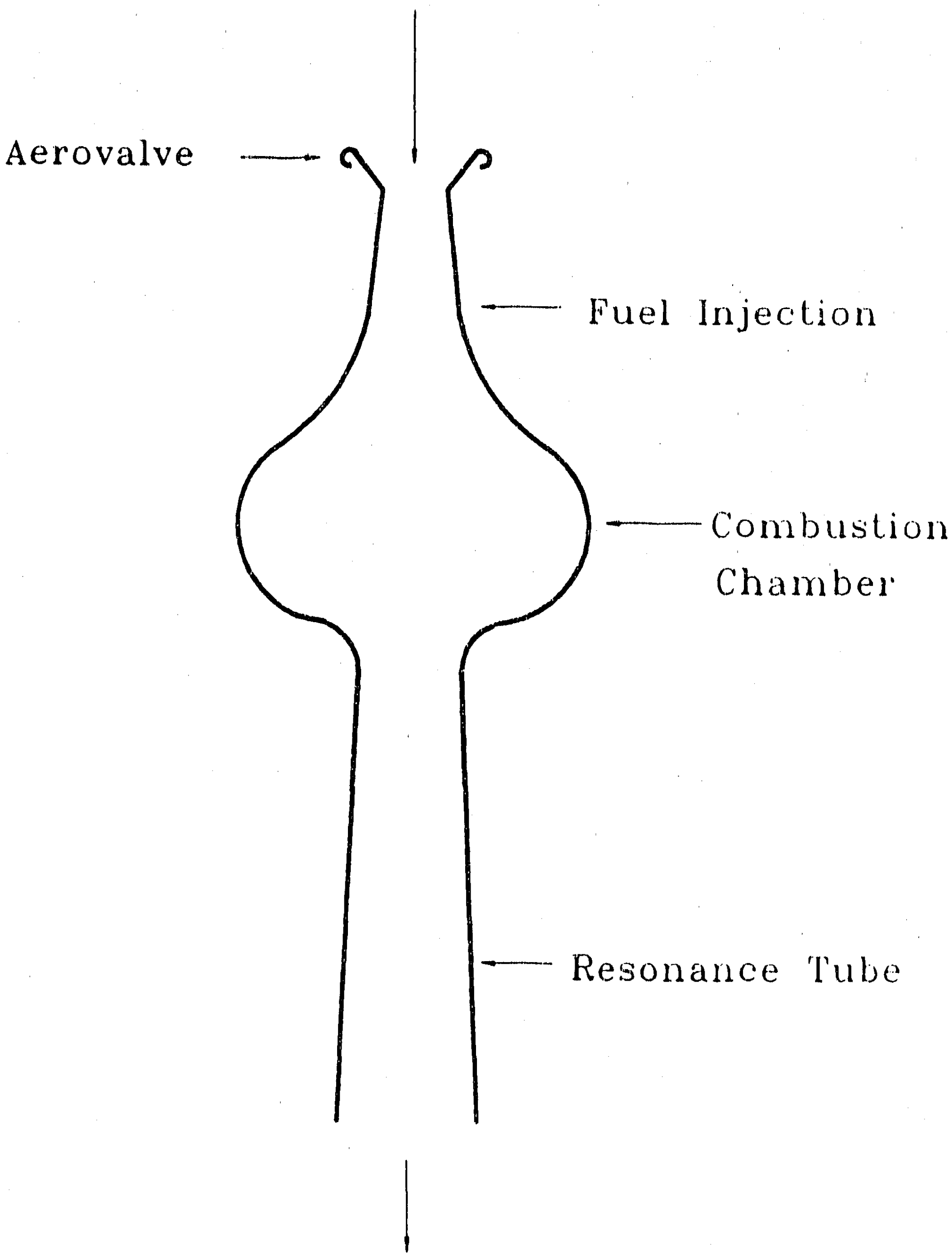


FIGURE 1-2: SCHEMATIC OF A PULSE COMBUSTOR

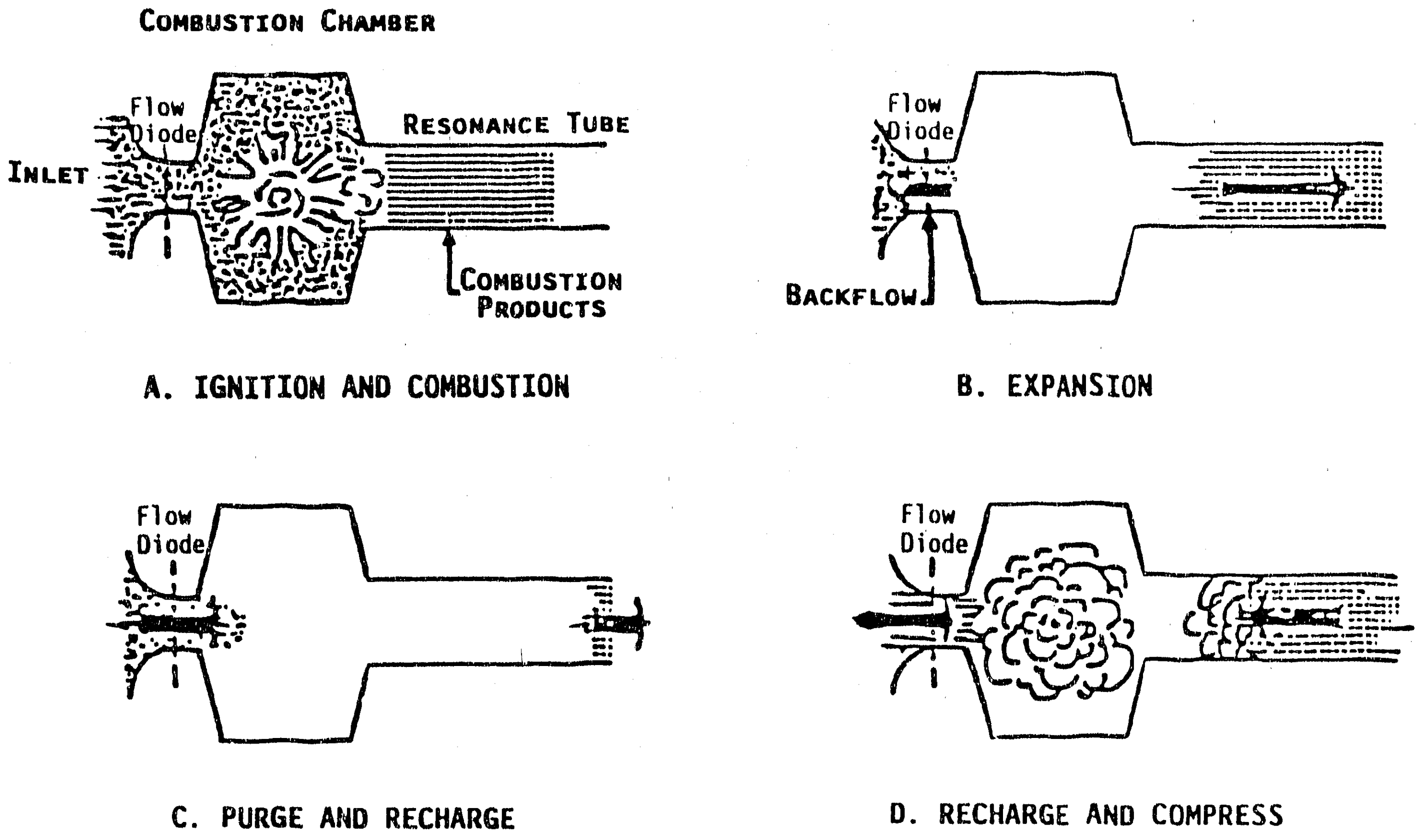


FIGURE 1-3: PULSE COMBUSTION PRINCIPLE OF OPERATION

resistance of the inlet diameter, in turn, is much higher than forward flow through the same opening (unlike liquids, gases exhibit a marked increase in viscosity with temperature rise). These phenomena, along with the high inertia of the exhausting gases in the resonance tube, combine to yield preferential and mean flow from inlet to exhaust. Thus, the nonmechanical pulse combustor is a self-aspirating engine, drawing its own air and fuel into the combustion chamber and auto-ejecting combustion products.

A wide tolerance of operating parameters gives excellent turndown ratios up to 20:1. Turndown ratio is the ratio of design capacity divided by lowest operating capacity. This enables the pulse combustor to operate from sub-stoichiometric to superstoichiometric regimes. These attributes allow great system flexibility. While operating in a superstoichiometric mode, the pulse combustor functions as a nonmechanical air pump. MTCI has obtained 400 percent excess air operation in an existing pulse combustor. With proper thrust augmenters, much more air than that needed by the PAFBC can be pumped by the pulse combustor.

The rapid pressure oscillations in the combustion chamber (from 25 psia to subambient on the order of 100 times per second) generate an intense oscillating flow field. This oscillating flow field effectively scrubs the boundary layer away from the burning particles (**Figure 1-4**). In the process of pulsating combustion or combustion-induced flow oscillations, much of the diffusion limitation is removed. These reactors tend to achieve high-pressure fluctuations and high-velocity flow oscillations. This results in a number of beneficial combustion process advantages that enhance system performance.

In the case of coal combustion, the fluctuating flow field causes the products of combustion to be swept away from the reacting solid, thus providing access to oxygen with little or no diffusion limitation. Second, pulse combustors experience very high mass transfer and heat transfer rates within the combustion zone. While these reactors tend to have very high heat release rates (6 to 8 times those of conventional burners), the vigorous mass transfer and high heat transfer within the combustion region result in a more uniform temperature. Thus, peak temperatures attained are much lower than in

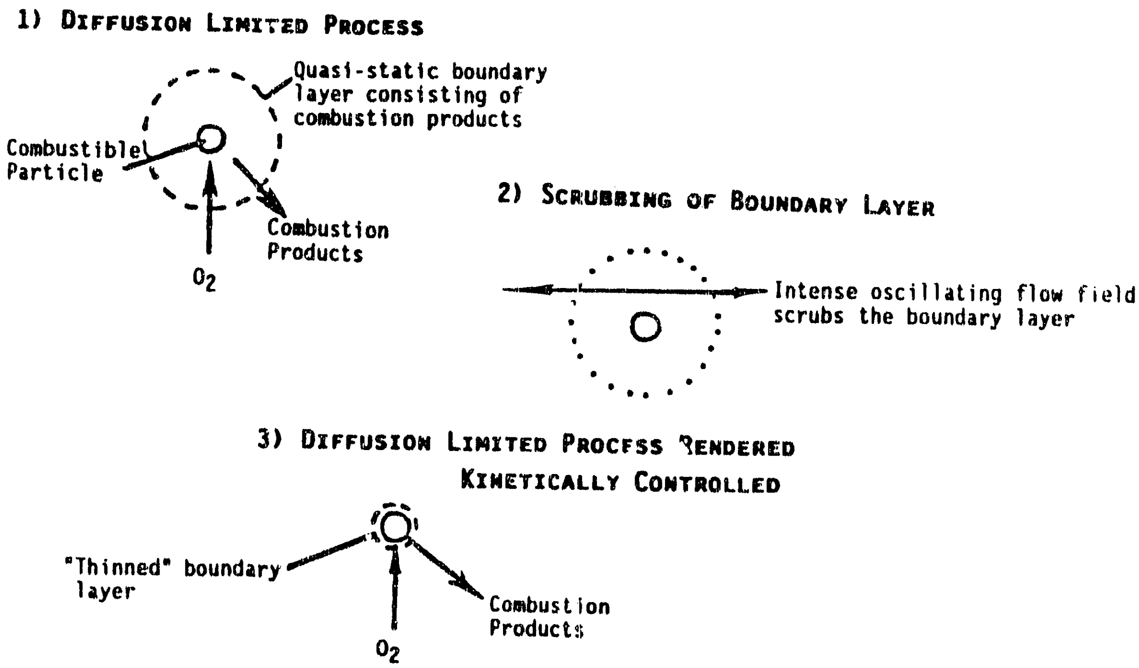


FIGURE 1-4: EFFECT OF AN INTENSE ACOUSTIC FIELD ON THE BOUNDARY LAYER

the case of conventional systems. This results in a significant reduction in nitrogen oxide (NO_x) formation.

The enhanced access by oxygen to the other reactants in pulse combustion reduces the need for significant excess air operation and higher reactor temperature. The high heat release rates also result in a smaller reactor size for a given rate of material processed and a reduction in the residence time required. Similar enhancement of heat and mass transfer rates can also be expected in the FBC, due to the acoustic enhancement transmitted to the bed from the pulse resonance tubes. The bubble sizes are expected to be smaller and more evenly distributed in the pulse fluid bed than in a regular BFBC.

Another benefit of utilizing pulse combustors is that they aspirate their own combustion air. The amount of air aspirated is a function of the firing rate of the burner and the aerodynamic valve fluidic diodicity and is automatically adjusted by fuel feed rate. Pulse combustors do not require combustion air fans nor do they require controls to coordinate the mass flow rates of fuel and combustion air. Pulse combustors also develop an induced mean pressure boost within the combustion chamber and expel the products of combustion at high kinetic energy levels (in the order of 600 - 800 ft/sec). The kinetic energy, which is totally combustion-induced with no mechanical systems required, can be employed to aspirate more air through a venturi section for supply of fluidization air if necessary.

Pulse combustors also have the ability to produce large pressure fluctuations at the desired frequency range without the need for energy to compress air or supply the electricity in electromagnetic devices. This, in turn, provides for sufficient oscillations in the flow velocity of the fluid bed to enhance mass transfer and heat transfer in the bed. This is expected to improve both combustion rate and the rate of sulfur capture in the bed while maintaining the bed temperature sufficiently low for suppression of NO_x. The pressure fluctuations are believed to be most effective in the low-frequency regime (50 - 150 Hz and cannot be economically achieved with other methods, i.e., air horns or electromagnetic devices).

Experiments with other methods of acoustic excitation have failed to affect the reaction rates in a fluid bed significantly because of these factors. First, higher frequencies tend to damp out in the fluid bed very quickly. This is due to the short wavelengths with small relative displacement amplitudes between the solids in the bed and the oscillating gas flow. Researchers mostly employed high frequencies due to the fact that high sound pressure levels can be achieved with high frequency by expending manageable amounts of energy when using air horns and electromagnetic devices. Second, excessive energy was required to achieve the necessary sound pressure levels at a more effective frequency range when such excitation was induced using compressed air horns and electromagnetic devices. This is not a problem with pulse combustion.

The pressure boost developed due to pulse combustion can also be employed to fluidize the bed and, if desired, operate a cyclone to separate particulate emissions from the AFBC effluent. With a high aerodynamic valve fluidic diodicity, the pressure drop for both fluidizing the bed and for particulate matter separation from the effluent of the AFBC (in a cyclone or a baghouse) can be supplied by the pulse combustor without the need for large fans or many moving parts. This increase in performance reliability reduces costs, simplifies operation, and increases throughput.

MTCI's pulse combustion experience ranges from bench-scale (50,000 Btu/hr) to pilot-scale (15 MMBtu/hr) for application to residential space heating, commercial and industrial retrofit, and direct coal-fired gas turbines. The fuels tested include natural gas, propane, fuel oil, dry pulverized coals, dry micronized coals, coal fines, and coal-water slurries. The test results have confirmed high volumetric heat release rate (3 to 5 MMBtu/hr/ft^3/atm), high combustion efficiency (99 + percent), low NO_x emissions (25 to 70 ppm), and stable operation for a wide range of stoichiometry.

1.4 REPORT ORGANIZATION

Section 2.0 provides a description of the project and the scope of work. Section 3.0 gives a summary of the feasibility study conducted under Task 1 of this program. Section 4.0 provides a detailed account of the laboratory-scale development and testing effort performed under Task 2. Section 5.0 deals with preliminary design for proof-of-concept integrated test facility development and field demonstration under Task 3.

SECTION 2.0

PROJECT DESCRIPTION AND SCOPE OF WORK

The overall objective of this program, sponsored by the U.S. Department of Energy (Contract No. DE-AC21-88MC25069), is to develop the pulsed atmospheric fluidized-bed combustion (PAFBC) technology to burn coal and to provide heat and steam to commercial, institutional, and industrial applications at a reasonable price and in an environmentally acceptable manner. This overall objective will be met by performing a number of tasks at two different levels.

The Task 1 objective is to establish preliminary feasibility by the use of theoretical and state-of-the-art information. The Task 2 objective is to build and experimentally establish operability and performance of the PAFBC for different types of coal.

2.1 TASK 1: FEASIBILITY

Subtask 1.1: Evaluation - The Contractor shall perform evaluation of state-of-the-art information on atmospheric fluidized-bed combustor (AFBC) technology and pulse combustion of coal. The Contractor shall review relevant published data and evaluate it for use in the feasibility study. Data on coals, sorbents, SO_2 and NO_x control, characteristics of fluidized-bed coal combustors, pulsed combustion of coals, regeneration of spent sorbents, steam generation, ash disposal, and other aspects shall be used to formulate a design basis for the study.

Subtask 1.2: Market Analysis - For the new technology, the Contractor shall identify potential markets for generating heat and steam for different uses and shall make projections on the increased use of coal. The Contractor shall assess the competition from oil- and gas-fired units.

Subtask 1.3: Conceptual Design and Cost Estimate - Using the design basis formulated in Subtask 1.1, the Contractor shall develop a conceptual design of a PAFBC system that will produce 1,000 lbs/hr of steam equivalent. The Contractor shall prepare a preliminary cost estimate and shall compare the cost of the proposed system with the cost of oil- and gas-fired units currently in use.

Subtask 1.4: Test Plan for Task 2 Work - The Contractor shall identify problematic aspects of the technology and develop a test plan to resolve the problems through theoretical and experimental approaches. The Test Plan shall be submitted to the DOE/Contracting Officer's Technical Representative (COTR) for review and approval.

Subtask 1.5: Task 1 Topical Report - A Topical Report shall be prepared summarizing the PAFBC package boiler concept. The report shall include market, technical, design and cost information developed under Subtasks 1.1, 1.2, and 1.3, and the Test Plan developed under Subtask 1.4. The report shall include a review of the coal/sorbent feed, ash handling and cleanup systems, and the sensitivity of these factors on performance, and system capital and operating and maintenance costs. The report shall also address the system's potential for meeting the following criteria and provide the material required to proceed to the performance of Task 2:

- The PAFBC combustor and controls technology must be competitive with gas-/oil-fired technology and scaleable to the 1,000 lb/hr steam equivalent range.

- The solids handling problems must be amenable to automated dust-free operation.

- Overall emissions (SO_2, NO_x, and particulates) must be comparable to those of conventional gas-/oil-fired equipment.

- The PAFBC system must require no operating or maintenance skills beyond those needed to operate equivalent gas-/oil-fired equipment.

- A significant market potential must exist for the integrated PAFBC technology.

2.2 TASK 2: LABORATORY-SCALE DEVELOPMENT AND TESTING

The testing specified in these subtasks will be conducted in accordance with the approved Test Plan.

Subtask 2.1: Design, Procurement, and Construction of an Atmospheric Fluidized-Bed Combustor - The Contractor shall design, procure, and build a fluidized-bed system with the following features:

Capacity:	1,000 lbs steam/hr
Fluidizing Velocity:	5 - 10 ft/sec
Sorbent:	Precalcined dolomite or limestone
Coal:	Bituminous/Sulfur Content: 2 - 4%
Temperature of Operation:	1400 - 1750°F

Subtask 2.2: Coal Combustion Tests in the AFBC System - The Contractor shall carry out coal combustion tests under a range of conditions as set forth in the approved Test Plan to establish baseline performance data. Tests shall be carried out under the following conditions:

Superficial Velocity:	5 - 10 ft/sec
Temperature:	1400 - 1750°F
Pressure:	Near Atmospheric
Mode of Operation:	Batch with respect to sorbent and continuous with respect to coal
Coal:	Bituminous/Sulfur Content: 2 - 4%
Sorbent:	Precalcined dolomite or limestone
Ca/S:	2 - 4

The Contractor shall use the test data to optimize operational parameters with respect to fluidization velocity, sorbent/coal ratio, temperature of operation, combustion efficiency, steam generation, NO_x control and sulfur capture, and establish optimum operational parameters and baseline performance data.

Subtask 2.3: Modification to a PAFBC System - The Contractor shall modify the AFBC system by the incorporation of a pulse combustor that supplies pulsed effluent gas to fluidize the bed. The needed modifications and the geometry of the pulsed combustor (PAFBC) shall be as determined under Subtask 1.3 study.

Subtask 2.4: Operation of the PAFBC Without Coal - The Contractor shall operate the fluidized-bed combustor in the pulsed mode to establish fluidization parameters under pulsing conditions and determine the effect of pulsations on fluidization velocity, bed expansion, and particle elutriation.

Subtask 2.5: Coal Combustion Tests in the PAFBC System - The Contractor shall carry out coal combustion tests under a range of conditions established under Subtasks 2.1 and 2.4, generating test data to evaluate operability, performance and pollution control efficiency of the PAFBC system, and optimization of design and operational parameters.

Subtask 2.6: Technical, Environmental, and Economic Assessment - The Contractor shall perform technical, environmental, and economic evaluations based on experimental data generated under Subtasks 2.2, 2.4, and 2.5.

SECTION 3.0

FEASIBILITY STUDY

The objective of this task was to establish preliminary feasibility by means of technical, market, and cost analyses. The work was divided into five subtasks comprising:

- Technical evaluation
- Market analysis
- Conceptual design and cost estimate for a PAFBC system
- Test plan for Task 2
- Task 1 topical report

The results from this study are summarized below. For detailed description and discussion, the reader is referred to the Task 1 Topical Report.[2]

3.1 TECHNICAL EVALUATION

Although there are many variations in the designs offered by different boiler vendors,[3,4,5] AFBC systems can usually be classified into two types: bubbling bed (BFBC) and circulating bed (CFBC). To control temperatures in the bubbling-bed design, water-wall enclosures and/or in-bed boiler tubes are used. The steam output is controlled by adjusting bed height, temperature, fuel input, and gas velocity. In the circulating-bed system, the air fluidization velocity is high enough (14 to 30 ft/s) so that the solids are entrained at a relatively high rate and then recirculated back into the lower, denser portion of the fluid bed. Circulating fluidized bed boilers tend to have higher combustion efficiencies than the bubbling-bed designs. Other advantages over the bubbling-bed design are that circulating systems require less demanding fuel-feeding techniques, less limestone to capture sulfur dioxide, and can be more easily adapted for reduced emissions of NO_x.

The operational mode sets the requirements for how the system is designed to control combustion and desulfurization. The heat of combustion must be removed to control the temperature at the optimal level for SO_2 absorption with good carbon utilization. SO_2 absorption is optimized at about 1500 to 600°F for typical units of either type. In BFBC, feed point location (overbed or underbed) can be crucial. The maximum velocity at which an FBC is to be operated determines the cross-sectional area and height of the combustor, as well as the design options for removing the heat of combustion. The design relationships are even more complex in a CFBC, which is essentially a longitudinal chemical reactor with cooling at the walls. Here, the height is a function of velocity and water-wall heat transfer requirement.

<u>BFBC</u>

At the lower velocities of bubbling-bed FBC, in-bed boiler tubes historically have been used to remove the heat released and maintain the desired temperature. The overall heat transfer coefficients in the fluidized bed are relatively high (40 to 70 Btu/hr/ft^2/°F). Therefore, good heat transfer characteristics are experienced with in-bed tubes at the moderate combustion temperatures. The disadvantage of in-bed tubes is that at velocities above approximately 7 ft/sec, the tubes must be protected against erosion. Techniques that appear to be working include studding the susceptible tube surfaces with closely spaced studs, attaching longitudinal or axial fins, and coating or sleeving the surface with a protective ceramic, harder metal, or sacrificial metal. Thick tubes may also be used to allow for wear.

Combustion and desulfurization control in BFBC depends on maximizing fuel and limestone retention in the bed to reduce the elutriation of fines and unburned carbon. This may be accomplished by the use of low gas velocities and screened stoker coal and limestone to limit the amount of incoming fines if overbed feeding is used. If the fines are pneumatically fed underbed or into the lower part of the bed, more fines in the fuel can be tolerated. The residence times in the bed are also increased, thereby ensuring more complete burnout. However, a problem with large capacity BFBC is uniformly distributing the fuel and limestone over the cross sectional area of a large bed.

Excessive burning of fines in the freeboard can lead to greater amounts of CO, NO_x and SO_2 in the flue gas. In cases of excessive carry-over of limestone fines and/or fuel fines, fly ash recycle may be necessary to maintain good limestone utilization and carbon burnout. The recycle must be pneumatically reinjected into the bed. In some cases, the fly ash is abrasive and can cause erosion problems in the recycle lines.

CFBC

Because of the high velocities in CFBC, combustion, heat transfer, and desulfurization controls are handled differently from that of BFBC. This design improves carbon burnout and NO_x, SO_2, and CO control relative to bubbling beds. Apart from the differences in the primary solids separation and solids reinjection system designs, an emerging design feature of various CFBC designs is the inclusion of an external, low-velocity fluidized bed heat exchanger (EHE) to control the temperature of the circulating hot solids.

The high velocities in the CFBC also dictate that the combustor be much taller than in a BFBC to provide sufficient residence time for combustion and SO_2 capture. Essentially all the carbon must be burned up before the gas-solid mixture reaches the cyclone to prevent hot spots and agglomeration in the cyclone. Typical heights are 60 feet from floor to roof for a 200,000 lb/hr unit and 100 to 120 feet for a 500,000 lb/hr unit. The tall combustor also provides additional residence time for CO burnout, multiple air staging, velocity control, and improved NO_x control relative to BFBC. Long gas phase residence time is afforded by combustor height, whereas long solids residence time is afforded by recirculation. Adequate residence times together with good mixing permit better sulfur capture at lower Ca/S ratios in CFBC than in BFBC.

ADVANCED CONCEPTS

Several advanced concepts[6-9] have been proposed for the small-scale market sector (10,000 to 150,000 PPH steam) and are under development with funding from DOE. Riley Stoker[6] is in the midst of a five-year program to develop a CFBC based on the multi-solids fluidized bed process for industrial applications (75,000 to 150,000 PPH steam). A technical analysis has been conducted and a conceptual design has been developed for meeting the process steam requirements of the intermediate-sized industrial boiler market. York-

Shipley Division of DONLEE Technologies, Inc.[7] is continuing development work on a two-stage, combined circulating fluidized bed and cyclone combustion process. The advantage claimed for this system as compared to conventional CFBC is reduction in combustor size (cross-sectional area and height) and, in turn, cost. Recall the discussion in Section 1.1 which points out that it is both impractical and expensive to scale-down conventional CFBC to sizes significantly smaller than 100,000 PPH steam equivalent. A 1.5 MMBtu/hr unit has been built and tested on wood. Coal combustion and further unit scale-up to 60,000 PPH steam equivalent are in process. Hydrocarbon Research, Inc. and its partners, Dr. F.A. Zenz and Petro-Chem Development Company, Inc., are developing a new concept[8] termed Dual-Sided Multi-Riser AFBC. This concept employs a dense-phase, bubbling fluidized bed with riser-downcomer for internal circulation of dilute-phase. This scheme claims to alleviate two major shortcomings of conventional BFBC, viz. turndown capability and compactness. Plans include the design, fabrication and testing of bench- and pilot-scale combustor units. Battelle[9] has developed and tested a spouted fluidized bed combustion (SFBC) concept. The experimental work included cold model studies and hot model (2.6 ft^2 cross-sectional area) coal combustion tests to evaluate concept performance. The SFBC hot model demonstrated small but statistically significant advantages in SO_2 and NO_x emissions and in calcium utilization when compared with BFBC performance.

Since the above-cited concepts as well as the MTCI PAFBC concept are passing through developmental phase, it is considered premature and imprudent to compare PAFBC with these advanced concepts. The conventional BFBC and CFBC, however, are established technologies and therefore the attributes of PAFBC in comparison to BFBC and CFBC will be pointed out in the discussion that follows.

3.1.1 <u>Performance Considerations</u>

The performance of AFBC is affected by the rate of combustion of coal, which in turn is affected by coal properties (devolatilization, swelling, fragmentation, and char combustion), feed particle size range, feed system and combustion-enhanced mechanical attrition, heat and mass transfer rates, and unit operating conditions. In AFBC, the carbon carryover into the primary particle separator is generally high due to limited residence time of fuel fines in the combustor. To achieve high carbon utilization efficiency, recycling of fines to the bed is often practiced. These recycle processes add to system complexity and cost and at times are prone to plugging. In the MTCI PAFBC technology, higher combustion efficiency can be attained because the fuel fines are burned in the pulse combustor and only the coarse coal is burned in the fluid bed.

The three "Ts" of combustion (temperature, turbulence, and residence time) for the pulse combustor and the bubbling fluid-bed freeboard are quite different, as shown below.

	Pulse Combustor	**AFBC Freeboard**
Temperature (°F)	> 2000 (High)	1550 (Low)
Turbulence	Very High (Oscillatory)	Moderate (Plug flow with back mixing)
Residence Time	10 to 100 milliseconds	2 to 3 seconds

Since MTCI's PAFBC employs both the pulse combustor and the AFBC technologies, it can handle the full-size range of coarse and fines. The oscillating flow field in the pulse combustor provides for high interphase and intraparticle mass transfer rates. Therefore, the fuel fines essentially burn under kinetic control. Due to the reasonably high temperature (> 2000 °F but less than the temperature for ash fusion to prevent slagging), combustion of fuel fines is substantially complete at the exit of the pulse combustor. The additional residence time of 2 to 3 seconds in the freeboard of the PAFBC unit then ensures high carbon conversion and, in turn, high combustion efficiency.

The devolatilization and combustion of fuel fines in the pulse combustor also enable the release of a significant portion of sulfur by the time the fuel fines leave the tailpipe. This sulfur has a high probability of capture in the dense fluid bed due to the pulse combustor effluxing into the fluid bed.

The acoustic field radiated into the fluid bed enhances the mass transfer rate and in turn increases the reaction rate between the sorbent and SO_2. This a priori sulfur release, acoustic enhancement in the fluid bed mass transfer process, and the fines recirculation as a consequence of the draft tube design help achieve high sulfur capture efficiency at low Ca/S molar feed ratio, which leads to lower limestone and waste disposal costs.

The solid waste will likely consist of lower alkali content, thus minimizing alkaline run-off if the PAFBC wastes are land-filled. Pulse combustors are inherently low NO_x devices.[10] Keller and Hongo[11] investigated the mechanisms of NO_x production in pulse combustion and concluded that several complementary mechanisms are responsible. The rate of heat transfer in the pulsating flow is higher than that in conventional steady flow and helps create lower overall temperature in the combustion chamber. Also, the high rates of mixing between the hot combustion products and the cooler residual products from the previous cycle and the incoming cold reactants create a short residence time at high temperature quenching the NO_x production. These complementary mechanisms create an environment which approximates a well-stirred tank at relatively low temperature and result in low NO_x production. The dense fluid bed, due to operation at low temperature (~ 1550°F) and with coarse fuel particles, enjoys a lower NO_x production as well. Consequently, the NO_x emissions from PAFBC are likely to be lower than that of AFBC.

In summary, the integration of the pulse combustor with the fluid bed serves to minimize the concentration of fuel fines in the freeboard and in turn improves carbon conversion, combustion efficiency, and sulfur capture efficiency and lowers CO and NO_x emissions. Therefore, it is anticipated that recycle of fines will not be necessary in the PAFBC configuration.

The overall heat transfer coefficient in the water-jacketed pulse combustor tailpipe is about 40 Btu/hr/ft^2/°F and is of the same order as that for tubes immersed in the dense fluidized bed. The replacement of the inefficient heat exchanger in the freeboard of a conventional BFBC by the water-jacketed pulse combustor tailpipe significantly decreases the heat transfer surface area requirement and cost.

The ability of the pulse combustor to also efficiently combust a wide variety of fuels makes it compatible with the fluid bed in that designs for alternative fueled systems can easily be integrated into a packaged product with a minimum of modifications. The result of being able to package systems for predominant regional usage provides an important advantage in a marketing strategy. In addition, the ability of the pulse combustor to burn fines provides advantages with respect to fluid-bed performance and fuel costs.

3.1.2 Coal and Sorbent Feed System

A uniform distribution of coal and sorbent feed over the fluid-bed area is highly desirable. For small-scale units with bed areas of less than nine square feet, a single feed point appears to be satisfactory (based on the experiences at Rivesville, Georgetown University, Alexandria PDU, Babcock & Wilcox 6′ x 6′, and TVA 20 MW_e) for the introduction of coal or limestone into the combustor. For larger scale units, multiple coal and sorbent feed points are required for maintaining a uniform solid particle distribution. However, there are several specific problems related to fuel feed which must be addressed by the developers of small-scale fluidized bed systems. These include maintaining accurate, continuous feed from the coal and limestone bunkers into the bed, eliminating plugging in the conveying lines, minimizing erosion of conveying lines, minimizing coal and sorbent storage requirements, and identifying the simplest, most reliable and least expensive coal/sorbent handling and feed subsystems.

Attributes of the coal feed system have a profound impact on the performance and economics for small-scale fluidized bed combustors. The method and location of coal introduction influences the achievable level of carbon burnout, CO emissions, and sorbent utilization within the bed, and it may have a direct relation to system reliability, turndown capability, and load response.

Ideally, the coal feed system for the FBC boiler should possess the following characteristics:

- Uniform and continuous metering of coal over a wide control range
- Low sensitivity to coal feed specifications, size distribution, and moisture content
- Utilization of commercially proven concepts and components
- Easily maintained and of high reliability
- Low capital and operating costs.

Basically, there are four feed systems that are applicable to the fluidized bed combustion system. Shang[12] compares gravity chute feed, screw conveyor feed, pneumatic injection and spreader stoker systems. The gravity chute feed system feeds the fuel and sorbent into the fluidized bed through a chute by gravitational force. Although it is a simple and inexpensive feed system, there are two major problems associated with this method. Pressure surges in the boiler may blow the fines in the feed back to the coal or limestone bunkers and boiler exterior. Another problem associated with this system is formation of a fuel-rich environment near the outlet of the gravity chute. Shang reports that the fuel-rich region is highly corrosive and could result in material failure. He suggests installation of slanted distributor plates with gravity chute feed for small-scale AFBC systems. A slanted distributor induces a strong "gulf stream" which forces the fresh feed to move downward and prevents the formation of a fuel-rich region in the bed.

A screw conveyor feeds fuel and sorbent into the fluidized bed by positive displacement of the screw flights. The screw conveyor may have a variable pitch to build up a pressure seal to prevent backflow of flue gas or leakage from the boiler. Shang also suggests installation of a by-pass vent between the coal feed tube and the combustor freeboard when feeding volatile coal. The ability of the screw feeder to maintain a constant feed against a high back pressure is a distinct advantage of this type of feeder. Generally, a single-screw feeder can be used for a bed area of up to nine square feet.

Pneumatic injection of fuels and sorbents into the fluidized bed is done by the introduction of solids in an air stream at a velocity above the saltation velocity of the solid particles. In theory, it is an ideal design. In practice, there are some problems associated with line plugging and erosion, and attrition of the solid particles in the pneumatic line. Another problem is elutriation of fines in coal and sorbent due to the necessary high air-solid stream pressure which penetrates the fluidized bed and discharges into the freeboard.

Spreader stoker is an alternative to pneumatic feeding. The spreader stoker spreads the coal particles into the FBC bed with a maximum reach of 23 feet. In a fluidized bed using spreader stoker, the fine particles tend to be carried out of the combustor before they land on the bed, thus resulting in high elutriation. The spreader also promotes size segregation by throwing the largest particle to the far side and small particles near the spreader. The size segregation can cause in-bed carbon concentration differences which will affect the overall performance of the fluidized bed. Unfortunately, the use of spreaders incurs a high amount of coal fine loss due to elutriation. Unless a high freeboard is used to burn up the elutriated fines in conjunction with fly ash recycle, the loss of combustion efficiency can be substantial.

As previously mentioned, a feed system must be selected which has low maintenance requirements and which can be automated and operated on demand with minimal operator attention. In contrast with AFBC boiler economics at a large-scale (greater than 10,000 PPH steam), steam production costs at the small-scale (< 50,000 PPH) are sensitive to operator costs. Therefore, it is evident that the FBC boiler, including feed components, must be capable of smooth operation with only occasional monitoring and maintenance performed by non-dedicated personnel or, where required by local law, the equivalent personnel used in oil- or gas-fired steam raising installations.

In the MTCI PAFBC system, both coarse and fine material will be used in order to take advantage of the lower cost of unsized feedstocks. The coarse coal fraction and the sorbent will be fed overbed using commercially proven screw feeders and the fine coal fraction will be pneumatically conveyed to the pulse combustor. A slanted distributor will be used for the fluidized bed to induce "gulf stream" solids circulation and minimize fuel-rich zones in the bed.

3.1.3 ENTRAINMENT AND ELUTRIATION

Excessive particle entrainment from a BFBC into the freeboard can be explained by the bursting of the bubbles at the bed surface which throws solid particles upward at high velocities. The gas bubbles bursting can be compared to intermittent jets imposing a highly irregular velocity across the combustor vessel. The jet velocities eventually are dissipated to the superficial gas velocity at some equilibrium height above the bed surface, commonly referred to as the Transport Disengagement Height (TDH). The entrainment above the TDH is relatively constant and can be the assumed to be maximum dilute-phase carrying capacity of the gas at its superficial velocity. The freeboard height then should be at least the TDH. The TDH is dependent on the gas bubble velocity and typically increases with increasing bubble size and fluid-bed diameter.

Zenz and Weil(13) presented an empirical correlation (based on operating data) for estimating TDH for different vessel diameters and superficial gas velocities. This correlation indicates that for a 2-foot diameter bed, 6 to 10 feet of freeboard height will be needed for a conventional BFBC. In the PAFBC, the TDH is anticipated to be lower than for conventional BFBC due to the following reasons: 1) the horizontal heat exchange tubes (in-bed heat transfer tubes) will tend to break up the bubbles, and 2) the oscillating flow field supplied by the pulse combustor will tend to limit the growth of the bubble size and make the bed more uniformly agitated. With respect to the stabilization of bubbles, A.D. Little(14) attempted to use sonic horns and Exxon R&D(15) has employed magnetic fields with mixed results. MTCI's pulse combustor generates acoustic waves that can potentially reduce the bubble size growth in a more practical manner leading to a more compact design and a higher carbon burn-out efficiency.

Based on these considerations, it is anticipated that for small-scale AFBC applications, the optimum configuration will consist of a refractory-lined furnace containing the fluidized bed. Heat removal from the bed will be controlled using immersed tubes. The freeboard will be expanded to decrease gas velocity, decrease elutriation of fines, and provide adequate gas and solids residence times for shorter freeboard and overall furnace heights.

3.1.4 AIR DISTRIBUTION SYSTEM

Conventional large-scale FBC boilers typically operate under balanced draft conditions employing a forced draft blower and an induced draft fan. The unit is generally balanced at the surface of the fluid bed. Conventional bubbling bed FBC boilers require a forced draft delivery pressure of approximately 3 psig. A portion of the forced draft pressure is dissipated through the air distributor grid, while the balance is dissipated in the fluid bed itself. The induced draft fan provides the necessary suction to draw flue gas through the boiler bank, economizer and baghouse dust collector prior to stack discharge. The capital and operating costs of the forced draft fan in a FBC boiler significantly exceed that for an oil- or gas-fired boiler, or even a pulverized coal boiler. The requirement for a high pressure fan is particularly detrimental to the economics of small-scale FBC boilers, and improvements in operating cost could be made by reducing the need for such fans.

In the MTCI PAFBC system, the pulse combustor would be employed to augment the pressure boost supplied from the forced draft fan. Pulse combustors were originally investigated as a low-cost thrust or propulsion device. Pulse combustors are aerodynamically designed to translate thermochemical energy into mechanical energy in the form of pressure boost or momentum. In the PAFBC design, the thrust capability of a pulse combustor is utilized to supplant or augment the function of the forced draft fan. Motive force from both the aerovalve and the tailpipe exhaust are used. A thrust augmentor is employed to supply combustion air to the bottom of the fluid bed. A diffuser at the tailpipe exit is used to recover pressure to the maximum extent. This design will minimize the need for an induced draft fan, greatly enhancing system operation costs.

3.1.5 LOAD CONTROL

Means for achieving rapid start-up and transient response over a wide range of load control is a key design issue for small-scale FBC boilers. Large industrial units may be designed for base-load operation at high capacity factors. In contrast, small FBC boilers generally exhibit low capacity factors and require high turndown ratios (5:1). Several different load control methods have been proposed for FBC boilers. These include 1) use of multiple or compartmentalized beds, 2) control of bed inventory to expose or immerse tube surface, and 3) allowance for some degree of bed temperature float.

Control method 3 offers a relatively limited means of load control. Optimum bed temperatures for efficient sulfur capture range from 1500 to 1600°F. At lower temperatures, the rate of lime sulfation is too low. At higher temperatures reduced sorbent activity through sintering can occur. Reduced bed temperatures also result in increased carbon inventory within the bed and typically lowered combustion efficiencies. Since the temperature differential between the fluid bed and the steam coils is large, small changes in bed temperature contribute little to changes in the heat transfer driving force. Furthermore, since the immersed tube area is relatively constant and the fluid-bed side heat transfer coefficient changes only modestly with load, little flexibility in load control can be achieved using a floating bed temperature approach.

Control method 2 affords an improved degree of load control by varying the quantity of heat transfer surface which is immersed within the bed. In this approach, load is reduced by discharging a portion of the bed material in order to expose heat transfer surface. Since the heat transfer coefficient in the freeboard is considerably lower than in the bed itself, a significant reduction in heat removal can be achieved. It should be mentioned that during turndown, a reduction in expanded bed height occurs. A properly designed system may utilize this fact to naturally expose heat transfer surface in a manner which follows load. Although this method allows an increased load control capability relative to method 3, it requires a more sophisticated, complex and costly solids-handling system, and is less well suited to a simple automated control scheme. Therefore method 2 is deemed to be poorly suited to the needs of small FBC boilers.

In method 1, the tubes are designed to be fully immersed at all times. Here, the bed is constructed of segregated compartments each served by individual windboxes, feeders, and control instrumentation. Load reduction is accomplished by cutting off air to individual compartments in increments consistent with the load demand. Since the heat transfer coefficient in the slumped bed drops to a very low value, the heat removal rate can be efficiently controlled. This method of load control has found wide acceptance in larger scale applications but is impractical for small FBC boilers requiring only a single feed point. Here, the use of multiple compartments would require the addition of numerous and expensive feeders. Furthermore, the simple and inexpensive construction of the single compartment FBC would be compromised.

It is evident from this discussion that conventional means of load control used in large-scale FBC boilers are generally not applicable when extended to the smaller size ranges. Therefore, an alternate load control means is proposed which is considered to be more suitable to the requirements of the small FBC boiler.

In the proposed method, several independent steam coils would be immersed in the fluid bed. The steam coils would be served by a single or multiple forced circulation pumps. Each steam coil would be furnished with a inexpensive solenoid shut-off valve which would be operated from a multiple range temperature switch. As the load requirement decreases and the bed temperature begins to diminish, the temperature switch would act to shut off the water flow to the steam coils in a successive fashion until the bed temperature stabilized within the desired control range.

This control system requires no proportional controllers and operates only with the less expensive digital switches. Under this control scheme, the immersed tubes must be designed for high-temperature service under dry-out conditions. Therefore, more expensive high alloy tube materials must be utilized. However, since the small-scale FBC boilers are likely to serve only low pressure (less than 150 psig) steam generation applications, constraints on tube construction are not as severe as would be encountered in large-scale FBC boilers operating in the range of 1,000 psi. Furthermore, the incremental cost of the more expensive in-bed tube materials is quite small compared to the cost of the additional equipment and controls required for alternative schemes. However, its greatest merits result from improved simplicity and anticipated reliability which is essential for the small-scale applications.

It is likely that the small incremental cost for more expensive tube materials would be insignificant compared to the reduced maintenance and operator intervention which this design would afford. Note that the design of convective tube banks for dry-out conditions during start-up of large-scale steam reformers used in the petrochemical industry is not uncommon. However, tube erosion and wastage in a fluid bed may pose a more serious problem.

3.1.6 System Response

The response rate of the fluidized bed is determined by a number of factors including an effect known as inventory lag. The actual rate of heat release within the fluid bed is a function of the instantaneous inventory of carbon contained within a bed for a given temperature. At steady-state, the feed rate and the heat release rates are equivalent since the inventory level has adjusted accordingly. In contrast, during transitory conditions, the feed rate and the bed heat release rate are not identical since the bed inventory has not achieved its steady-state value.

For very fine coal, such as might be used in underbed feed systems, the steady-state carbon inventory is in the range of 0.1 percent and the time constant for approaching steady state after a step change in feed rate is of the order of 25 seconds. For very large coals, carbon inventories in the bed are in the range of 2 percent and the response time constant is approximately 500 seconds. Of course, these time constants increase with decreasing temperature.

It is evident that conventional FBC boilers employing overbed feeding of large coal only will have a sluggish response. Underbed feeding of fines will offer improved response. In an optimal system, variations in the rates of fines combustion might beneficially be employed as a trim control during transients.

The pulse combustor as integrated with an FBC boiler offers a practical avenue for implementation of this solution. The inherent response time of the pulse combustor exceeds virtually all known combustion devices. For example, complete combustion of pulverized fuels occurs in the order of milliseconds.

This, of course, is due to the highly turbulent conditions which exist in the pulse combustion chamber and tailpipe.

As such, load changes would be accommodated by leading with a change in the proportion of coal combusted in the pulse combustor. This would result in a rapid response that would later be stabilized by achievement of the steady-state bed inventory level. It should be noted that since a portion of the fuel will be combusted in the pulse chamber, the steady-state carbon inventory in the fluid bed will be lower than that in a conventional FBC at equivalent conditions. This lower carbon inventory may have a positive impact on reduced attrition rates and elutriation of fines.

3.1.7 Control System

The control system must be designed for complete automatic control. The economics of the small-scale FBC boiler are contingent upon achieving an operational simplicity which matches that of typical oil- or gas-fired packaged boilers.

Thus, the system will include an automatic combustion control system and a safety interlock system that will shut down boiler activities in the event of out-of-range conditions.

3.2 MARKET ANALYSIS

A market analysis indicated that a coal-based system that provides competitive levels of capital and O&M cost, performance, and reliability at the 1,000 to 10,000 pounds of steam per hour (PPH) steam-generation rate can displace as much as 2.5 Quads of gas and oil within the residential, commercial, and light industrial sectors. In the industrial sector, systems from 10,000 to 50,000 PPH steam can displace another 1.1 Quads of energy per year.

The objective of the market analysis was to identify and quantify the potential markets for an advanced pulsed atmospheric fluidized bed combustor (PAFBC) at the 1,000 to 10,000 PPH level and to assess the competitive posture of this new technology vis-a-vis oil and gas systems. The intent was to determine the ability for the given technology, to enter the market place competitively and eventually to replace oil and gas consumption with coal consumption. The key elements to be determined were, therefore, the size and nature of the market and the cost of the replacement system.

The methodology used to determine the potential for the PAFBC to replace oil and gas was as follows: First, the total demand for fossil fuels presently being used and projected to be used in the residential, commercial, and "light industrial" sectors were determined. Second, for each major market sector, the segments that fall within the 1,000 - 10,000 PPH (50,000 PPH for industrial) were disaggregated. Projections for growth for these market sector segments are then determined as a fraction of the total, using the projected rate of growth for the total sector. This provides the potential market size for the technology as a new additional capacity system.

In addition, the age of existing systems and the projected need for replacements were evaluated to provide the potential market size for replacement systems. No attempt was made to identify retrofit markets for the new technology because of the small size of the system. The cost for the design, fabrication, and installation modifications for a retrofit would reduce or eliminate the cost advantages accruing from the "mass production" techniques of packaged and modular systems requiring a minimal installation cost. However, for systems approaching 10,000 PPH, this option may be competitive.

Because the intent was to determine, in part, the potential for oil and gas replacement in each sector, the energy consumption of coal-based electricity, renewables and coal-based steam were not considered to be markets of interest for the technology and were therefore not included in the values for either determining the present or projected consumption values. Although coal is being used now to a limited extent in the residential and commercial end-use sectors, the amount at the size levels evaluated is not considered to be a major factor in the market determination. However, it too, was eliminated from the assessment where it was possible to identify the present and continued use of the coal fuel in these sectors.

In addition, a market entry scenario was developed which considered both the social and economic factors for possible early use. These factors were: availability and cost of fuel and a delivery system, traditional use of the fuel (acceptance), population density and regional climatic conditions. Although it was possible to easily deduce the results of such an evaluation on a regional basis, the methodology, when taken to finer levels of resolution, could be used for determining early market potential and density for focusing sales initiatives.

In the following subsections, each of the market sectors of interest; residential, commercial/institutional, and light industrial, are discussed with respect to historical and projected consumption and cost.

3.2.1 RESIDENTIAL

Coal, once the major fuel used in most American households, has, since 1940, declined to the point where its use is less than one percent of the residential fuel market. This decrease resulted not only from the availability of other fuels and electricity at competitive prices, but also by the performance and convenience of these systems. However, the continued long-term difference in the prices of coal, fuel oil, and natural gas has led to some stability in coal use since 1979.

Bartis[16] has prepared a fairly comprehensive analysis of the residential end-use sector and has shown that approximately 75 percent of the residential demand is dependent upon small units capable of firing 80,000 to 140,000 Btu per hour. Only 15 percent of the households are located in apartment complexes of five or more units and represents about 10 percent of the total demand.

It is obvious that the residential sector demand for systems in the 1,000-10,000 PPH is small but still presents a substantial market opportunity by the penetration of that fraction represented by apartment complexes of five or more units. If it is assumed that regional differences by heating and cooling degree days (HDD, CDD) for these structures are similar to the total distribution of households, then about 70 percent would be located in regions greater than 6000 HDD, primarily in the Northeast and Midwest, and provide sufficient usage of fuel (capacity factor) to warrant inclusion of this market sector. If it is further assumed that for fairly large apartment complexes, all heating, ventilating, and air conditioning are provided by steam/hot water boilers and absorption refrigeration systems, then the market sector considered could be expanded to other regions. The feasibility study did not anlayze this possibility because of the unavailability of data and the relatively small percentage of residential units in the size category. <u>**Table 3-1**</u> represents EIA[17] and GRI[18] projections of energy consumption by the residential sector. The EIA forecast assumes residential energy consumption will increase at a rate of 1.2 percent per year between 1985 to 1995, to 10 quadrillion (Quads) Btu. GRI projected energy consumption is based on an increase rate of only 0.5 percent. Both EIA and GRI project total residential energy consumption to grow modestly. Actual energy consumption for 1985 is also shown for comparison purposes.

If it is assumed that the growth rate for apartment complexes are similar to the rate of growth and the demand rate for the total population, this sector segment would increase proportionately to the values shown in the table. The increase in potential annual coal usage could amount to 25 million short tons by the year 2000. Although small compared to the total residential demand, it does represent a significant increase in coal production and a market potential. These values only include the replacement of petroleum and gas usage. It is possible that the economics of the technology will provide a potential for replacement of electricity usage for heating and hot water, but this will not generally displace oil or gas usage.

The EIA and GRI projections indicate electricity demand by residential sector will continue to grow, while shares of natural gas and petroleum will continue to decline in the foreseeable future. However, technological breakthroughs and changes in economic environment could change these trends. For example, coal consumption could increase at a faster rate than those projected if economic and easy-to-operate systems become available by the early 1990s.

TABLE 3-1: RESIDENTIAL SECTOR PROJECTED ENERGY CONSUMPTION (QUADRILLION BTU)

	1985			1990		1995	2000
	Actual	EIA	GRI	EIA	GRI	EIA	GRI
Gas	4.6	4.7	4.5	5.0	4.5	5.0	4.2
Electricity	2.7	2.7	2.8	3.1	3.1	3.5	3.8
Petroleum	1.5	1.5	1.4	1.5	1.4	1.5	1.2
Renewables	-	-	0.9	-	0.8	-	1.1
Coal	0.07	0.1	0.1	0.1	0.1	0.1	0.1
TOTAL	8.9	8.9	9.7	9.7	9.9	10.0	10.1
Sector Segment*	0.38	0.38	-	0.41	0.42	0.43	0.43

*Represents portion of total that may become a potential for displacement of oil and gas

Sources: EIA, April 1987, State Energy Data Report, 1960 - 1985, DOE/EIA-02114(85).

EIA, January 1985, Annual Energy Outlook 1984, DOE/EIA-0383(04).

GRI, December 1986, 1986 GRI Baseline Projection of U.S. Energy Supply and Demand to 2010, GRI, Chicago, Illinois.

Bartis[16] has also analyzed mandatory and early replacements for a hypothetical advanced system equivalent to approximately 1,000 PPH (1 MMBtu). Assuming the installed system was twice the cost of the conventional system and maintenance costs were $1,000 per year more, he concluded that early replacement opportunities become attractive when the fuel differential is between $4 and $5 per MMBtu for a five-year payback period. For mandatory replacements, a fuel differential of $2 to $3 per MMBtu would also be sufficient for mandatory replacement opportunities.

Table 3-2 provides a distribution of residence by age. Assuming that the population of the sector segment is similar in age and growth rate to the total population, an estimate of first and second replacement units can be made to determine a potential sales market. The total potential sales market would then include new units and replacement units for older gas and oil-fired units. For new capacity units, it is assumed that the technology becomes more advantageous than gas, oil, or electricity, and replaces all new required capacity except coal and renewables for that fraction with sufficient capacity factor based on climate conditions.

TABLE 3-2: AGE OF RESIDENCES

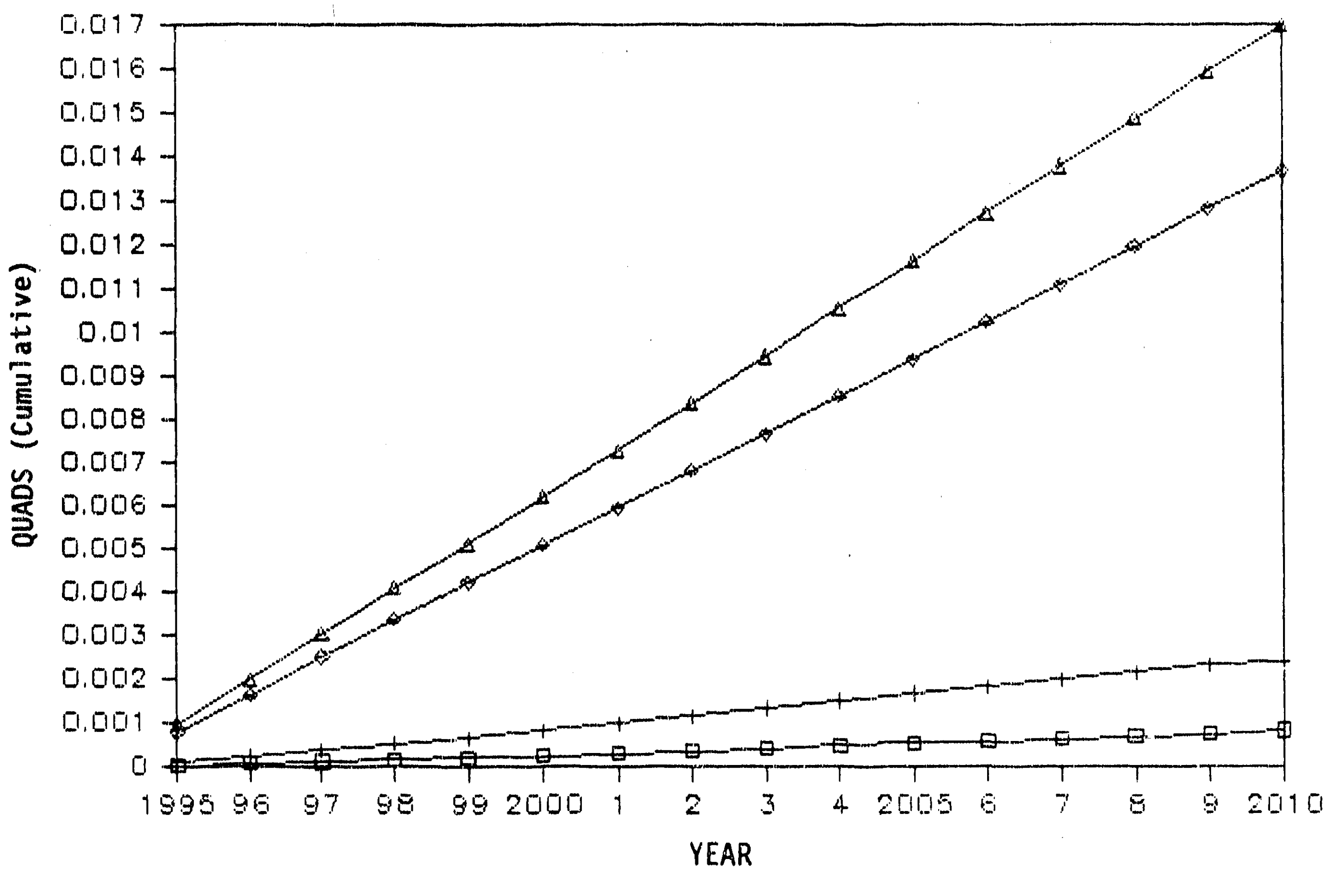
YEAR OF CONSTRUCTION	% OF TOTAL	% OF APARTMENTS* IN MARKET SEGMENT
< 1939	29.0	4.76
1940 - 1949	8.0	1.31
1950 - 1959	14.6	2.39
1960 - 1964	8.7	1.43
1965 - 1969	9.5	1.56
1970 - 1974	12.3	2.01
1975 - 1979	11.7	1.92
> 1980	5.8	.95

*Assumes 70% of total in regions > 6000 HDD

A growth rate of 0.6 percent per year for end-use of energy [DOE/EIA-0383(85)] was assumed beyond 1995. This value is about half the primary energy demand and seems a reasonable value for long-term projections. Figure 3-1 shows the 15-year market sales potential for both replacement and new units in terms of total energy demand with a market entry date of 1995.

3.2.2 COMMERCIAL

The information on energy use patterns within the commercial sector used data from the Nonresidential Building Energy Consumption Survey (NBECS)[19] conducted by EIA in 1983. This survey covered the 48 contiguous states and the District of Columbia. NBECS is designed to provide energy-related data on nonresidential buildings, primarily those in the commercial sector. Nonresidential buildings are defined as "roofed and walled structures that houses some kind of commercial or industrial activity, excluding buildings on military installations." Commercial buildings are defined as those



LEGEND:

+ = First Replacement

□ = Second Replacement

◊ = New Capacity

△ = Cumulative Total

FIGURE 3-1: POTENTIAL SALES MARKET - RESIDENTIAL

nonresidential buildings in which industrial or agricultural activities do not occupy more floor space than any other single activity. This definition of commercial buildings included assemblies (e.g., recreational facilities, entertainment centers, passenger terminals, stadiums). education buildings (e.g., schools, colleges and universities), food sales and services buildings (e.g., cafeteria, full-service restaurant, supermarkets, bakeries), health care centers (e.g., hospitals, mental facilities, medical clinics), lodging facilities (e.g., motels, hotels, shelter homes, boarding house, orphanages, nursing homes, dormitories), mercantile sales and services buildings (e.g., shopping malls, strip shopping centers, department stores, furniture stores), office buildings (e.g., management, consulting, engineering, law, brokerage, and real estate firms, banks), warehouses, and other buildings such as fire stations, police stations, jails, courthouses, and parking garages. Included in commercial buildings are also those multi- and single-family residential units and mobile homes which are involved in some nonresidential activity but have more square footage devoted to residential use than to any single commercial use.

Commercial sector and commercial buildings mean the same in this report as those defined by EIA and described before. The data provided was analyzed to identify the commercial segments with highest potential for application of PAFBC technology.

In 1985, the commercial sector consumed 6.0 Quads of energy (**Table 3-3**). It accounted for 16 percent of total energy consumed by the four major end-use sectors (industrial, transportation, residential and commercial). The commercial sector energy needs were provided for by four major sources: natural gas, electricity, petroleum, and coal. **Table 3-4** indicates that natural gas accounted for 2.5 Quads of the energy consumed by commercial sector in 1985, electricity for 2.3 Quads, petroleum for 1.0 Quads, and coal for 0.1 Quads. The commercial sector projected energy consumption to the year 2000 are also shown.

TABLE 3-3:
COMMERCIAL SECTOR ENERGY CONSUMPTION BY SOURCE
(QUADRILLION BTU)

YEAR	COAL	NATURAL GAS	PETROLEUM	ELECTRICITY SALES	TOTAL
1960	572.1	1055.9	1227.5	542.7	3398.3
1961	521.0	1114.5	1247.5	570.8	3453.8
1962	515.6	1248.9	1279.7	619.6	3663.8
1963	438.8	1301.6	1262.2	686.8	3689.5
1964	374.9	1412.0	1246.9	738.0	3771.8
1965	356.5	1483.3	1386.5	789.0	4015.3
1966	359.4	1668.7	1435.7	859.1	4322.9
1967	307.6	2014.7	1483.1	926.0	4731.4
1968	275.8	2134.3	1510.1	1015.5	4935.7
1969	260.3	2315.8	1519.8	1109.8	5205.7
1970	217.1	2454.6	1551.1	1203.2	5426.1
1971	203.6	2568.9	1509.8	1290.1	5572.4
1972	156.6	2674.1	1530.0	1409.4	5770.2
1973	148.1	2660.0	1565.5	1518.8	5892.3
1974	151.7	2614.2	1422.7	1502.1	5690.6
1975	123.4	2556.2	1309.7	1597.7	5587.0
1976	120.4	2716.8	1460.9	1677.6	5975.7
1977	121.8	2546.9	1510.9	1753.9	5933.5
1978	129.2	2642.1	1449.8	1814.3	6035.5
1979	114.9	2834.0	1334.1	1853.8	6136.8
1980	87.3	2665.7	1287.5	1906.5	5947.0
1981	98.8	2577.5	1090.2	2033.1	5799.6
1982	113.8	2670.8	1008.4	2077.1	5870.1
1983	119.0	2504.6	1136.1	2118.2	5877.9
1984	128.7	2593.9	1158.7	2240.8	6122.2
1985	109.1	2508.1	1035.6	2355.4	6008.2

Source: EIA, April 1987, State Energy Data Report, Consumption Estimates, 1960 - 1984, DOE/EIA-0214(85)

EIA projects that between 1985 and 1995, commercial energy use will increase at an average annual rate of 1.3 percent, to 6.7 Quads. GRI projects commercial energy consumption will grow to 7.5 Quads by the year 2000. GRI projection is based on an energy consumption growth of 1.0 percent per year between 1985 and 1990 and 1.5 percent per year between 1990 and 2000. Both EIA and GRI project that electricity consumption will continue to grow over the forecast period. EIA projects that electricity will replace natural gas as the primary fuel used in commercial sector during the next decade, accounting for about 45 percent of total commercial energy use by 1995.

TABLE 3-4:

COMMERCIAL SECTOR PROJECTED ENERGY CONSUMPTION
(QUADRILLION BTU)

	1985	1990		1995	2000
	Actual	EIA	GRI	EIA	GRI
Gas	2.5	2.8	2.6	2.8	3.1
Electricity	2.3	2.7	2.4	3.0	2.8
Petroleum	1.0	0.9	1.3	0.8	1.4
Renewables	-	-	-	-	0.1
Coal	0.1	0.1	0.1	0.1	0.1
TOTAL	6.0	6.5	6.4	6.7	7.5
Sector Segment*	1.56	1.65	1.73	1.60	2.007

*Represents portion of total that may become a potential for displacement of oil and gas

Sources: EIA, April 1987, State Energy Data Report, 1960 - 1985, DOE/EIA-02114(85).

EIA, January 1985, Annual Energy Outlook 1984, DOE/EIA-0383(04).

GRI, December 1986, 1986 GRI Baseline Projection of U.S. Energy Supply and Demand to 2010, GRI, Chicago, Illinois.

In mid-1983, there were 3,948,000 commercial buildings in the United States. The total floor space in these buildings was 52.3 billion square feet. These buildings consumed energy for six end uses: space heating, water heating, cooling, manufacturing, and electricity generation. The type, location, age, and size of the buildings affected the amount and the source of energy used. Table 3-5 presents the number, square footage, and energy consumption by building type.

TABLE 3-5: NUMBER, SQUARE FOOTAGE AND ENERGY CONSUMPTION OF COMMERCIAL BUILDINGS BY BUILDING TYPE

PRINCIPAL ACTIVITY WITHIN BUILDING	NO. OF BUILDINGS		SQUARE FOOTAGE		ENERGY CONSUMPTION	
	THOUSANDS	PERCENT	MILLION SQUARE FEET	PERCENT	TRILLION BTU	PERCENT
Total Commercial Buildings*	3,948	100.0	52,325	100.0	5,150	100.0
Assembly	475	11.6	5,483	10.5	377	7.3
Educational	177	4.5	6,044	11.6	484	9.4
Food/Sales Service	380	9.6	2,051	3.9	437	8.5
Health Care	61	1.5	2,277	4.3	465	9.0
Mercantile/Services	1,071	27.1	10,427	19.9	838	16.3
Lodging	106	2.7	2,241	4.3	365	7.1
Office	575	14.6	8,454	16.2	1,039	20.2
Residential	236	6.0	2,454	4.7	179	3.5
Warehouse	425	10.8	6,791	13.0	506	9.8
Other	179	4.5	2,760	5.3	276	5.4
Vacant	281	7.1	3,342	6.4	184	3.6

Source: DOE/EIA - 024(83)
DOE/EIA - 0318(83)

EIA[20] reports that the source of energy supplied to the commercial buildings also varies with building size. Electricity was supplied to 94.3 percent of all buildings containing 5,000 square feet or less. It was supplied to 99.0 percent of all buildings of more than 200,000 square feet. Natural gas was used in 51.4 percent of the buildings containing 5,000 square feet or less and in 75.1 percent of buildings containing more than 200,000 square feet. Fuel oil was used in 13.6 percent of the buildings containing 5,000 square feet or less and in 44.1 percent of the buildings with more than

200,000 square feet. A negligible amount of purchased steam was used in buildings containing 5,000 square feet or less, but purchased steam was used in 20.8 percent of all buildings of more than 200,000 square feet.

A simple attempt at disaggregating the commercial sector on the basis of square footage and the average energy demand to provide average sizes in equivalent PPH steam systems for several capacity factors was made and shown in Table 3-6. Energy consumption values exclude electricity and reflect oil and gas usage only.

TABLE 3-6: AVERAGE SIZE OF UNIT

SIZE CATEGORY (SQUARE FEET)	NO. OF BUILDINGS (THOUSANDS)	ENERGY CONSUMPTION TRILLION BTU	PPH UNIT CAPACITY FACTOR		
			25%	50%	100%
< 5,000	2,248	514			
5,000 to 10,000	725	332			
10,000 to 25,000	567	429			
25,000 to 50,000	222	410	944	472	236
50,000 to 100,000	107	363	1200	600	300
100,000 to 200,000	50	348	2800	1400	708
Over 200,000	29	643	9440	4720	2360
TOTAL	3,948	3,039			

The above analysis indicates that the buildings with 50,000 square feet or more provide a potential market for coal-fired systems. These buildings not only are a major consumer of natural gas and fuel oil but are also equipped with central heating and cooling distribution systems. Such central systems provide sufficient capacity factor values to permit coal-fired system replacements or new capacity.

Among various commercial buildings, central heating systems were present in more than 90 percent of the residential, health care, office, and assembly buildings. These buildings are more likely to lend themselves to installation of a coal-fired system for new or replacement units because the central heating equipment is already in place. Health care facilities in particular are most suited for installation of coal-fired systems. Hospitals have a continuous and somewhat constant demand for heating and cooling compared to other types of commercial buildings. Therefore, coal-fired systems designed for hospitals could prove to be more economic because of their higher capacity factor compared to other buildings in the commercial sector.

Table 3-7 presents number of buildings, floor area, and energy consumption as a function of building size. The majority of commercial buildings are small in area. Over 75 percent contain less than 10,000 square feet and over 56 percent are smaller than 5,000 square feet. Buildings smaller than 10,000 square feet contain only about 19 percent of total floor area in the commercial building. They consume about 28 percent of total energy within the commercial buildings. The largest amount of floor space is in over 200,000 square feet category. They also account for the largest percentage (21.2) of energy consumed in a single commercial building category.

TABLE 3-7: NUMBER, TOTAL FLOOR AREA, AND ENERGY CONSUMPTION OF COMMERCIAL BUILDINGS BY BUILDING SIZE

SIZE CATEGORY (SQUARE FEET)	NO. OF BUILDINGS THOUSANDS	NO. OF BUILDINGS PERCENT	SQUARE FOOTAGE MILLION SQUARE FEET	SQUARE FOOTAGE PERCENT	ENERGY CONSUMPTION TRILLION BTU	ENERGY CONSUMPTION PERCENT
< 5,000	2,248	56.9	4,908	9.4	514	16.9
5,000 to 10,000	725	18.4	5,246	10.0	332	10.9
10,000 to 25,000	567	14.4	8,912	17.0	429	14.1
25,000 to 50,000	222	5.6	7,692	14.7	410	13.5
50,000 to 100,000	107	2.7	7,168	13.7	363	12.0
100,000 to 200,000	50	1.3	6,642	12.7	348	11.4
Over 200,000	29	0.7	11,757	22.5	643	21.2
TOTAL	3,948	100.0	52,325	100.0	3,039	100.0

Source: DOE/EIA - 024(83)
DOE/EIA - 0318(83)

Next, Table 3-8 indicates the number of commercial buildings as a function of building age.

Table 3-8: Number, Total Floor Area, and Energy Consumption Of Commercial Buildings By Year of Construction

SIZE CATEGORY (SQUARE FEET)	NO. OF BUILDINGS		SQUARE FOOTAGE		ENERGY CONSUMPTION	
	THOUSANDS	PERCENT	MILLION SQUARE FEET	PERCENT	TRILLION BTU	PERCENT
1900 or Before	288	7.3	2,940	5.6	194	3.8
1901 to 1920	388	9.8	5,453	10.4	354	6.9
1921 to 1945	726	18.4	8,639	16.5	846	16.4
1946 to 1960	946	24.0	9,612	18.4	938	18.2
1961 to 1970	721	18.3	9,947	19.0	1,099	21.3
1971 to 1973	209	5.3	3,442	6.6	366	7.1
1974 to 1979	530	13.4	6,616	12.6	861	16.7
1980 to 1983	140	3.5	5,675	10.8	491	9.5
TOTAL	3,948	100.0	52,325	100.0	5,150	100.0

Source: DOE/EIA - 024(83)
DOE/EIA - 0318(83)

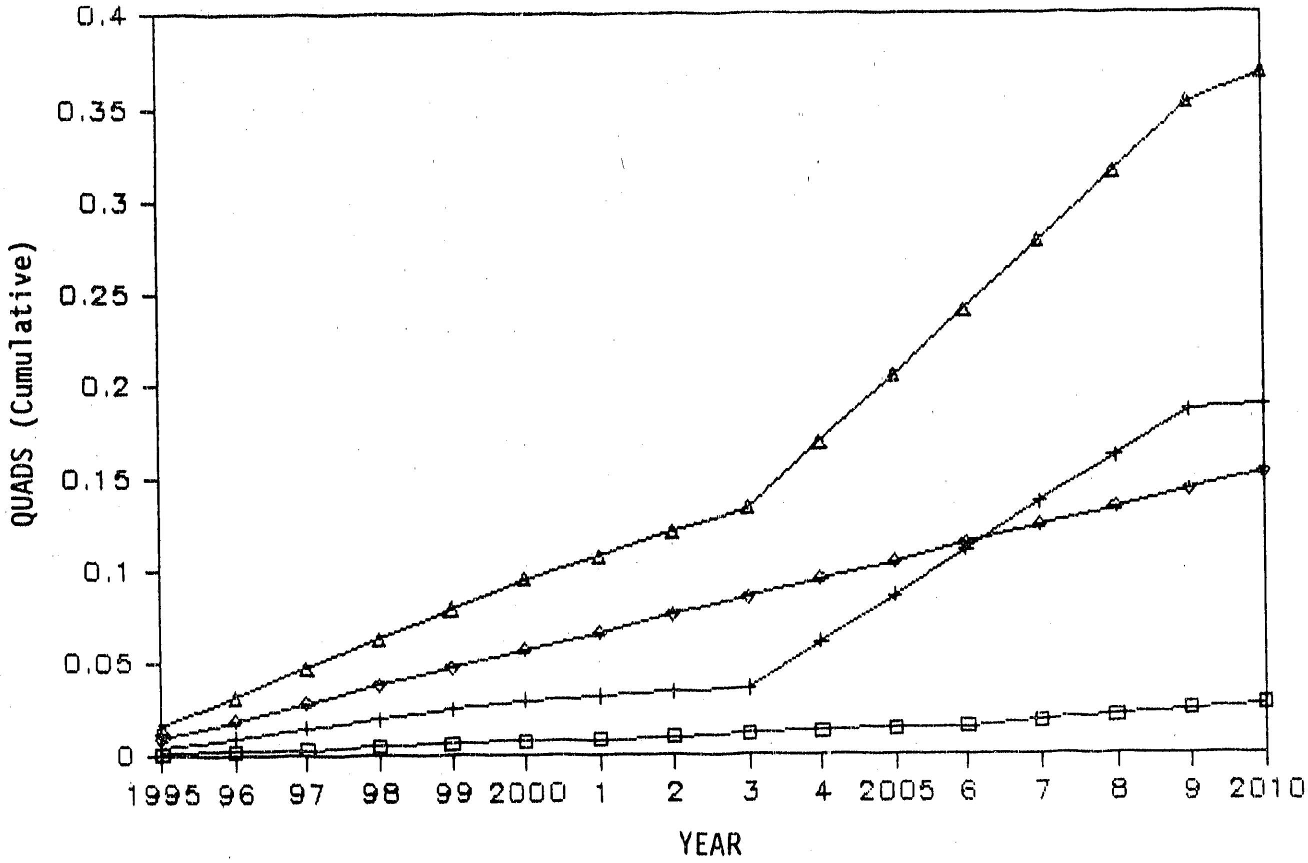
The potential energy demand for units producing 1,000-10,000 PPH appears to be somewhere between 1.697 and 2.99 Quads but this includes electricity demand as well, depending upon the capacity factor for the use. No attempt was made to disaggregate any further by redundancy of system (multiple units) or specific use, although for the larger systems there is a distinct possibility that multiple units would be the preferred mode of operation. In order to determine the projected energy demand for new and replacement systems, it was assumed that new buildings would be constructed at about the same distribution rate as the building population age. This assumption is probably more correct for buildings constructed after 1970 than before. Because construction fluctuates strongly with the state of the economy, projections were made on the basis of projected energy demand for the new market opportunities and on the basis of 30 year life for replacement values with initial introduction in the year 1995. In order to provide some reasonable estimates, it was also assumed that only that fraction utilizing fossil based fuels would be considered as replacement capacity without distinguishing whether or not it referred to gas, oil, propane, etc. The assumption in this instance being that if the capital and operational costs were advantageous, the replacement system would form part of the potential coal replacement market and that electricity sales did not contribute because electricity was not primarily used for heating, cooling, etc. Coal-fired units would be advantageous over all other kinds so that new potential capacity is equal to a fraction of total consumption for the segments consisting of commercial buildings with over 50,000 square feet.

The potential oil and gas replacement values were shown in Table 3-4 as a sector segment. This refers to the potential replacement for projected gas and petroleum use for commercial buildings over 50,000 square feet and with capacity factors greater than 50 percent. The potential sales market is provided in Figure 3-2. The same methodology used in determining the residential sales market was used here. In each case, only that sector segment capable of utilizing the technology was considered.

3.2.3 INDUSTRIAL

The industrial sector is the largest end-use consumer of energy. The total energy use is projected to be 22.7 Quads in 1995[17]. In a recent study (Burns & Roe, 1986), a methodology was devised for determining the population and size of industrial boilers < 50 MMBtu. Much of the disaggregated data was based on engineering judgement because of the paucity of data available. However, for purposes of this report, the values for potential market sector will be based on those reported values as shown in Table 3-9.

For industrial usage, it was assumed that Table 3-9 actually represented plate capacity rather than energy demand and that a value of 60 - 70 percent was a reasonable capacity factor value for these units. The assumption that this net value of energy demand is the only available oil and gas replacement market segment with the balance of gas and liquids used for other purposes. Therefore, for the 1984 population (assumed the same as 1980) the total industrial energy



LEGEND:

+ = First Replacement

□ = Second Replacement

◊ = New Capacity

▲ = Cumulative Total

FIGURE 3-2: POTENTIAL SALES MARKET - COMMERCIAL

Table 3-9: Total Energy Distribution (Trillion Btu)

FOR DIRECT-FIRED COMBUSTORS

Size Range (MM Btu)	Population (Number)	Energy (10^{12} Btu)
1-9	14,882	447.19
10-24	3,816	391.53
25-49	1,529	350.59
TOTAL	20,227	1,189.31

FOR BOILERS

Size Range (MM Btu)	Population (Number)	Energy (10^{12} Btu)
1-9	34,678	105.00
10-24	13,211	140.00
25-49	7,193	246.00
TOTAL	55,082	491.00

Totals represent sum of distillates, residual and natural gas.

use of natural gas and liquids was 9.59 Quads. That fraction used in boilers < 50 MMBtu was about 12 percent or 1.15 Quads. Table 3-10 represents total industrial energy use by fuel projected to 1995. For the present calculations, a growth rate of 0.6 percent per year was used in projecting oil and gas replacement values beyond 1995. Figure 3-3 indicates the projected sales market for new units after 1995. No estimate was made of the replacement market because of the unavailability of age and population data for the segments of interest.

TABLE 3-10:
INDUSTRIAL ENERGY USE BY FUEL, 1974 - 1995
(QUADRILLION BTU)

FUEL	HISTORY 1974	HISTORY 1984	PROJECTIONS 1985	PROJECTIONS 1990	PROJECTIONS 1995
Natural Gas	10.00	7.45	7.41	7.82	7.25
Metallurgical Coal	2.41	1.18	1.08	1.01	0.88
Electricity	2.34	2.87	2.95	3.27	3.80
Residual Fuel	1.73	0.78	0.70	0.64	0.43
Steam Coal	1.45	1.68	1.75	1.93	2.03
Distillate Fuel	1.35	1.36	1.37	1.62	1.73
Liquefied Petroleum Gas	1.23	1.60	1.67	1.80	1.90
Still Gas Used In Refineries	1.05	1.15	1.18	1.12	1.06
Petrochemical Feedstocks	0.74	1.82	0.81	0.78	0.69
Other Raw Material Oil	2.26	2.14	2.09	2.28	2.29
Motor Gasoline	0.24	0.11	0.12	0.30	0.48
Kerosene	0.13	0.13	0.14	0.17	0.19
Net Coke Imports	0.06	-0.01	-0.01	-0.01	-0.01
Industrial Hydropower	0.03	0.03	0.03	0.03	0.03
TOTAL	25.00	21.30	21.30	22.74	22.73

Source: DOE/EIA - 0383(85)

3.2.4 MARKET ENTRY

Although coal was once the predominant fuel in the residential, commercial and industrial markets, it has not occupied that position for decades. Although there was once a fairly extensive coal distribution system servicing those market sectors, it no longer exists except in some rudimentary way in local areas of the country. The penetration of a new technology is always a difficult problem since early items are generally high cost, of mediocre quality and performance with a great deal of consumer reluctance to upset the status quo. Obviously, situations can exist, like the fuel oil problem, which propels the consumer into action despite technology shortcomings. That situation is somewhat of an anomaly and cannot be predicted either in time or in value. A market entry scenario for a coal technology should therefore primarily be concerned with the largest (most dense) geographic areas of population, industry, commerce, coal production, heating

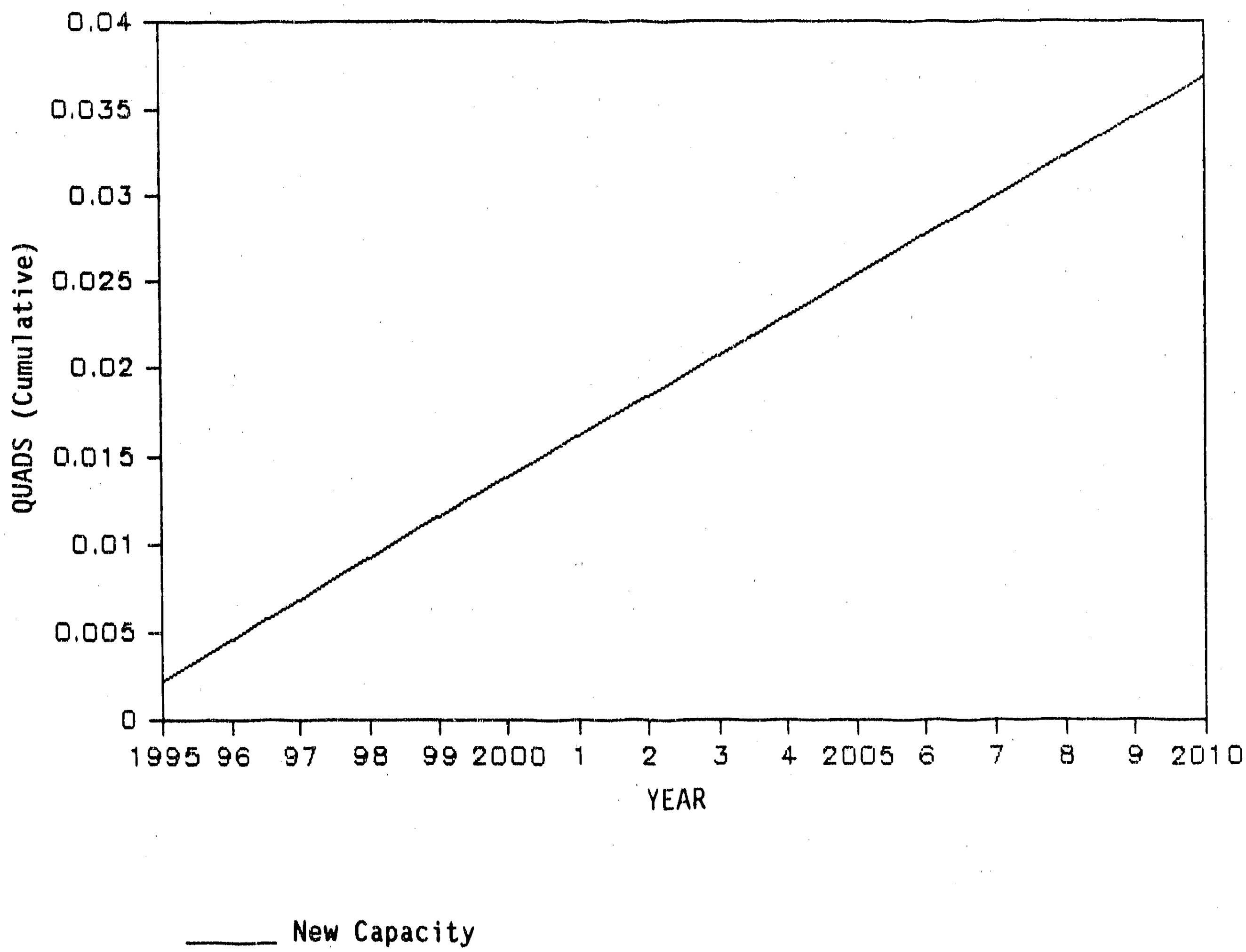


FIGURE 3-3: POTENTIAL SALES MARKET - INDUSTRIAL

demand, and finally, a tradition of continued coal use or acceptance of coal use. The centers of market penetration are shown in **Figure 3-4** as a regional opportunity. Obviously, more detailed analysis of the factors can probably locate centers of opportunity in other areas of the country where the demographics are supportive of coal utilization.

The estimated capital cost of a PAFBC system for the market sectors identified above would be three to four times the cost of equivalent oil or gas systems, but even at this early stage, the total cost would be competitive when the price differential for fuel exceeds $2/MMBtu and the system capacity (utilization) factor remains higher than 60 percent. A coal-fired PAFBC system is more capital cost-intensive than either a gas- or oil-fired system. However, the ability to utilize the less expensive coal fuel provides savings in operational cost over comparable payback periods and results in a more economical system overall. This has been amply demonstrated by both utilities and large industrial users who, by and large, have primarily chosen coal as their fuel.

3.2.5 COST AND SENSITIVITY ANALYSIS

Penetration of light industrial, commercial, and large residential market sectors by coal-fired boilers offers a significant opportunity for the displacement of oil and gas fuels. Commercial acceptance of coal-fired boilers is contingent upon several factors including system operability, reliability, and performance, environmental characteristics, and compatibility with end-user needs. However, satisfaction of the end-user's technical requirements is not in itself a sufficient condition for market penetration.

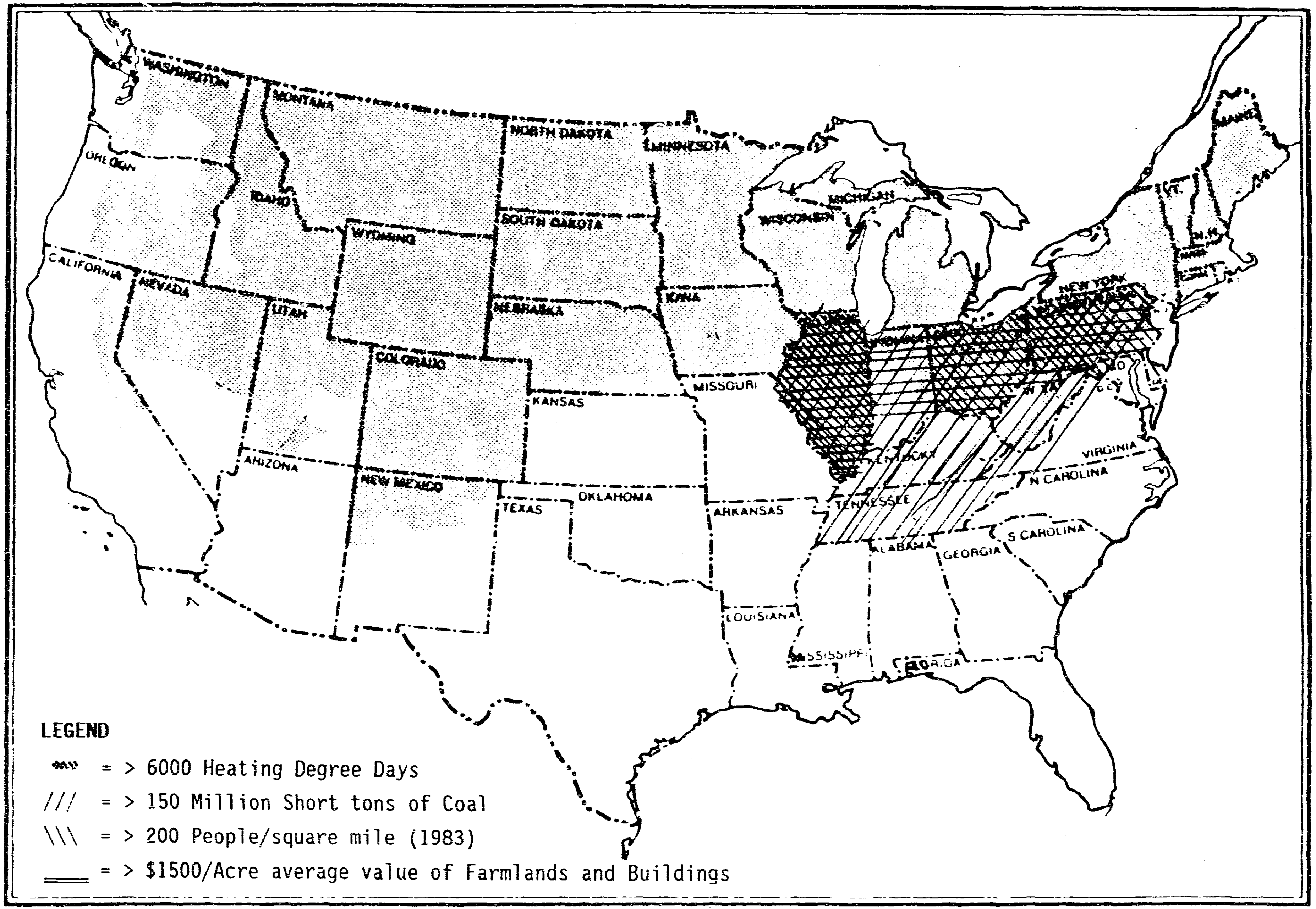


FIGURE 3-4: REGIONS WITH HIGH PROBABILITY OF MARKET ENTRY

Instead, a key issue will involve the ability of suppliers to offer coal fired systems at a cost which is economically competitive with oil and gas boilers currently dominating this market.

Clearly, the primary economic driving force for displacing oil/gas with coal is due to the price differential between these fuels. However, economic barriers currently exist which prevent suppliers from taking better advantage of these price differentials. These barriers result from the higher capital costs which are typically associated with the utilization of coal fuels in a environmentally acceptable manner.

Therefore, it is of primary interest to establish what capital cost target goals are necessary if coal fired boilers are to compete with oil/gas fired equipment. In order to establish these goals, a steam production cost model was constructed.

STEAM PRODUCTION COST MODEL

A steam production cost (SPC) model was specifically developed to compare the economics of steam production in a AFBC boiler with that in a natural gas boiler. The purpose of this model was to define the competitive capital cost range for a AFBC under a defined set of technical and economical conditions. In so doing, the capital costs of the advanced conceptual designs prepared under this project can be evaluated to determine if they satisfy or approach the required economic criteria.

The steam model has a number of flexible input variables covering technical, economic, and financial assumptions. In order to simplify this multidimensional model, a baseline parameter set was defined. For these baseline parameters, specific fixed values were employed. Selection of these fixed parameters was based on the degree of relative certainty to which estimates of these values could be reasonably made. The remaining values specifically, capacity factor, natural gas fuel cost, and coal fired boiler capital cost were allowed to vary in order to generate a master parametric curve for estimating steam production costs. Once the prevailing cost of natural gas is specified, and an application specific capacity factor is selected, the map allows determination of the capital costs for the coal fired AFBC system which is economically equivalent to a natural gas boiler. This, of course, represents the capital cost target goal for the advanced AFBC boilers. In addition, certain selected variables were analyzed to determine steam cost sensitivity. Table 16 summarizes the input parameters for the steam cost model. The baseline values for each fixed parameter are also indicated.

As seen in <u>**Table 3-11**</u>, an installed cost for a 1,000 PPH oil/gas boiler was selected as $13,000, which is a value indicative of current market prices. Perhaps most significant to note from Table 3-11 is the selection of a zero value for the number of dedicated operators required for either unit. As previously mentioned, it is assumed that existing personnel can include regular monitoring of the automated boiler within the frame work of their normal daily schedule. This assumption is prerequisite for economic operation of either gas or coal-fired boiler at the 1,000 PPH scale.

<u>RESULTS</u>

The results generated from the steam cost model utilizing the baseline parameter values given in Table 3-11, are shown in <u>**Figure 3-5**</u>. The steam cost map is used as follows. First, desired values for the application capacity factor (CF) and the prevailing natural gas fuel cost are selected. The point of intersection between the capacity factor and fuel cost curve is located on the steam cost map. Finally, the corresponding capital cost for the coal fired AFBC is found on the X-axis.

For example, with a capacity factor of 60 percent and a natural gas cost of $4/MMBtu, a coal fired AFBC can be competitive if its installed cost is approximately $48,000. This corresponds to a steam cost of approximately $7/1,000 lb. Thus, in this case, a coal-fired unit can be competitive if it is priced up to 3.7 times the installed cost of a typical natural gas boiler. note that this case represents a fuel price differential of $2.33/MMBtu.

TABLE 3-11: INPUT PARAMETERS TO STEAM COST MODEL WITH BASELINE INPUT VALUES INDICATED

ITEM	ADVANCED COAL-FIRED AFBC	NATURAL GAS BOILER
Boiler Capacity, PPH	1000	1000
Thermal Efficiency, %	80	80
Combustion Efficiency, %	99	100
Capacity Factor, %	Variable	Variable
Fuel HHV, Btu/lb	10,000	23,875
Sulfur, Wt. %	3.0	0
AS, Wt. %	10.0	0
Ca/S	2.0	0
Sulfur Retention, %	70	0
Fuel Cost, $/MMBtu	1.67	Variable
Limestone Cost, $/Ton	12	----
Waste Disposal Cost, $/Ton	15	----
Dedicated Operators, No.	0	0
Maintenance, % Installed	3.0	3.0
Tax & Insurance, % Installed	2.5	2.5
Installed Cost, $	Variable	13,000
Payback Period, Yr	3.33	3.33
Annual Interest Rate, %	9.0	9.0

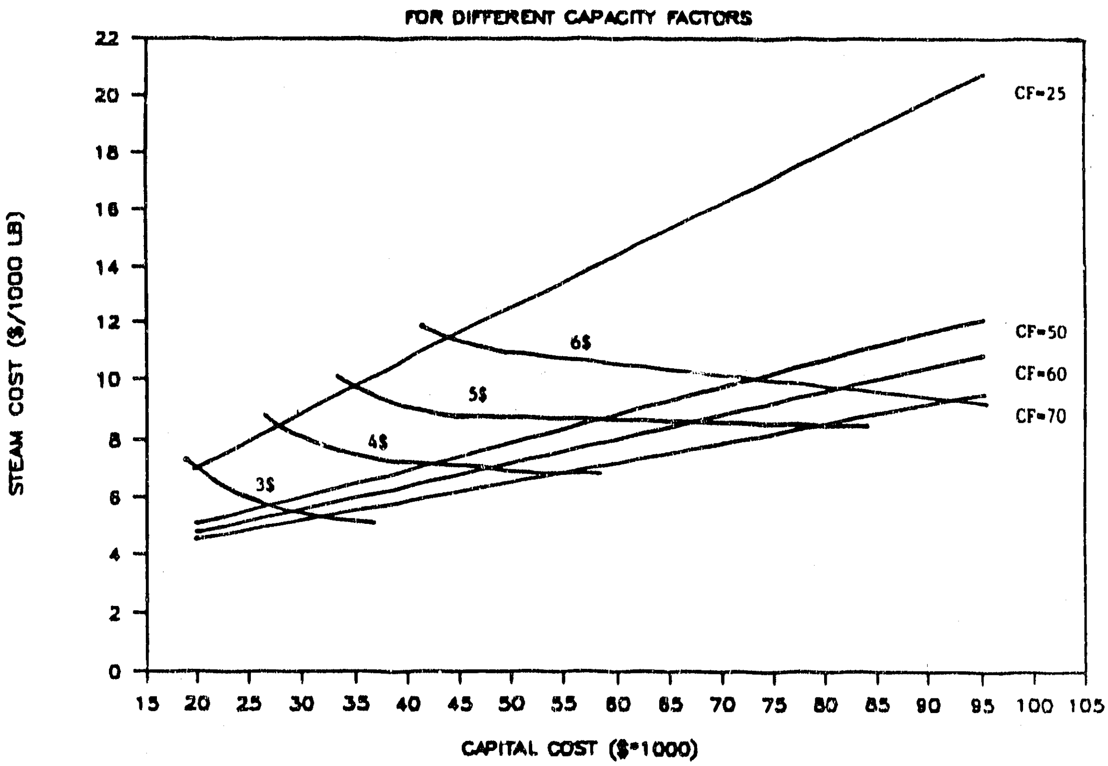


FIGURE 3-5: STEAM COST VERSUS CAPITAL COST

For a fuel price differential of $3.33/MMBtu, the allowable AFBC installed cost increases to $67,000 at a 60 percent capacity factor, and diminishes to approximately $31,000 for a $1.33 price differential.

It is evident from Figure 3-5, that changes in capacity factor have a profound impact on the allowable installed cost for the coal fired AFBC. For instance, given a natural gas cost of $4/MMBtu, the allowable AFBC costs drop from $48,000 at a 60 percent capacity factor to $28,000 at a 25 percent capacity factor.

SENSITIVITY ANALYSIS

In order to establish the sensitivity of steam cost to changes in parameter values, a cost sensitivity analysis was performed. First, a base case cost model scenario was chosen using an assumed capacity factor of 60 percent and an installed cost for the coal fired AFBC of $48,000. This base case capital cost value corresponds to the system target cost when natural gas is priced at $4/MMBtu. The balance of the base case parameters were unchanged from Table 3-11. The sensitivity analysis was performed by varying the sensitivity parameters +20 percent and calculating the resulting percent change in steam production cost. Note that the base case steam cost is $7/1,000 lb.

The sensitivity variables tested included the following:

- Coal cost
- Limestone cost
- Capital cost
- Payback period
- Number of operator

The last variable included a single sensitivity test to determine the effect of a single shift operator (costing $18/hr plus a 70 percent overhead factor) on the steam cost.

Table 3-12 summarizes the cost breakdown for the coal fired base case model and shows the percent contribution of each cost component. As seen from Table 3-12, coal fuel costs and capital charges represent the bulk of the total steam cost. Total steam cost is approximately equally split between operating expenses and capital charges. In contrast, for the base case natural gas fired boiler, the operating costs account for 87 percent of the total steam production cost. Fuel costs represent the bulk of this share.

TABLE 3-12: COST BREAKDOWN FOR BASE CASE MODEL

ITEM	COST ($/1000 lb)	% TOTAL
Coal	2.34	33.4
Limestone	.20	2.9
Solid Waste	.31	4.4
Electric	.33	4.7
Operator	.00	.0
Maintenance	.29	4.1
Tax & Insurance	.24	3.4
Total Operating	3.71	53.0
Capital Charge	3.29	47.0
Total Steam Cost	7.00	100.0

The results of the sensitivity analysis performed on the coal fired base case are summarized in **Table 3-13**. The input values for each sensitivity variable are shown with the middle value representing the base case value. The input values were varied ± 20 percent when possible.

For each case, the steam cost is given along with the corresponding cost differential compared to the base case. The percent change in the steam cost is provided. A sensitivity parameter calculated in the last column by dividing the percent change in steam cost by the percent change in the input variable.

From Table 3-13 it can be seen that the steam cost is not particularly sensitive to limestone cost. Similar trends exist for waste disposal cost. It may thus be inferred from these results that the Ca/S ratio also does not have a pronounced influence on steam cost. However, while these variables show a low economic sensitivity, the analysis does not account for the social and regulatory impacts of high sorbent utilization on the overall viability of the process. Therefore, the importance of efficient sorbent utilization can not be disregarded.

As seen from Table 3-13, the coal fuel cost and the payback period exhibit similar sensitivities. A 20 percent change in these input values results in approximately a 7 percent change in steam cost. Steam cost shows a strong sensitivity to capacity factor and boiler cost. Here, a 50 percent change results in approximately 10 percent change in steam cost.

Finally, the assumption regarding operator requirement exhibits a profound influence on steam cost. For instance, if even a single dedicated operator is required ($18 per hour and 70 percent overhead), then the cost of steam increases by 167 percent.

TABLE 3-13: SENSITIVITY ANALYSIS

SENSITIVITY VARIABLE	INPUT VALUE	STEAM COST $/1000 LB	COST DIFFERENCE $/1000 LB	PERCENT CHANGE	Δ COST/ Δ INPUT
CAPACITY FACTOR (%):	72	6.33	- .64	- 9	- .45
	60	6.97			
	48	7.91	+ .94	+ 13	+ .65
COAL COST ($/TON):	2.00	7.43	+ .46	+ 7	+ .33
	1.67	6.97			
	1.34	6.51	- .46	- 7	- .33
LIMESTONE COST ($/TON):	14.4	7.01	+ .04	+ .6	+ .03
	12.0	6.97			
	9.6	6.93	- .04	- .6	- .03
OPERATOR COST (NO., $/HR):	1,18	18.61	+ 11.64	+ 167	N/A
	0,0	6.97			
BOILER COST ($):	55,600	7.73	+ .76	+ 11	+ .52
	48,000	6.97			
	38,400	6.21	- .76	- 11	- .52
PAYBACK PERIOD (YR):	4.0	6.49	- .48	- 7	.33
	3.3	6.97			
	2.7	7.63	+ .66	+ 9	.43

SYSTEM COST ANALYSIS

Commercial experience gained in the larger AFBC size range (greater than 50,000 PPH) has indicated that the installed cost for bubbling bed combustors is typically four to five times that of an equivalent gas-fired boiler. However, economic analysis suggests that competitive coal-fired boilers must be priced at a factor less than four times that of gas-fired systems. Thus, significant market penetration will require the incorporation of design concepts which can reduce capital costs by 25 percent or more.

The AFBC proposed in this investigation is anticipated to improve system performance while simultaneously reducing capital costs. This can be accomplished due to the unique characteristics of the design.

Table 3-14 summarizes areas where significant cost reductions are expected. For a conventional AFBC, a start-up burner is required. The start-up burner, which may represent a significant cost element, is not required in the proposed design.

TABLE 3-14: COMPARISON OF PAFBC WITH CONVENTIONAL AFBC

ITEM	CONVENTIONAL AFBC	PAFBC
Start-up Burner	Required	Not Required
Fines Recycling & Grit Refiring	Required for High Combustion Efficiency	Not Required
Forced Draft Fan	Large, 3-5 psi thread	Small, Reduced Head
Freeboard	Tall for High Combustion Efficiency	Shorter
Limestone Storage & Feeder Capacity	Baseline	Smaller
Air Preheater	May Be Required	Not Required
Convective Tube Bank in Freeboard	Required	Not Required

If conventional AFBCs are to achieve reasonable combustion efficiency target goals, then fines recycle is required. Additionally, collection and refiring of grit accumulated in boiler passes may be necessary. In the proposed design, fines recycle and handling can be eliminated.

The conventional AFBC requires a large blower capable of providing 3 to 5 psi air to the distributor. Since the pulse combustor will subsidize the forced draft fan head requirements, a significantly reduced wheel size and motor horse power rating can be used.

Since fines will be burned in the pulse combustor, combustion residence time in the freeboard will be reduced compared to conventional systems. This should allow reduced freeboard heights.

Also, since improved in-bed mass transfer will allow a reduction in the Ca/S ratio for equivalent sulfur capture efficiencies, limestone storage and handling facilities can be down-sized.

The use of a water-jacketed pulse combustor tailpipe will eliminate the need for locating the convective tube bank in the freeboard.

3.3 CONCEPTUAL DESIGN AND COST ANALYSIS FOR A PAFBC SYSTEM

3.3.1 Conceptual Design

Two basic design configurations for a 1000 PPH PAFBC boiler were proposed. Based on an engineering evaluation, a conceptual design was selected as shown in Figures 3-6 and 3-7. As depicted in Figure 3-1, the PAFBC is arranged with a side-mounted convective boiler section. As can be seen in both figures, the fluid bed at the lower portion of the furnace includes a conical geometry for uniform distribution of fluidizing air in the absence of a distributor grid. The bed also includes multiple cooling coils which are immersed within the bed and can be independently controlled. The pulse combustor penetrates the roof of the furnace box and extends downward into the fluid bed to a point slightly above the conical tip. A coal classifier separates the feed coal into fines and coarse particles. The pulse combustor burns the coal fines and pumps the additional air required for combustion of coarse coal within the fluidized bed. The relative ratio of heat release in the pulse combustor and fluidized bed is anticipated to be in the range of 1:9 to 3:7. The freeboard region incorporates an expanded section to provide an increase in freeboard residence time. The acoustics radiated from the pulse combustor into the fluidized bed are likely to be attenuated rapidly before reaching the walls of the fluidized bed so that refractory integrity is not expected to be affected by pulse combusotr operation.

The pulse combustor will consist of an aerodynamic valve, a combustion chamber, and a tailpipe. The aerovalve contains no moving parts and is thus more reliable than designs employing mechanical flapper valves which are

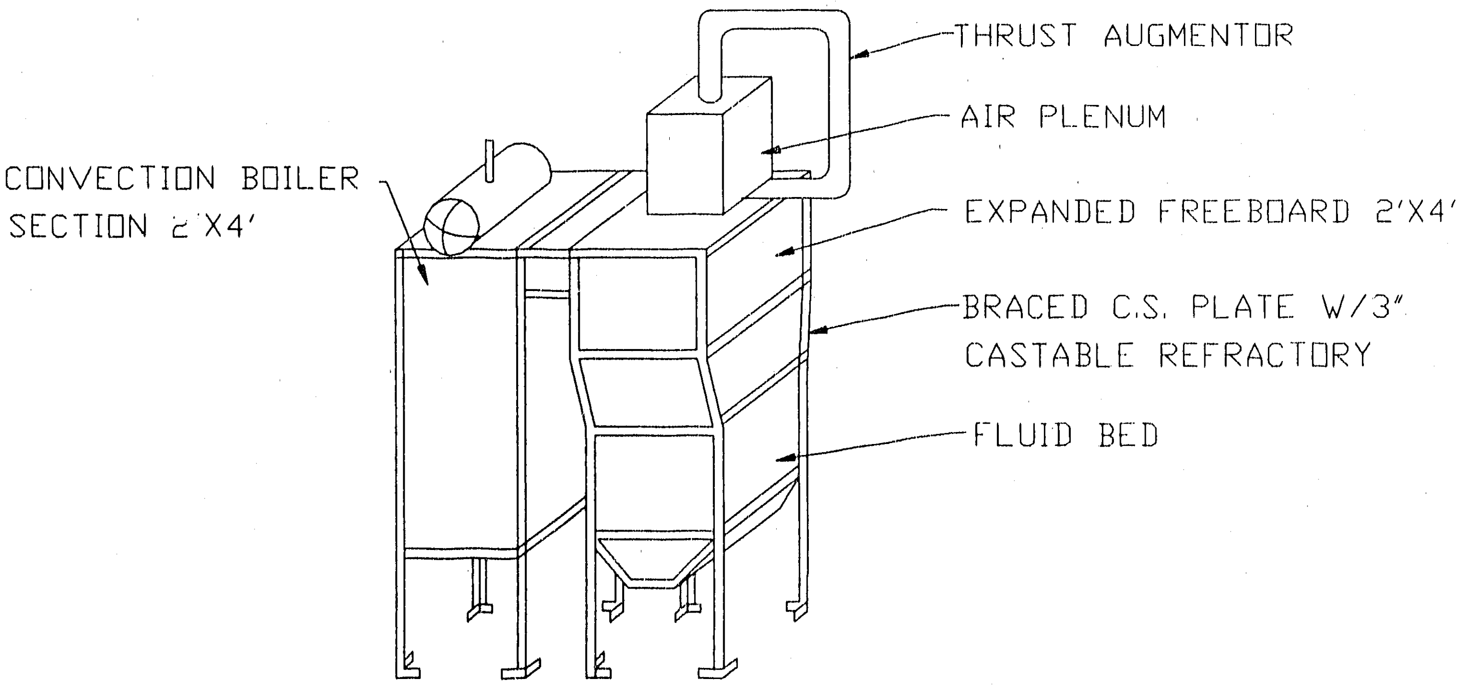


FIGURE 3-6: PAFBC BOILER - GENERAL ARRANGEMENT

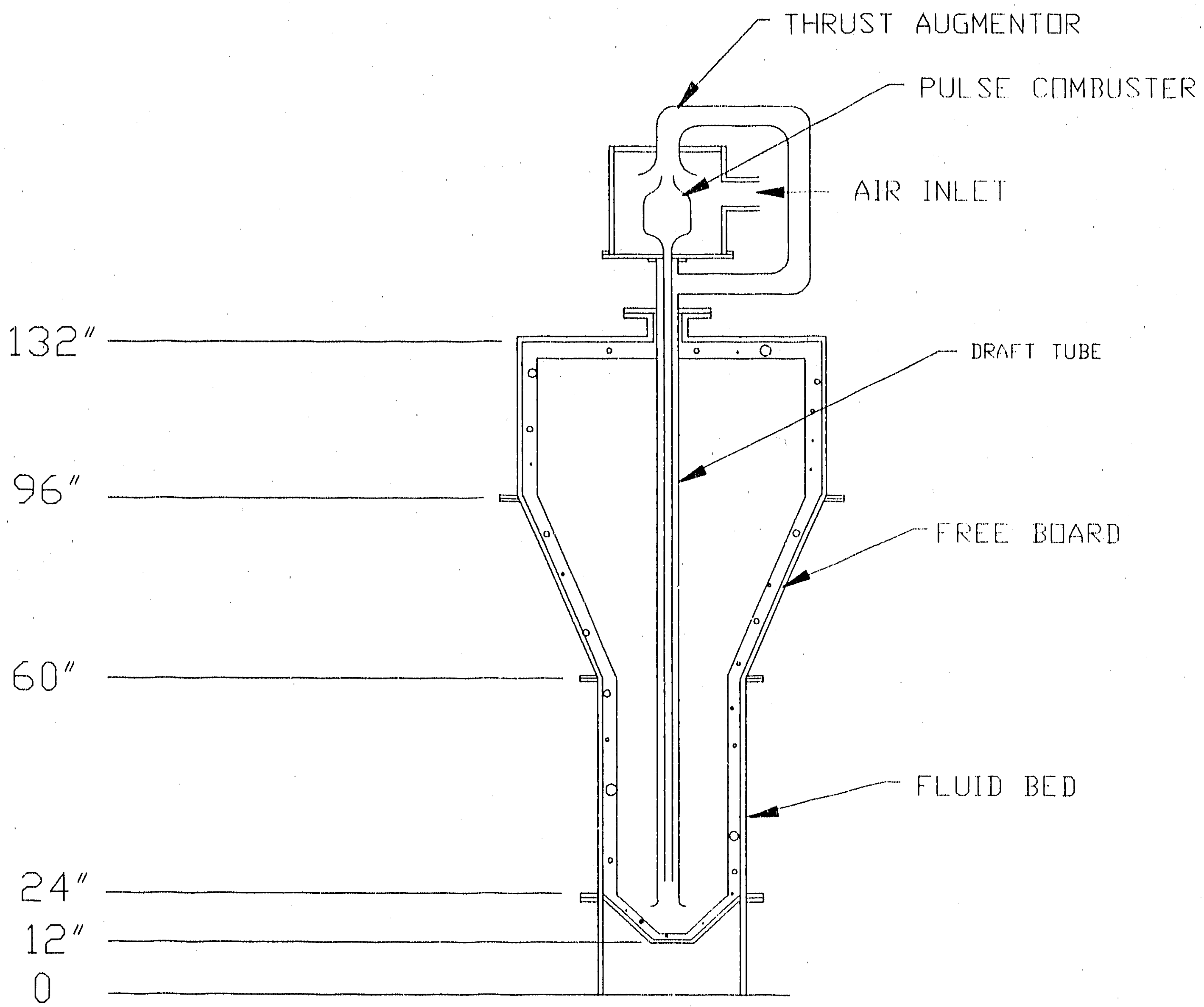


FIGURE 3-7: PAFBC - SIDE VIEW

likely to erode in coal combustion applications. The chamber and aerovalve will be enclosed in an air plenum. A thrust augmentor will be employed to pump combustion air to a draft tube which surrounds the tailpipe in an annular fashion. The draft tube supplies combustion air to the bottom of the fluid bed. The end of the draft tube will be fashioned into a diffuser for maximum pressure recovery.

3.3.2 General Arrangement

Different options for packaging the shop-fabricated PAFBC boiler were considered, including a fully integrated packaged system and a modular construction arrangement. It was decided to provide major subsystem elements in the modular form. Each subsystem would be delivered on an individual pallet and a minimum degree of interconnection would be necessary at the end-user's site. Here, the user has the flexibility to locate individual pallets in a manner which makes the best use of the existing site space. If, for instance, a user requires two boilers for maximum reliability, the user may select a single set of feed system and particulate collection modules which are sized at the dual boiler capacity. In this way, the user may avoid the purchase of two complete packaged systems and thus save through improved economy of scale.

Figure 3-8 shows a conceptual arrangement for a common wall, side-mounted PAFBC employing the modular construction approach. The boiler system is shown to comprise three independent pallets which can be easily shipped. Pallet No. 1 consists of the cyclone, baghouse, and solids removal equipment. Pallet No. 2 contains the PAFBC boiler itself. Pallet No. 3 contains the feed hoppers, metering screws, and classifier.

3.3.3 Control System

Figure 3-9 depicts a conceptual P&ID and control scheme. Although a top-mounted convection section is shown, the control scheme would be equally suitable for the side-mounted design. The coal-metering screw receives a steam demand signal from the steam drum pressure controller, adjusting the fuel feed rate accordingly. The limestone metering screw is ratio-controlled against the coal feed rate.

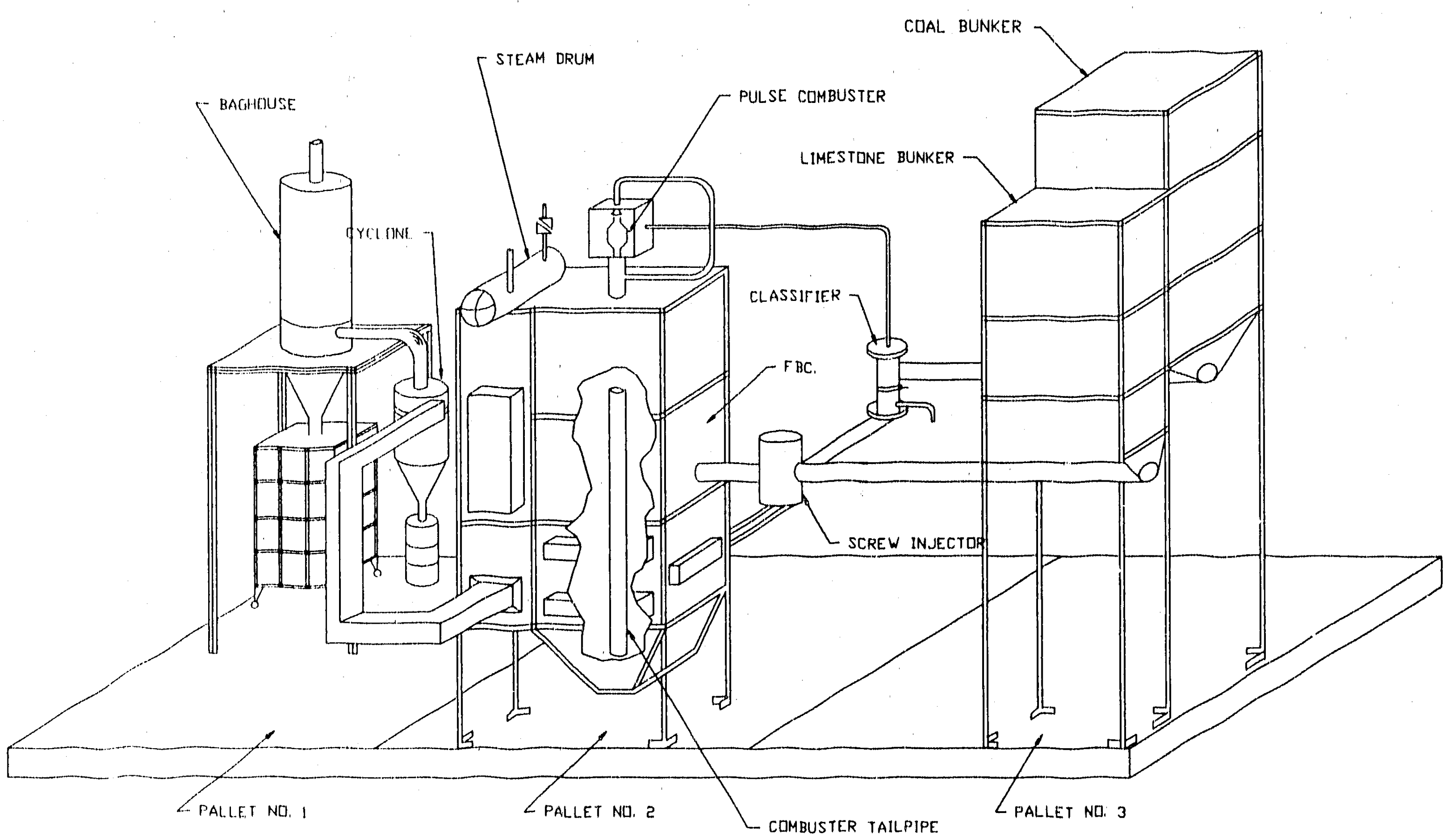


FIGURE 3-8: GENERAL ARRANGEMENT FOR MODULAR PAFBC

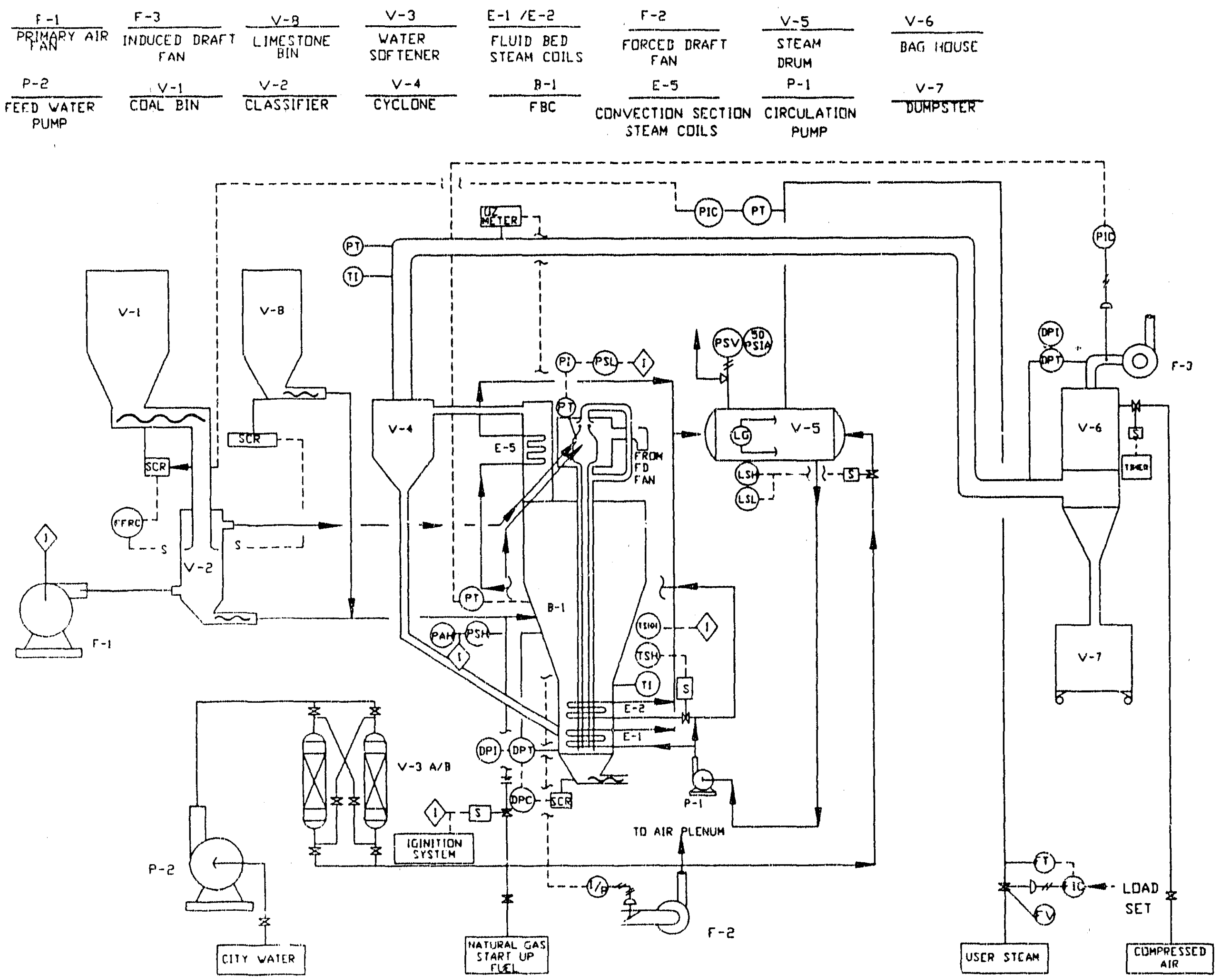


FIGURE 3-9: CONCEPTUAL P&ID

The coal is first introduced into a classifier. Primary air is supplied from fan F-1. Here, the fines are separated from the coarser coal particles for use in the pulse combustor. The particle size cut point is established by damper positioning. Coarse coal is then mixed with limestone and fed into the fluid bed using a screw injector.

City water is softened and supplied to steam drum V-5. The level control operates using a simple high-low range switch which is suitable for less critical steam generation applications. The feed water is then circulated to the immersed coils and the convection boiler coils.

Temperature control within the bed is achieved using a simple temperature switch which cuts off water flow to coils in a successive fashion. Two or three independent coils may be employed. This configuration resembles the use of multiple electric coils found in electric water heaters.

The excess air may be controlled by feedback from an oxygen meter as shown. The precise details concerning integration of the combustion air control with the pulse combustor must be resolved after experimental investigation in Task 2.

Removal of bed material is accomplished using a water-cooled screw device which is controlled based on bed pressure drop. Alternatively, a simple overflow tube may be employed in some cases.

In addition, the system will include a safety interlock device for shutdown under out-of-range conditions. Shutdown action may result from bed over temperature, steam over pressure, loss of fan pressure, etc. The pulse combustor will include an automated burner controller for sequenced start-up and monitoring. Combustor failure can be detected by loss of peak pressure or mean pressure boost.

3.3.4 <u>EQUIPMENT LIST</u>

A preliminary equipment list for a conceptual PAFBC design of 1,000 PPH steam capacity is given in <u>Table 3-15</u>. Major equipment items are summarized in this table along with preliminary design features. Note that the PAFBC is assumed to have a modestly expanded freeboard, and a side-mounted convection section without a common wall. The equipment list was used as a basis for developing a cost estimate.

3.4 PRELIMINARY COST ESTIMATE

The development of cost estimates for an advanced conceptual plant prior to testing and detailed design involves an inherently high degree of uncertainty. This is particularly true for the conceptual PAFBC which addresses a capacity range which is not currently being explored by conventional AFBC technology. Therefore, the most meaningful approach at the present time will involve a direct comparison of PAFBC technology with the available AFBC technology to determine the relative cost savings which can be anticipated due to the unique characteristics of the PAFBC design.

A high-volume AFBC boiler based on current technology is anticipated to cost approximately $65,000 (five times that of an equivalent gas-fired boiler) for an installed capacity of 1,000 PPH. The cost reductions achievable upon incorporating PAFBC technology can then be applied against the base cost of $65,000.

MTCI's PAFBC has several cost-saving features over conventional AFBC:

- PAFBC does not require a separate air heater (cost saving: 5 percent).
- PAFBC does not require a start-up burner (cost saving: 3 percent).
- PAFBC allows down sizing of fan and motor compared to a conventional AFBC because the pulse combustor pumps air into the fluid bed (cost saving: 2 percent).

TABLE 3-15: EQUIPMENT LIST

(1,000 PPH FBC)

ITEM	DESCRIPTION	DESIGN
V-1	Coal Bunker	5′ x 5′ x 10′ (10-day storage) braced carbon steel plate with 150 lb/hr variable-speed screw meter
V-8	Limestone Bunker	2′ x 5′ x 6′ (30-day storage) braced carbon steel plate with 35 lb/hr variable-speed screw meter
V-2	Classifier	4" x 2′ CS pipe with damper
V-5	Steam Drum	2′ x 4′ CS (50 gal. hold-up)
P-1	Circulation Pump	20 gpm at 20 psi
P-2	Feedwater Pump	20 gpm at 100 psi
E-1/ E-2	Bed Steam Coils	1" Sch SS 310, 48 linear feet
E-5	Convection Coil	1" Sch 40 CS, 450 linear feet
B-1	Fluid Bed and Freeboard	Braced CS plate, 3" LW refractory
	Section 1:	3′ x 2′ x 2′
	Section 2:	3′ expansion to 4′ x 2′
	Section 3:	3′ at 4′ x 2′
	Pulse Combustor	Aerovalve, chamber, tailpipe, and draft tube
V-6	Baghouse	500 CFM with ID fan
V-4	Cyclone	1.5′ x 4′ CS with dipleg
F-1	Primary Air Fan	100 CFM at TBD
F-2	Forced Draft Fan	300 CFM at TBD
F-3	Induced Draft Fan	500 CFM at 10"

- PAFBC requires shorter freeboard and thus less volume of reactor and lower capital cost for the vessel (cost saving: 5 percent).

- PAFBC does not require solids recycle because it has high calcium utilization and high carbon conversion in single pass and the fines are directly burned in the pulse combustor (cost saving: 5 percent).

- PAFBC uses less sorbent, and consequently, generates lower solid waste to be disposed of. This reduces solids storage and handling equipment costs (cost saving: 5 percent).

- PAFBC eliminates the inefficient heat exchange in the freeboard that is characteristic of conventional AFBC. The heat transfer coefficient in the pulse combustor tailpipe is comparable to that in the dense fluidized bed, thereby reducing the total cost of heat transfer surface required for steam production (cost saving: 5 percent). However, the incorporation of the pulse combustor and its control is expected to increase the system cost by about 5 percent.

Thus, the overall capital cost of the PAFBC is anticipated to be reduced by about 25 percent compared with that of AFBC.

Similarly, operating costs will be lower for the PAFBC due to: 1) the ability to use lower cost unsized coal, 2) a reduction in sorbent feed rate, and 3) a reduction in electricity consumption. Hence, the total cost of steam will be lower for PAFBC than for AFBC by nearly 25 percent.

From this analysis, the projected cost of a PAFBC at 1,000 PPH is $49,000. Given the lower operating and capital costs of the PAFBC boiler, it is evident from the economic analysis that the PAFBC boiler can be competitive with an equivalent natural gas boiler if the application capacity factor and fuel price differential are sufficiently high.

In conclusion, the economics of steam production at the 1,000 PPH level does not support the use of a dedicated operator. The system must be designed with highly automated instrumentation in order to minimize operator attendance, even if this incurs a significant increase in capital expenditures.

The anticipated higher capital cost of a coal-fired system requires that applications with higher capacity factors will provide the initial market opportunities when fuel price gaps are moderate. Thus, specific small-scale markets offering reasonably high capacity factors should be targeted for initial commercial service entry of the technology.

SECTION 4.0

LABORATORY-SCALE DEVELOPMENT AND TESTING

4.1 OBJECTIVE

The overall objective was to establish the technical merit of the MTCI PAFBC technology by building and testing a laboratory-scale system. In this developmental effort, important aspects of operational and performance boundaries of the system were to be established experimentally. Based on the results, economic projections were to be updated, and given positive results, a plan for an integrated test facility was to be formulated.

The work was organized into seven subtasks dealing with:

- Design, procurement and construction of an AFBC,
- Coal combustion tests in the AFBC system,
- Modification to a PAFBC system,
- PAFBC system characterization tests,
- Coal combustion tests in the PAFBC system, and
- Technical, environmental, and economic assessment.

A considerable amount of effort was invested in the initial tasks of constructing an AFBC that would represent a reasonable baseline against which the performance of the PAFBC could be compared. A detailed description of that effort is included here to emphasize how well the PAFBC unit resolved the scale-down issues associated with an AFBC.

4.2 DESIGN, PROCUREMENT, AND CONSTRUCTION OF AN AFBC

4.2.1 Design

Key design criteria were as follows:

- The freeboard should allow for particle disengagement and provide a minimum residence time of three (3) seconds.

- Heat removal in freeboard should be minimized to promote complete combustion.

- Flexible heat removal system should be incorporated to allow a wide range of turndown.

- System height should be limited to less than 15 feet.

- Unit should be shop fabricated and truck transportable to the greatest extent possible.

- Design geometry should minimize accumulation of ash and particulates.

- Particulate collection should be localized at minimum number of points.

- System should consist of simple modular construction.

The AFBC system was designed to burn high sulfur bituminous coal at a nominal firing rate of 1.4 MMBtu/hr and generate 1000 PPH of low-pressure saturated steam. The design configuration for the AFBC is shown in Figure 4-1. From fabrication standpoint, the AFBC comprises three separate sections: 1) Furnace section, 2) Transition Duct, 3) and Downflow Convection section.

Furnace Section. Figure 4-2 is a drawing of the furnace section. The fluidized bed furnace consists of four separate subsections. These include: 1) a 24-inch high convergent lower subsection for air distribution; 2) an intermediate subsection of dimensions 34"W x 34"L x 36"H to accommodate the dense bed; 3) a 36-inch high expanded subsection, with lower dimensions of 34"W x 34"L and upper dimensions of 34"W x 58"L, which constitutes the transition freeboard zone; and 4) an upper straight freeboard subsection of dimensions 34"W x 58"L x 36"H. Each subsection is provided with mating flanges and is constructed from 1/4-inch carbon steel plate. The furnace

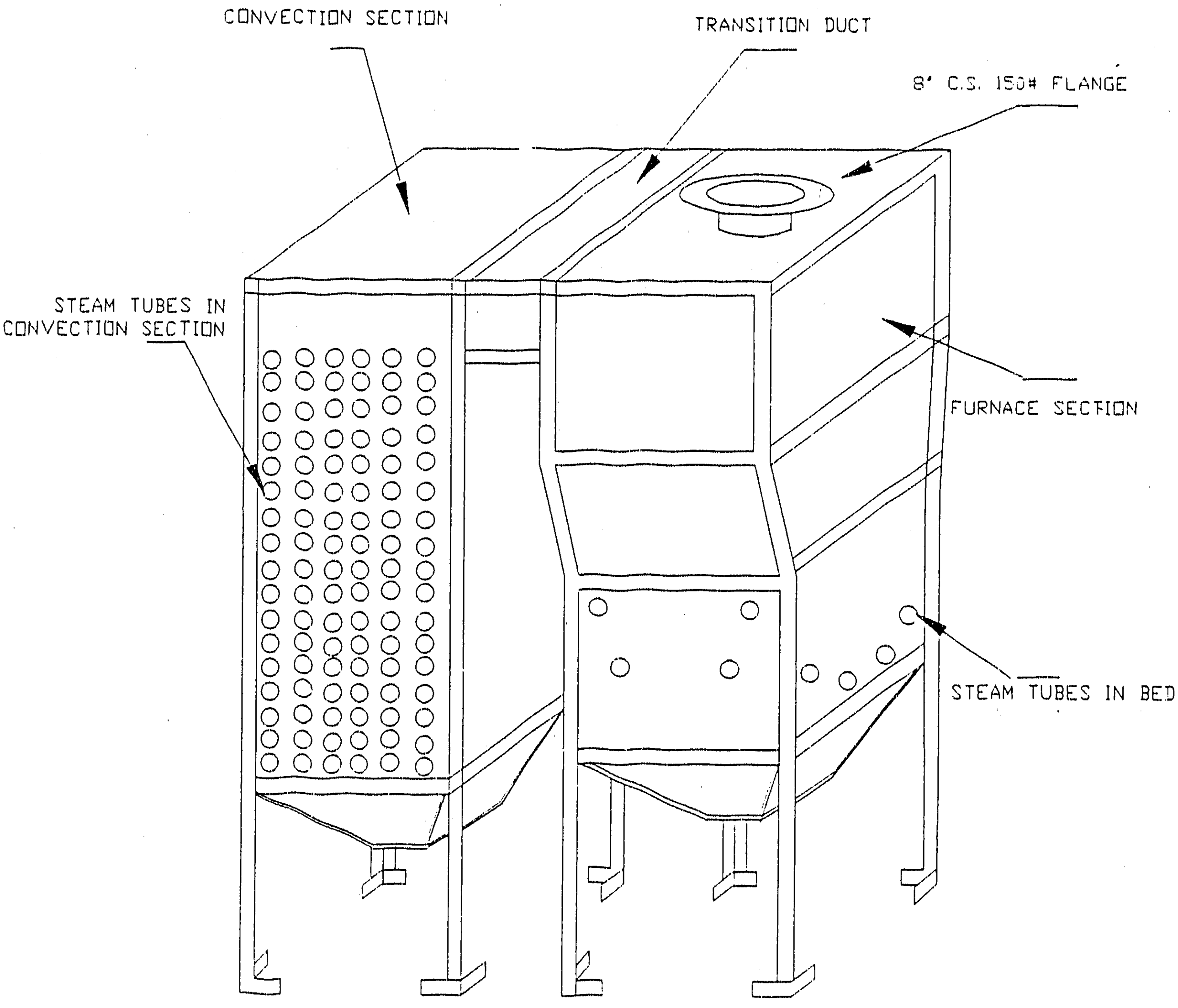
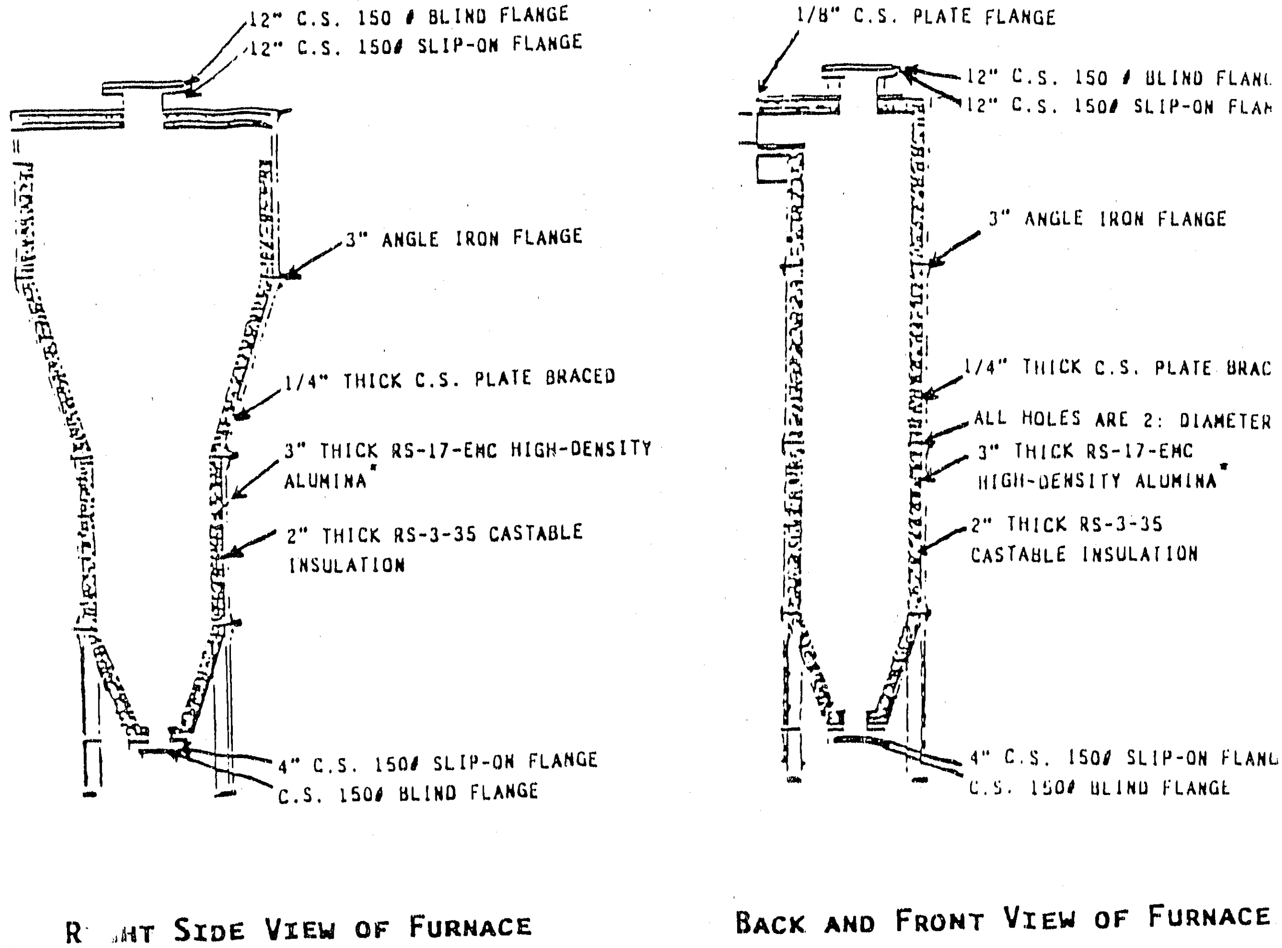


FIGURE 4-1: AFBC BOILER - GENERAL ARRANGEMENT



*Refractory materials are by:
Pyro Engineering, Santa Fe Springs, CA

FIGURE 4-2: DESIGN DRAWING FOR FURNACE SECTION

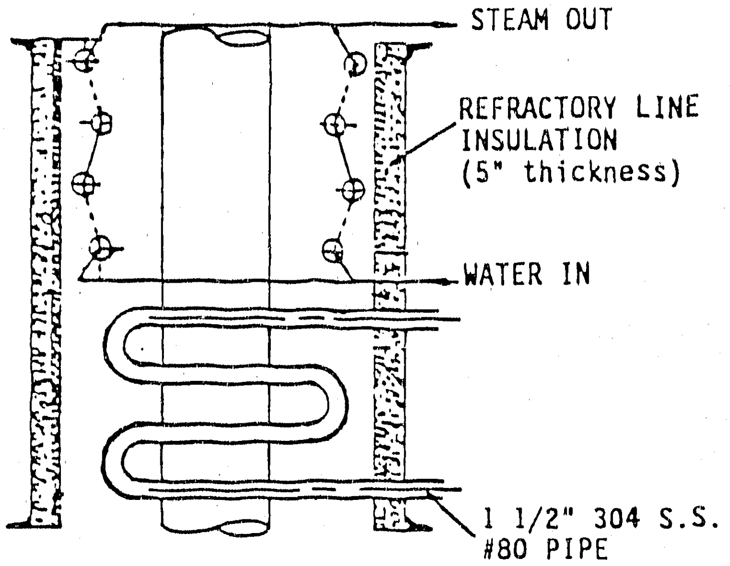
superstructure or frame, shown in Figure 4-1, is formed from welded 3-inch angle iron located on the outer surface of the 1/4-inch plate.

Each subsection is internally lined with a double layer of castable refractory. The outer insulating layer is 3 inches thick and consists of a lightweight insulating castable with a density of 41 lb/ft^3, and a K value of 1.25 $Btu.in/ft^2/°F/hr$ at 1500°F. The inner layer is 2 inches thick and consists of an abrasion-resistant, dense castable refractory with a density of 118 lb/ft^3, and a K value of 5.6 $Btu.in/ft^2/°F/hr$ at 1500°F. The total heat lost from the furnace walls is less than 5 percent of the total input heat. The refractory is anchored at a number of locations to ensure adherence to the furnace walls.

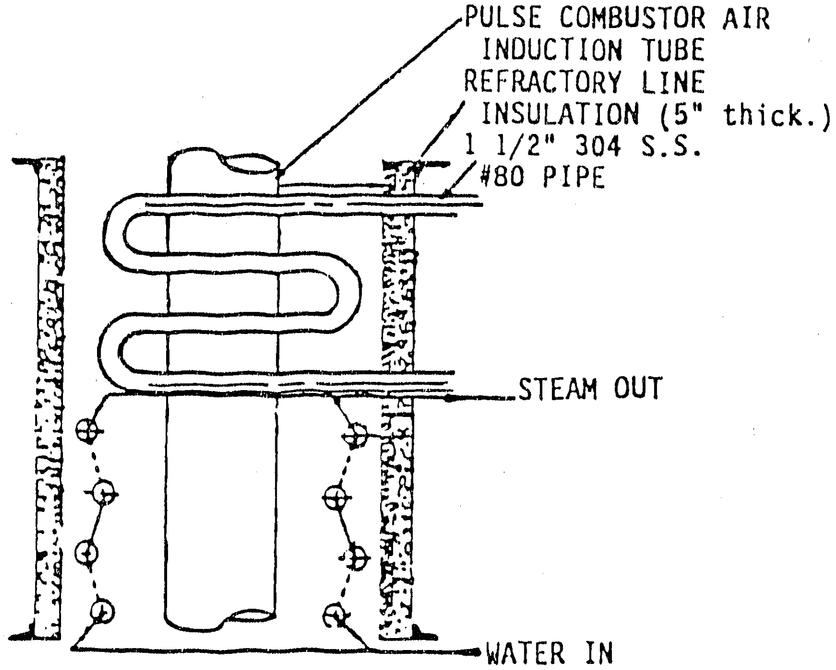
The upper furnace subsection is provided with a circular connection flange for the centrally located pulse combustor, and a rectangular flange for the transition duct. The lower furnace subsection is provided with a circular flange as an outlet means for discharging solids contained in the furnace under normal operation.

The fluidized dense bed is approximately three feet deep and four square feet in cross-section. Horizontal boiler tubes are mounted within the bed to maintain the bed temperature between 1500°F and 1600°F. The bed contains four separately manifolded tube bundles (for maximum flexibility in bed temperature control) formed from 1 1/2-inch sch 80 S.S. 304 pipe. The tubes are arranged in a triangular pitch, four-pass arrangement. Each tube pass is 21 inches long, and the total heat transfer surface area is 14 ft^2. **<u>Figure 4-3</u>** shows the tube layout in the dense bed section.

The boiler tubes are mounted in such a way as to obtain a uniform temperature within the bed. Two of the tube bundles are both vertically and orthogonally displaced within the bed relative to the other two tube bundles. About 70 percent of the total steam is generated within the bed section and the remaining is generated in the convection section. Six feet of expanded height above the fluidized bed allows for the disengagement of solids



BACK SIDE VIEW



RIGHT SIDE VIEW

FIGURE 4-3: DRAWING OF TUBE LAYOUT IN THE BED SECTION

entrained by the bed fluidization action. The combustion gases exit the furnace at a temperature of approximately 1600°F and at atmospheric pressure.

Transition Duct and Convective Section. The hot gases pass through the transition duct and enter the convective section. The transition duct is constructed from 1/4-inch carbon steel plate, with rectangular flanges at both ends for connection to the furnace section and the convection section. The transition section is insulated with 3-inch thick, lightweight insulating castable refractory. Total length of the transition section is 2 ft long, with a flue gas passage cross-sectional area of 2.2 square feet.

The convection section consists of three separate subsections: 1) the lower convergent subsection, 2) the main body, and 3) the upper subsection. Each subsection is constructed from 1/4-inch carbon steel plate with mating flanges. The upper subsection is provided with a flanged inlet for connecting to the transition duct. The lower subsection is provided with a circular flanged outlet for ash collection and a rectangular flanged outlet for exiting flue gas. The main body houses the steam generation tube bundle which consists of 1 1/2-inch sch 40 C.S. pipes. The tubes are arranged in a square pitch, with 6 tubes per row in an 18-pass arrangement. The tubes are 62 inches long from weld to weld and are supported by a vertical tube sheet. The tube sheet face is sealed with an additional tube sheet cover. The total heat transfer area is 233 ft^2. An inspection port is provided to check the tube bundles periodically and to clean the tubes from accumulated solid deposits during operation. An end cover is provided for the tube bundle. It is constructed from 1/8-inch carbon steel plate, with 1-inch thick ceramic fiber insulation. The convection section is lined with a single layer of insulating castable refractory. The insulating layer is 3 inches thick, and consists of a lightweight castable with a density of 41 lb/ft^3, and a K value of 1.25 $Btu.in/ft^2/F/hr$ at 1500°F.

The initial design drawings were provided to four separate vendors for quotation. Each vendor provided MTCI with quotations for fabricating the furnace section and the convection section separately. Review of the quotations revealed that fabrication of the convection section would approximately double the overall system cost. Since the primary objective of this work was to investigate the integration of a pulse combustor with the fluidized bed portion of the furnace and since the convection section did not incorporate any novel component technology, the additional expense for the convection section was considered to be unjustified. Therefore, the convective section, cyclone and baghouse were replaced by a hot cyclone and a direct quench scrubber. This method of cooling the hot flue gases from the furnace section was anticipated to be less costly. This modification did not affect either the design or operating characteristics of the furnace. However, the usable steam output of the modified system was estimated to be 700 lb/hr instead of 1000 lb/hr as in the initial design. **Figures 4-4** and **4-5** show the process flow diagrams for the initial AFBC system design and the modified design, respectively.

Based on the quotations cited above, MTCI selected a qualified vendor (SEC Construction Corporation) and provided the final mechanical drawings of the furnace section for fabrication. There were subsequent minor changes to the initial furnace design. The thickness of the outer castable refractory insulating layer was changed from 3 inches to 2 inches and also the thickness of the inner, high-density, abrasion-resistant castable refractory was changed from 2 inches to 3 inches. This change was made after consulting with the refractory professionals who suggested that, since the abrasion-resistant, castable refractory was subjected to higher thermal cycling, it had to be made thicker than 2 inches to avoid possible cracking. One 4-inch port was added to the furnace section 1 ft above the bed surface to use as the feeding port for coal and limestone. A 4-inch port was also added to the lower convergent subsection for bed dump.

A pipe grid air distributor was designed for the AFBC furnace (**Figure 4-6**). It consists of two 4-inch schedule 40 CS pipe headers with four 1-inch schedule 50 SS sparge pipes branching from each header. Each sparge pipe has 76 orifices of 5/64 inch diameter placed 90 degrees apart radially at 19 longitudinal locations.

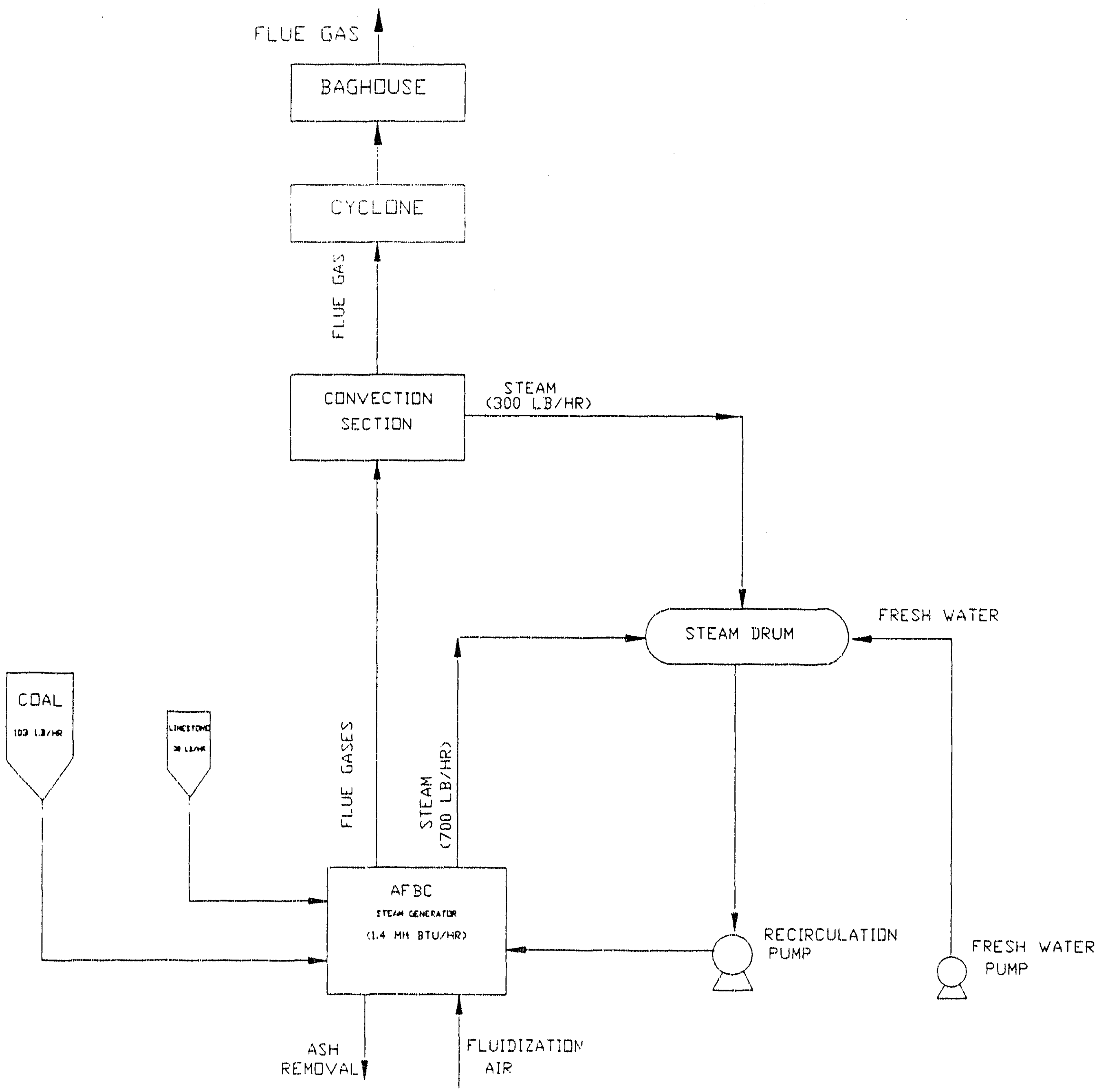


FIGURE 4-4: PROCESS FLOW DIAGRAM FOR THE INITIAL AFBC SYSTEM DESIGN

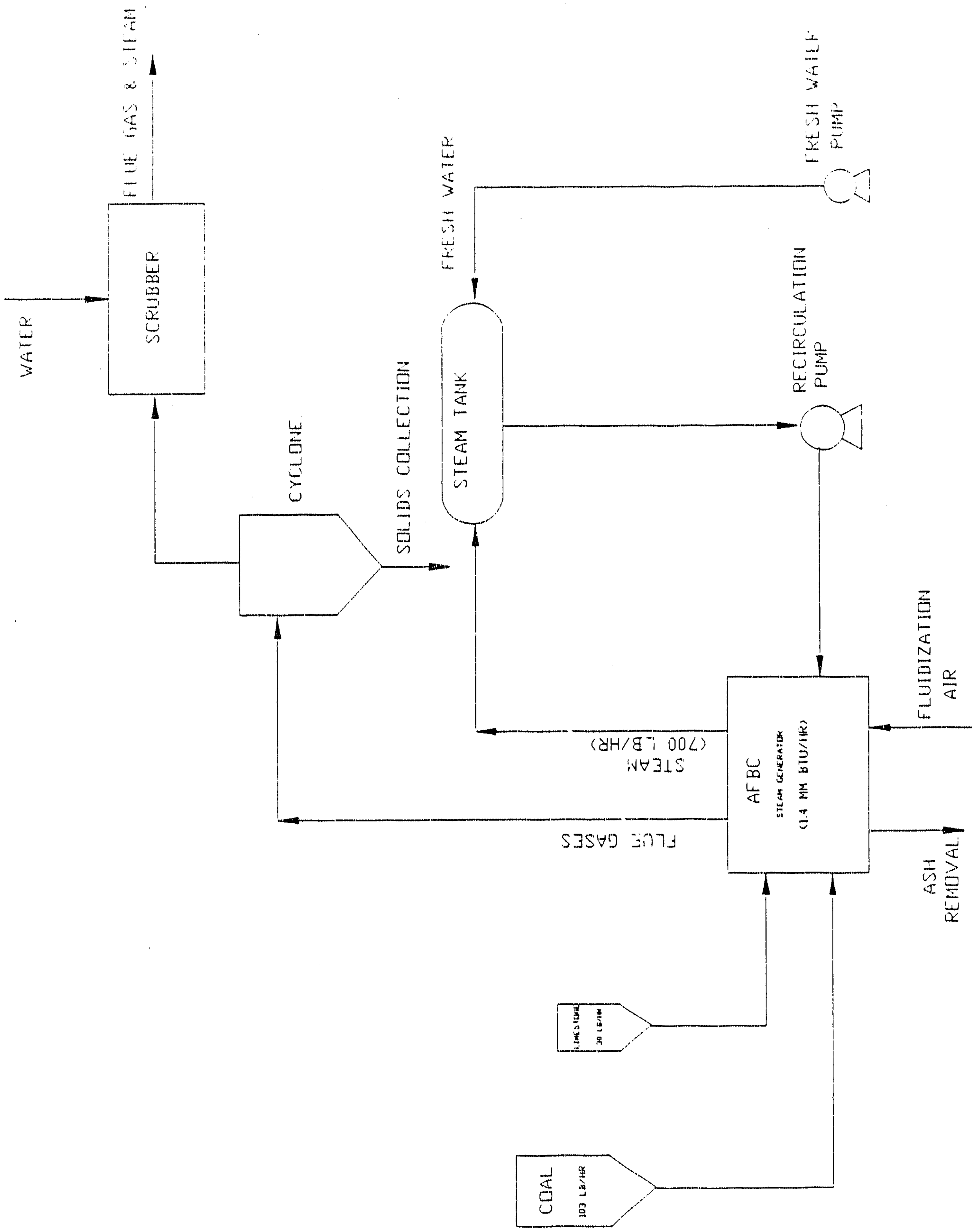


FIGURE 4-5: PROCESS FLOW DIAGRAM FOR THE MODIFIED AFBC SYSTEM DESIGN

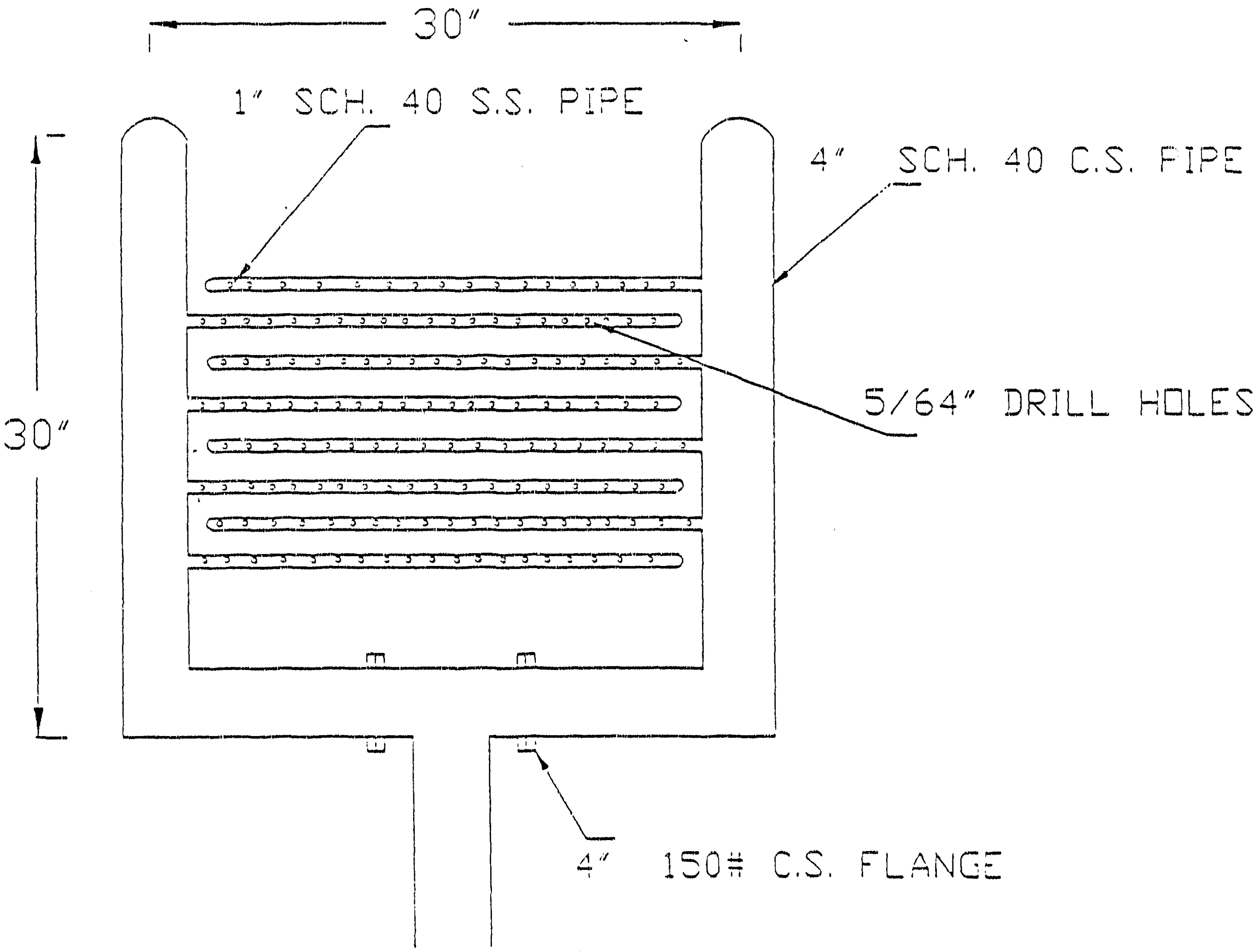


FIGURE 4-6: PIPE GRID AIR DISTRIBUTOR DESIGN

4.2.2 Procurement and Construction

Some of the components of the test facility, such as FD fan, ID fan, water pump, screw feeder, etc., were purchased as per the design specifications. The furnace section was fabricated by SEC Construction Corporation and the remaining components of the test facility such as the cyclone, scrubber, steam drum, etc., were fabricated in-house at MTCI's West Coast Technology Development Laboratory.

An outdoor test site (24′ x 12′ area, 20′ high) at MTCI's West Coast Technology Development Laboratory was selected for the PAFBC system. A plot plan for the system is shown in Figure 4-7. The system was configured in a compact but accessible arrangement.

Figure 4-8 shows a schematic of the AFBC test facility. The system comprises a fluidized bed furnace, coal and sorbent feed systems, a steam-generating circuit, air handling equipment, a cyclone, a venturi scrubber, start-up burner, and an overflow drain. The total furnace height corresponds to 10 feet from the distributor plate to the top of the furnace. A description of the system components follows.

Combustor Section. Primary combustion air is supplied through a 4-inch CS manifold to the pipe grids located beneath the fluidized bed. Air is introduced into the bed through 76 orifice nozzles per tube which are uniformly spaced, both circumferentially and longitudinally, around the pipe grids. Boiler tubes are mounted within the bed to maintain the bed temperature between 1500°F and 1600°F. The primary combustion air blower (Roots blower, type 710 AF) is of a positive displacement variety. The air flow rate to the AFBC is controlled by a blow-off vent valve. Due to high noise level at the air blower vent valve, a silencer is mounted at its exit to reduce the noise level by expanding the airflow from a 2-inch pipe into a 40-gallon C.S. tank. Figure 4-9 shows a schematic of the silencer.

As a combustor safety feature, a pilot flame has been placed slightly above the bed surface in order to avoid the accumulation of any unburned gases in the freeboard section. Figure 4-10 shows a schematic of the 8,000 Btu/hr

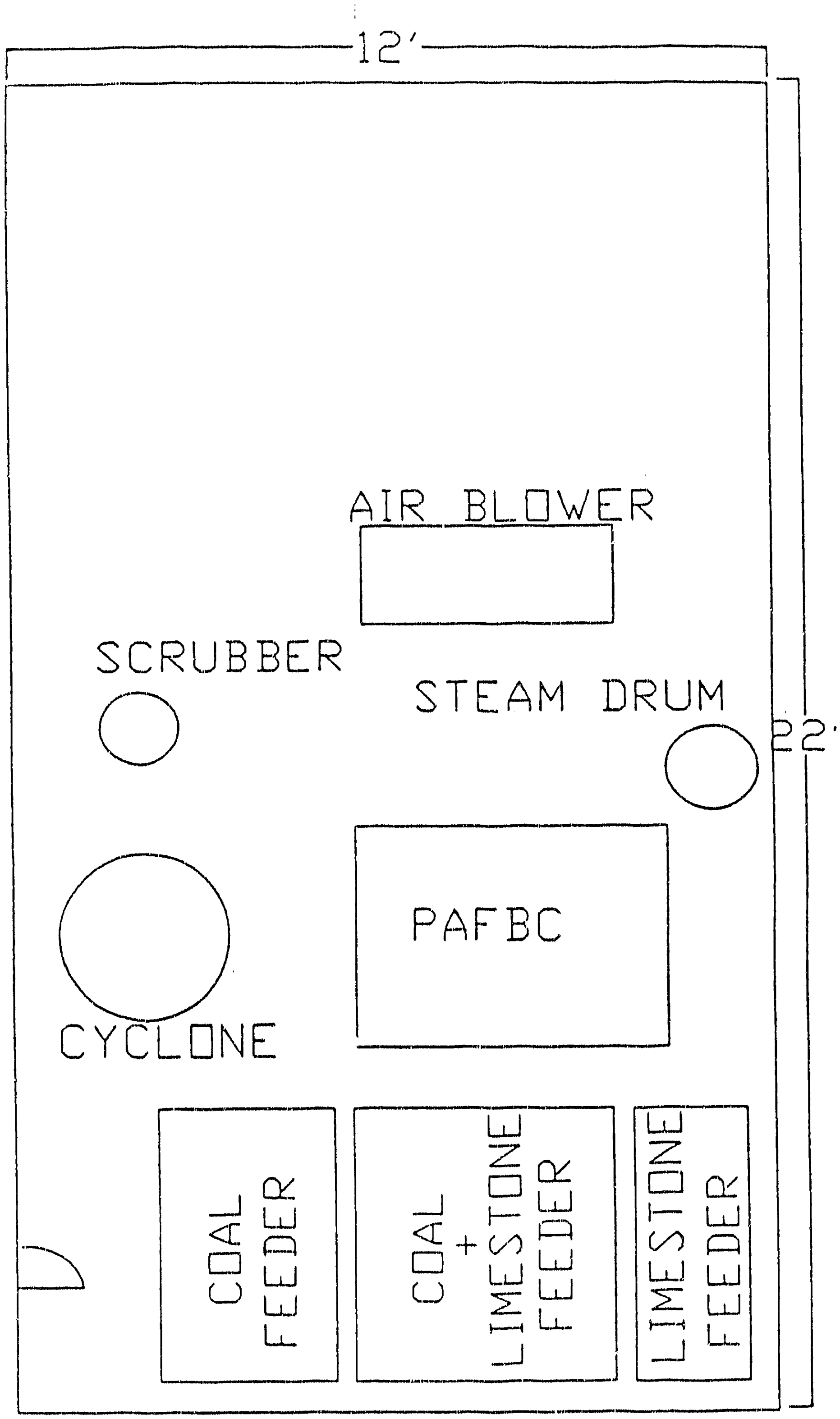


FIGURE 4-7: PLOT PLAN FOR THE AFBC SYSTEM

V-1	V-2	V-3	V-4	V-5	V-6	V-7	B-1
STEAM DRUM	COAL & LIME-STONE BIN	BED SOLIDS COLLECTION DRUM	CYCLONE SOLIDS COLLECTION DRUM	WATER DRAIN DRUM	CYCLONE	SILENCER	FBC

B-2	B-3	B-4	F-1	P-1	E-1/E-2	S-1
PRIMARY AIR BLOWER	PREHEAT AIR BURNER	PILOT BURNER	INDUCED DRAFT FAN	LIQUID PUMP	FLUID-BED STEAM COIL	SOLIDS DRAIN VALVE

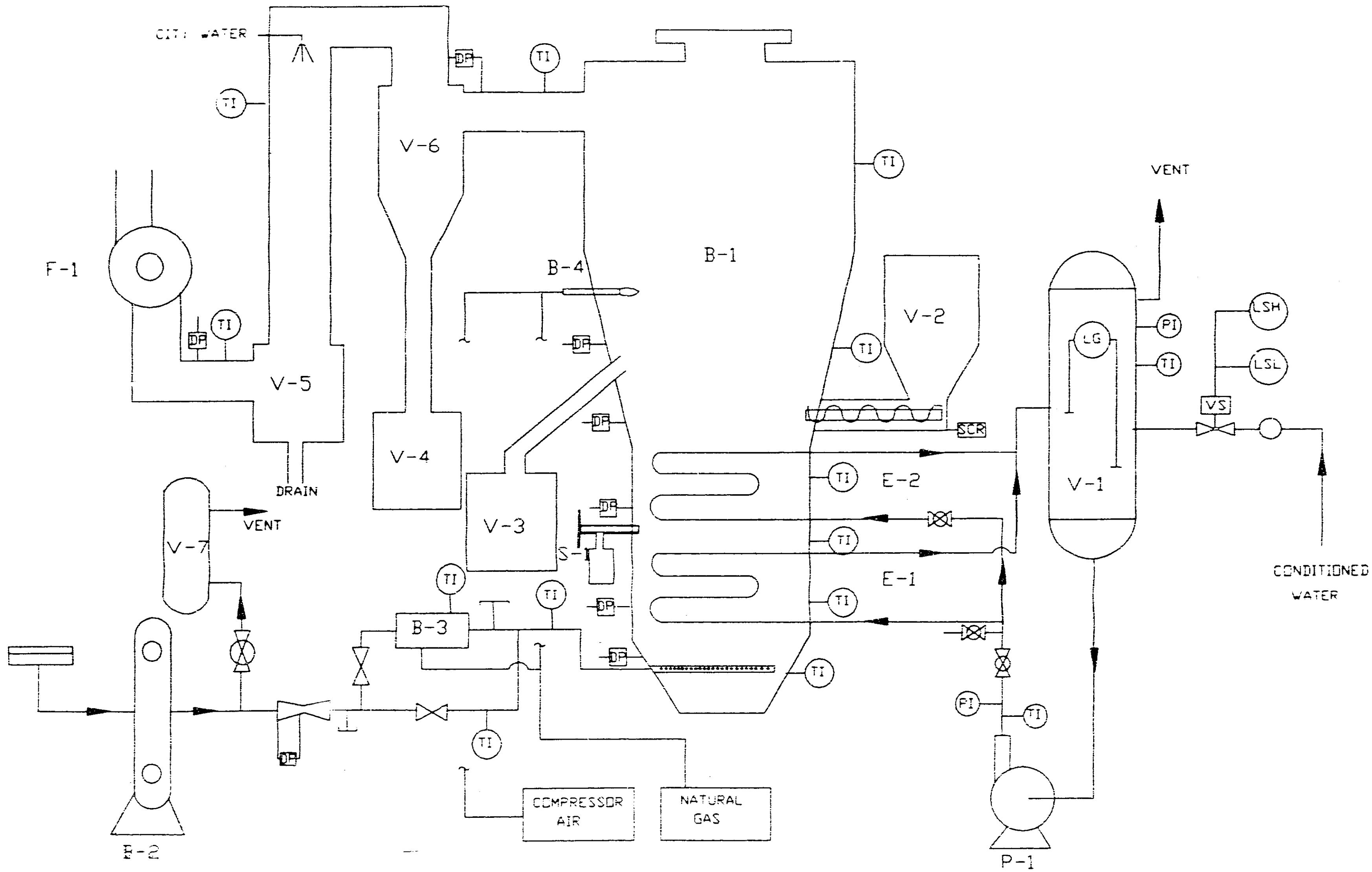


FIGURE 4-8: AFBC SYSTEM LAYOUT

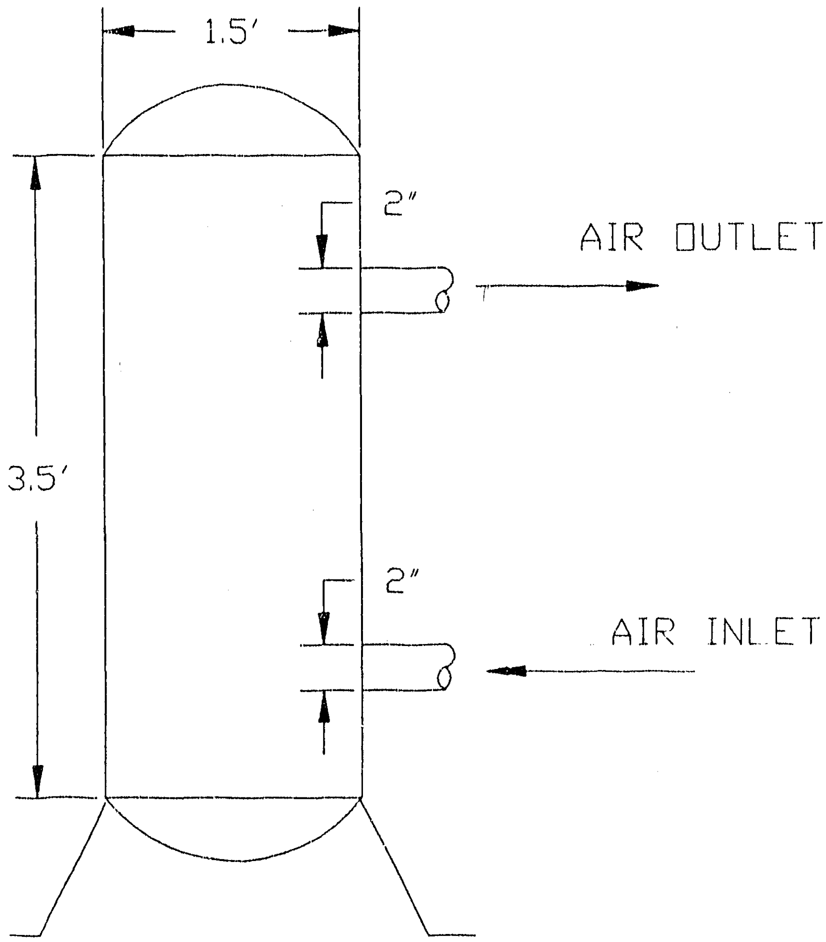


FIGURE 4-9: SCHEMATIC OF THE SILENCER

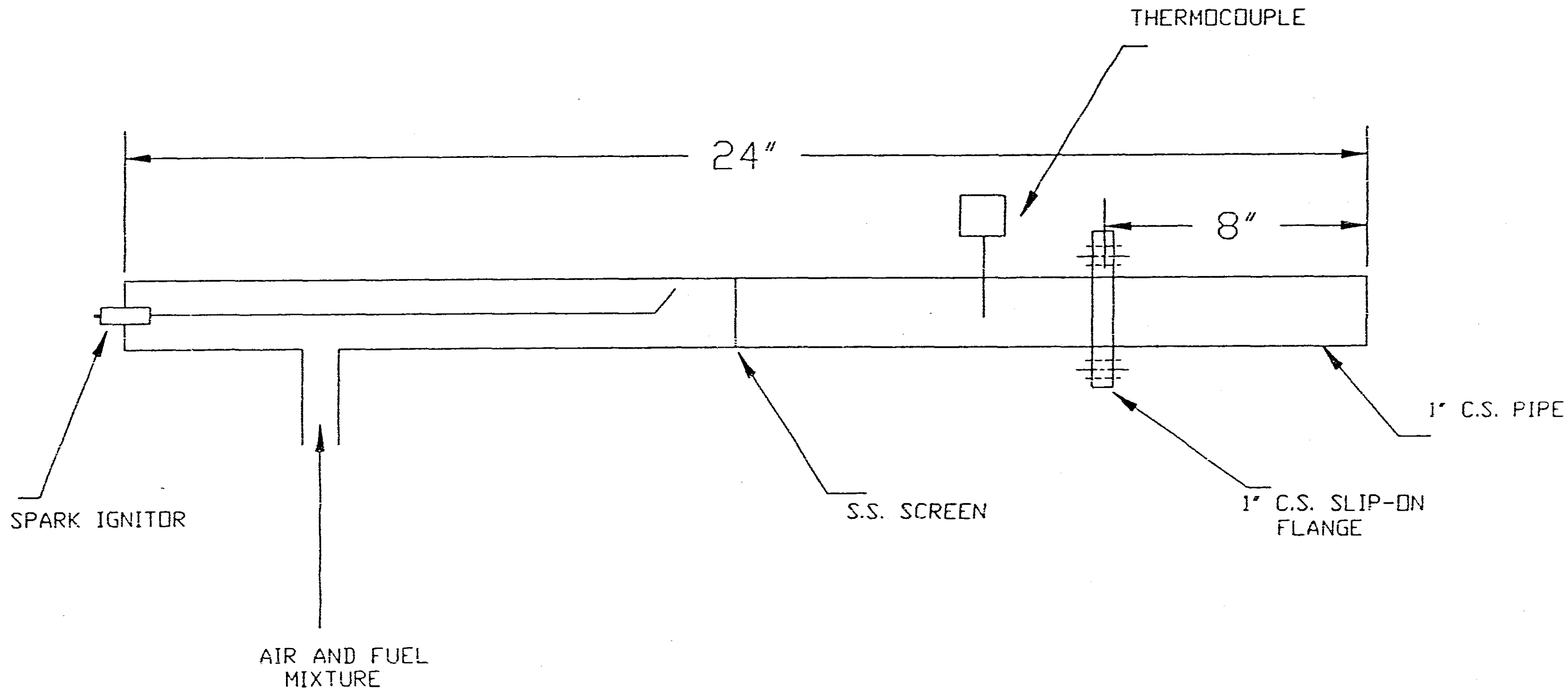


FIGURE 4-10: SCHEMATIC OF THE PILOT BURNER

pilot burner. A pre-mixed mixture of gas and air enters the burner tube and an electrical spark plug ignites the mixture. A flame holder has been positioned to keep the flame source inside the tube. A thermocouple is placed downstream of the flame holder in order to verify existence of the flame.

All of the designated ports were placed on the furnace body to prepare the furnace for pouring the two layers of refractory inside the furnace walls. V-shaped anchors 4 inches long were prepared and welded to the furnace walls in order to hold the refractory layers in place. The curing period for the refractory layers was about one week.

The in-bed steam coils were fabricated and placed inside the furnace before pouring the refractory, for ease of installation. The pipe grid air distributor was installed after the refractory was poured. A 1-inch solids draw-off valve was placed in the furnace section to maintain the bed level at the desired height. The draw-off valve was slanted to allow gravity overflow of the bed solids to a sealed collection drum. In addition, a screw-type solids sample valve was placed on the furnace wall. The sample valve will allow monitoring of the bed carbon inventory level during a test run. Figure 4-11 shows a schematic of the sample valve.

Coal and Limestone Feeding System. Premixed coal and limestone (at the desired Ca/S molar feed ratio) was supplied from a 3′ x 2′ x 4′ CS live bottom hopper into a speed-controlled, over-bed screw feeder for injection into the combustor. In order to avoid overheating of the screw which could result in coal pyrolysis and agglomeration within the screw flights, a water-cooled hollow screw was employed. In addition, the screw barrel was water-jacketed. Figure 4-12 shows the injection screw water-cooling system. A rotating joint was used to supply water from a stationary source to the rotating hollow injection screw. Water entered the rotating joint through a 1/4-inch tube and returned through a concentric annulus.

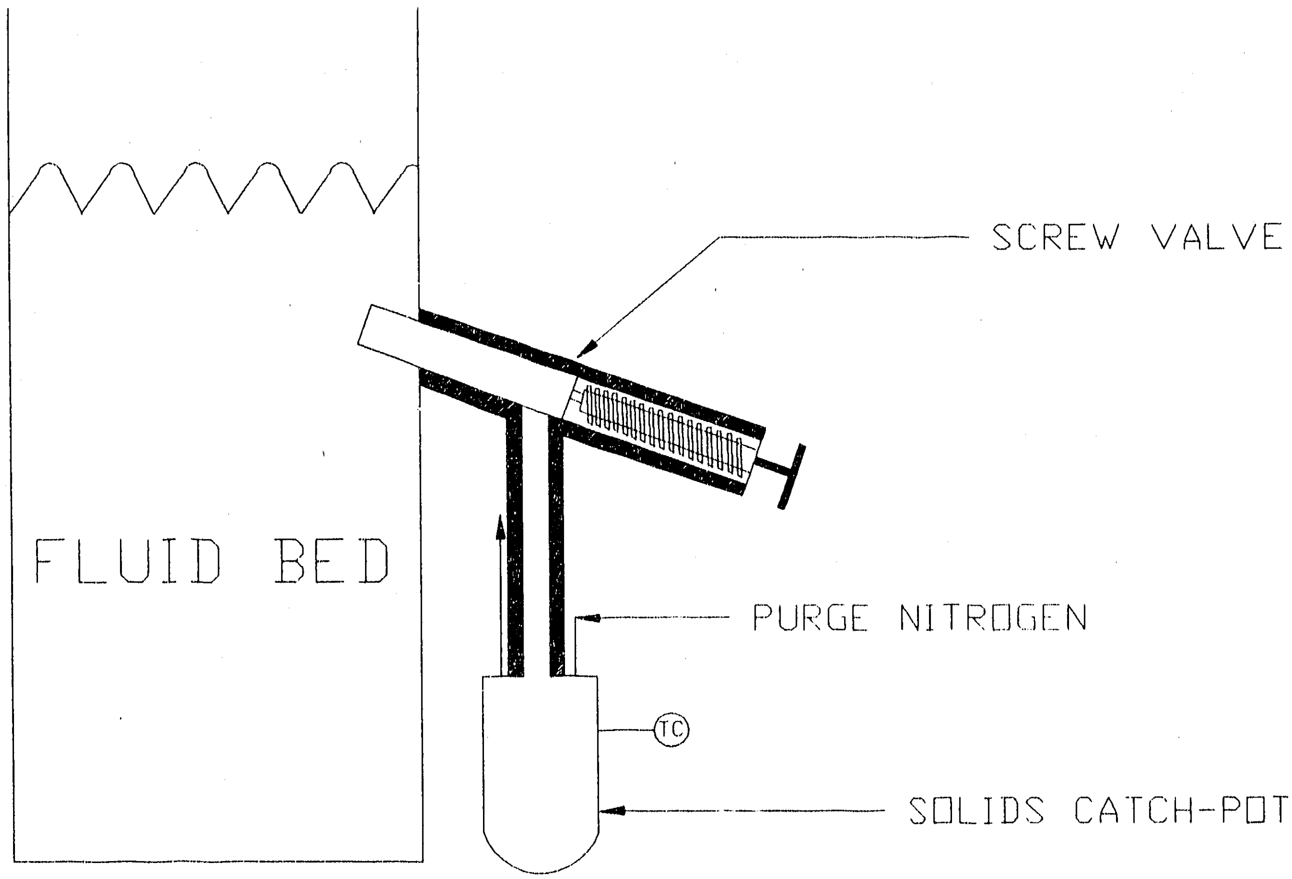


FIGURE 4-11: SCHEMATIC OF THE BED SOLIDS SAMPLE VALVE

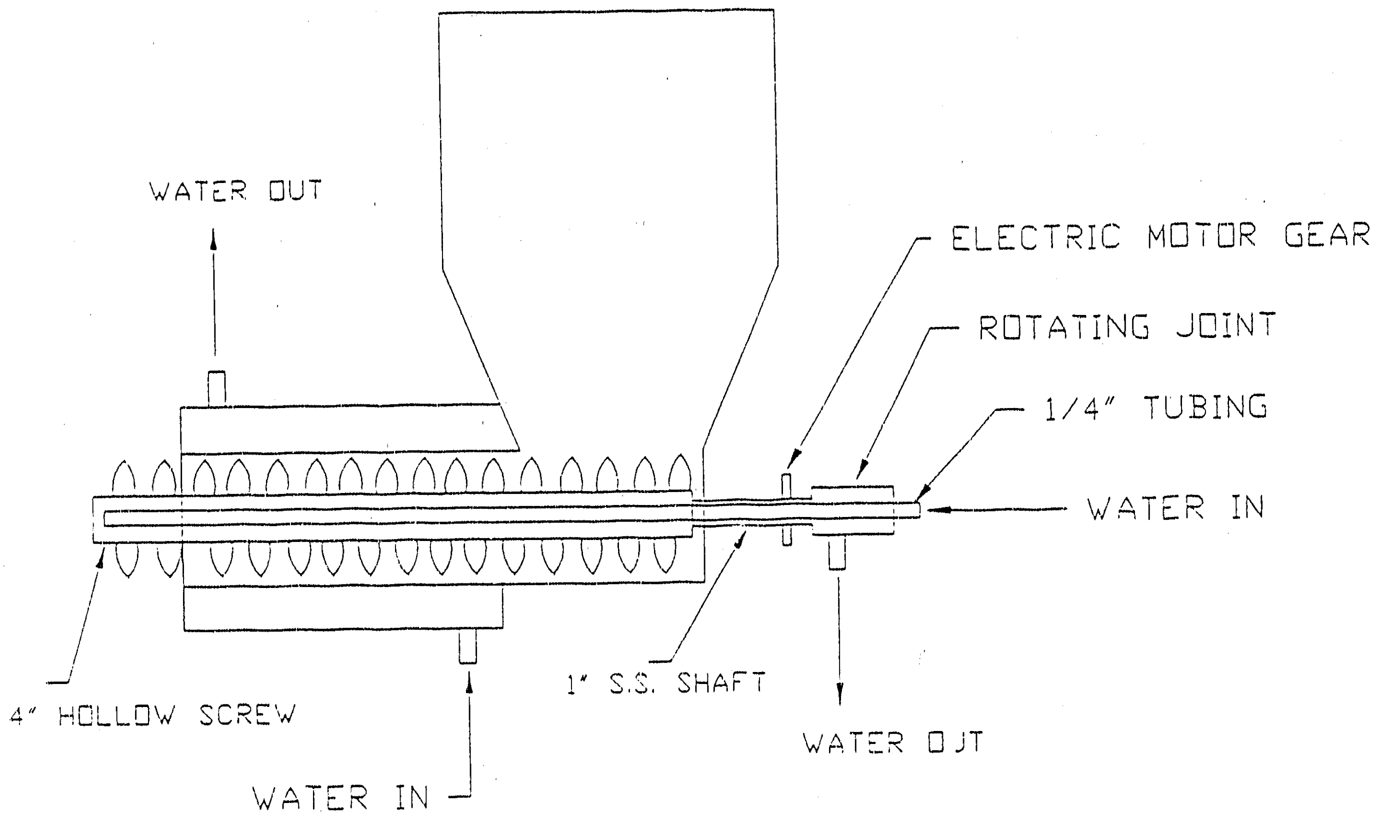


FIGURE 4-12: DIAGRAM FOR THE MAIN SCREW WATER-COOLING SYSTEM

__Flue/Gas Heat Exchange System__. The combustion gases exit the fluidized bed combustor at a temperature between 1500°F and 1700°F. An induced draft fan maintains a suction draft for the flue gases. The hot gases, containing fly ash and elutriates, enter a stainless steel hot cyclone (__Figure 4-13__). The cyclone catch solids are collected in a stainless steel drum. The flue gas exiting the cyclone is then cooled to approximately 300°F as it passes through the water spray quench system (10-inch diameter) before it is vented to the atmosphere.

__Start-Up Burner__. A 500,000 Btu/hr gas burner is installed in the main combustion air bypass line to preheat the air to about 1200°F before it enters the fluidized bed furnace. The air from the main air blower is supplied to the burner through a bypass line and gate valve that will control the air flow to the burner. __Figure 4-14__ shows a schematic of the start-up burner system. During start-up, the burner will be down-fired into the bed while maintaining low-velocity fluidization conditions in order to distribute heat uniformly throughout the bed. As the bed temperature reaches 1000°F, the start-up burner will be shut off and coal and limestone will be fed into the bed. The start-up gas burner will be controlled manually; however, it will include a gas shut-off valve which will be actuated in the case of a flame-out or bed over-temperature condition.

__Air Handling Equipment__. It consists of a Roots blower (frame-type, 710 AF) and a 10-HP electric motor. The pulley ratio between the blower and the motor is approximately 3 to 1. __Figure 4-15__ shows the general performance curve for the frame 760 AF blower.

After installing the Roots blower, a series of tests were performed on the blower to define its performance characteristic. __Figure 4-16__ shows the setup used for these tests. __Table 4-1__ summarizes the results of these tests. The measured flow rates are in satisfactory agreement with those given in Figure 4-15. The speed of the blower was determined by using a D-C generator manufactured by Servo-Tek Products Company with a rating of 7V at 1000 rpm. A computer program using Lotus 1-2-3 was developed to calculate the flow rate through a 4" x 2" venturi as a function of pressure drop through the venturi.

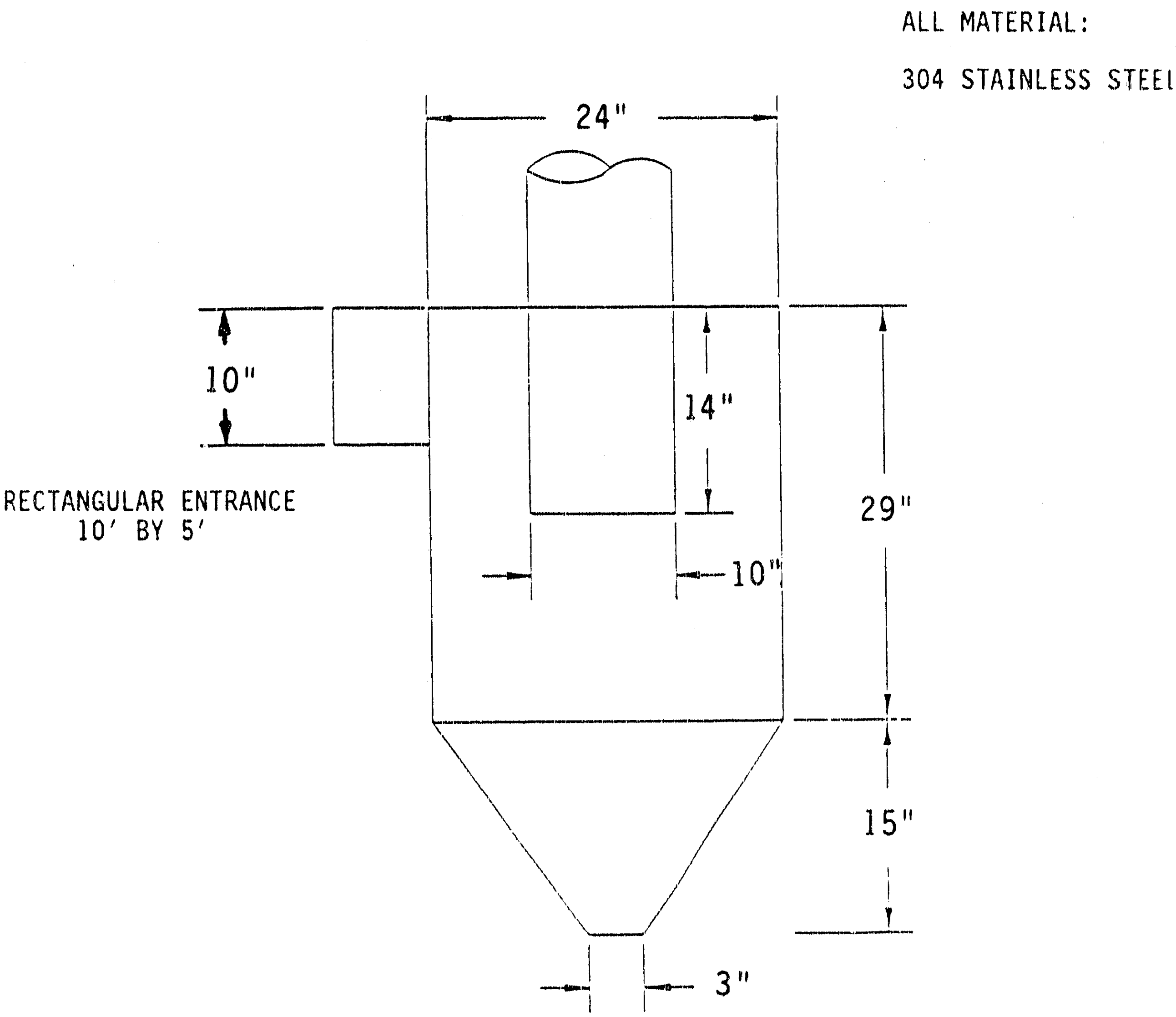


FIGURE 4-13: DRAWING OF THE AFBC CYCLONE

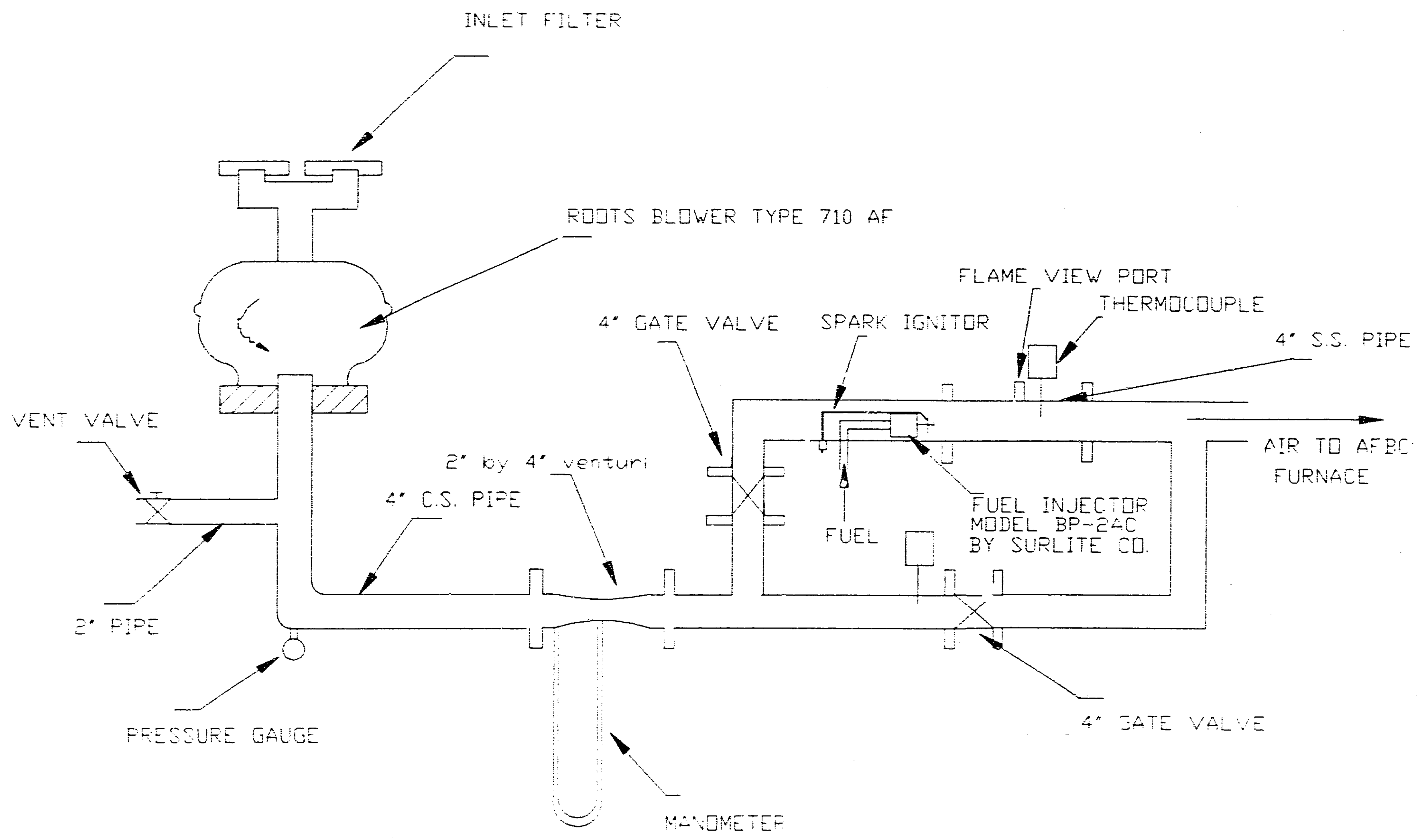


FIGURE 4-14: SCHEMATIC OF THE AIR PREHEAT BURNER

DRESSER INDUSTRIES, INC.

ROOTS BLOWER & VACUUM PUMP DIVISION
CONNERSVILLE, INDIANA
PRINTED IN USA

PERFORMANCE BASED ON
INLET AIR AT 14.7 PSIA & 68°F
JAN. 1971 SUPERSEDES APRIL 1969

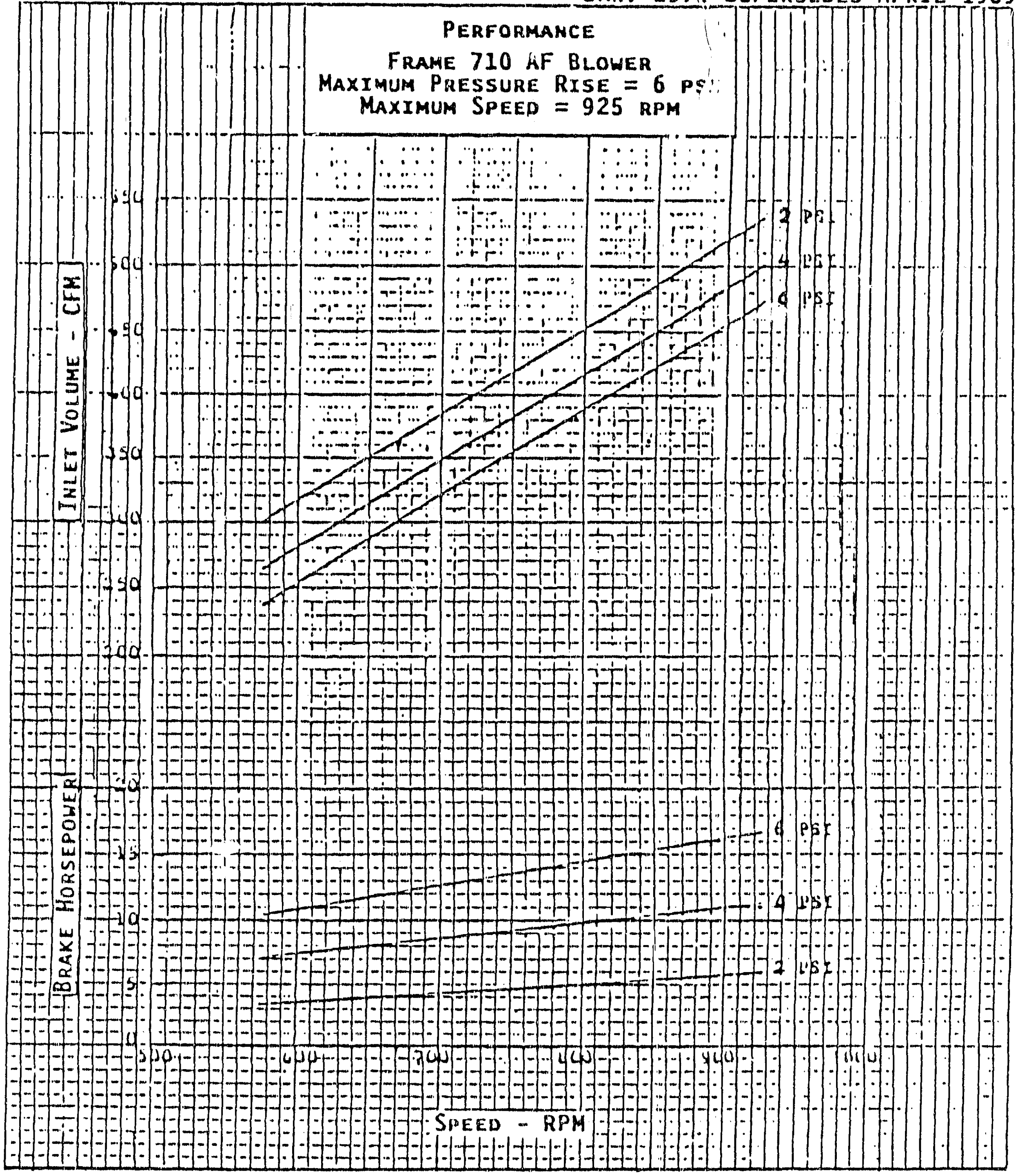


FIGURE 4-15: GENERAL PERFORMANCE CURVE FOR ROOTS BLOWER

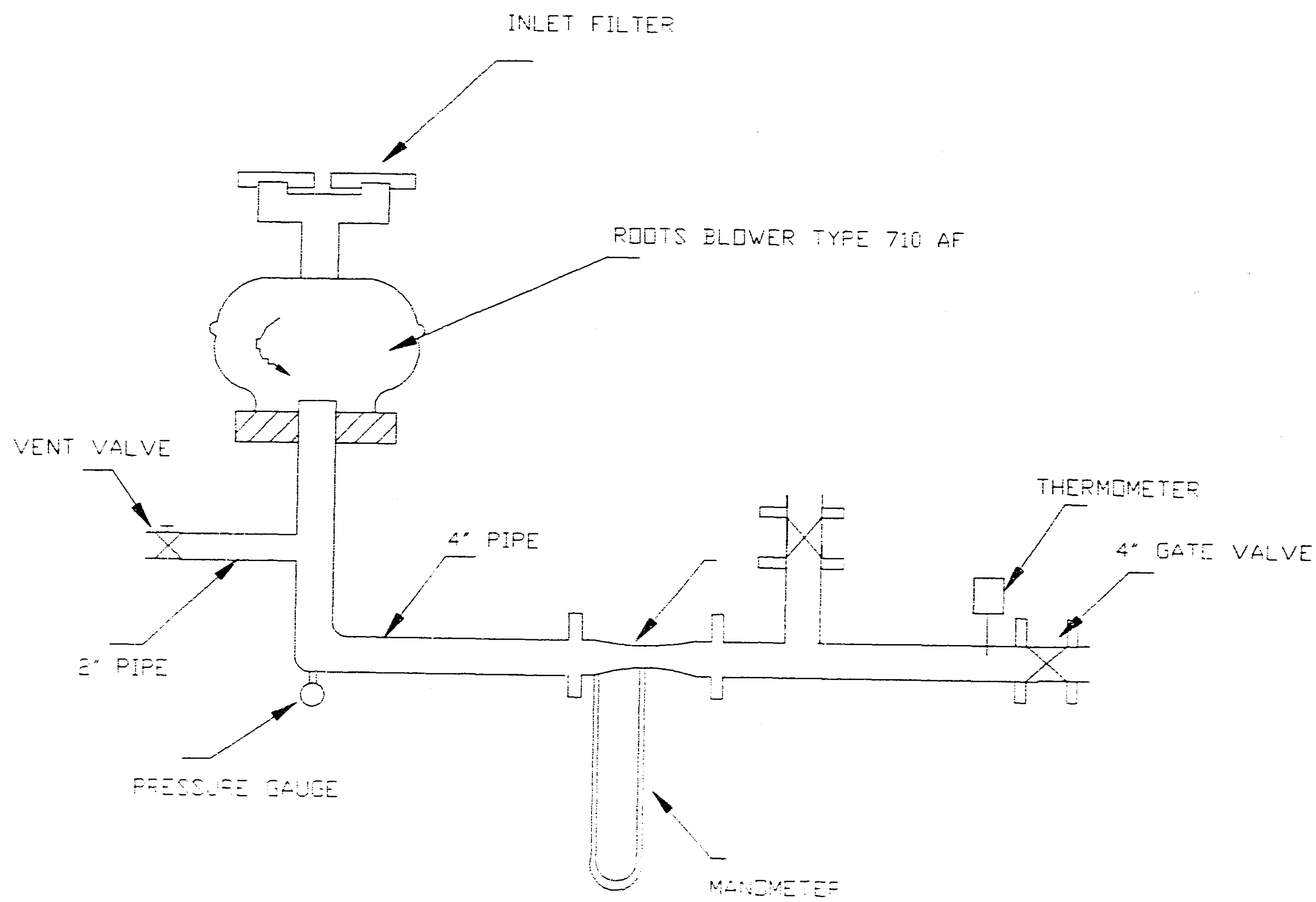


FIGURE 4-16: TEST SET-UP FOR DETERMINING THE PERFORMANCE OF THE ROOTS BLOWER

TABLE 4-1: RESULTS OF THE PERFORMANCE TESTS ON THE ROOTS BLOWER

Blower RPM = 670

PRESSURE HEAD (psi)	FLOW RATE (cfm)	AIR TEMPERATURE (°F)
0	415	86.2
0.5	380	91.0
1.0	375	95.3
1.5	360	99.0
2.0	350	102.4
2.5	340	107.7

<u>Steam Generation Circuit</u>. A commercial water softener was used for pretreating the feed water entering the circuit. A 4-inch diameter impeller driven by a 2-HP electric motor was used to circulate water through the tube bundles and the steam drum. A sketch of the steam drum and the water level controller is shown in <u>Figure 4-17</u>. A liquid level switch, composed of two stainless steel electrodes displaced vertically inside the steam drum and a dual function relay, attempts to maintain adequate water level in the drum. The capacity of the drum is approximately 80 gallons.

<u>System Instrumentation and Controls</u>. A total of 12 thermocouples were placed at different heights and locations within the fluidized bed to monitor the bed temperature. Thermocouples were also placed in the expanded and straight sections of the freeboard. In-bed pressure taps were placed at one-foot intervals to monitor the bed depth and fluidization dynamics. Valves were incorporated at two steam coil inlets to regulate the heat extraction from the bed. Sample ports for flue gas analysis were located in the freeboard cyclone exit and stack. A portable Teledyne analyzer is used to monitor oxygen, carbon monoxide and combustibles. NO_x and SO_2 are monitored using Horiba NDIR analyzers. Flue gas temperature is monitored at different

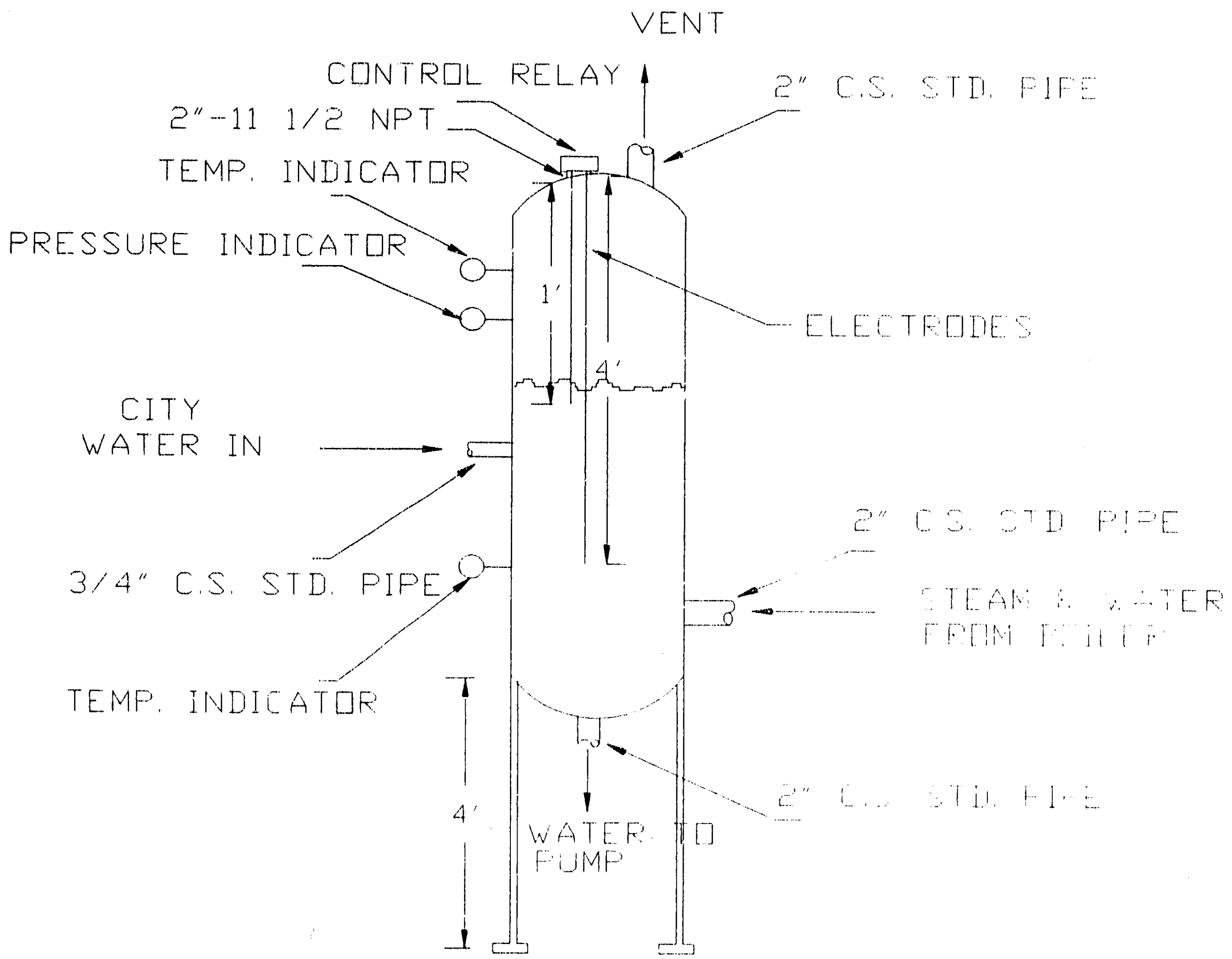


FIGURE 4-17: SKETCH OF THE STEAM DRUM AND THE LIQUID LEVEL SWITCH

locations by means of thermocouples. The required air and natural gas flow meters and controllers, temperature and pressure monitors, ignitor switches and alarms are mounted on a control panel to facilitate centralized readout and control.

Photographs of the AFBC furnace section, cyclone, and steam drum taken before assembly are shown in Figures 4-18 through 4-20.

Modifications to the AFBC system deemed necessary as a result of testing will be discussed under the relevant test subtask.

4.3 COAL COMBUSTION TESTS IN THE AFBC SYSTEM

4.3.1 Test Coals and Limestone

Two high volatile bituminous coals (Kentucky No. 9 and Pittsburgh No. 8) and a limestone (Shasta) were procured for the tests. The Kentucky No. 9 coal was obtained from the Island Creek Coal Company and the Pittsburgh No. 8 coal from TRW. The coal particle top size specified was 1/4-inch but some of the coal drums received contained about 25 percent by weight of coal particles larger than 1/2 inch with some as large as 2 inches. The ultimate and proximate analyses are given in Table 4-2 and the particle size distribution of the as-received coals in Table 4-3.

The Shasta limestone was purchased from the Pfizer Company near Los Angeles, California. The chemical composition of the limestone is given in Table 4-4 and the particle size analysis in Table 4-5. Cold air fluidization tests were performed to evaluate the fluidization characteristics of the limestone as bed material. Figure 4-21 shows the test set-up and Figure 4-22 the pressure drop variation with air velocity. The minimum fluidization velocity turns out to be approximately 2.5 ft/s and this experimental value is in reasonable agreement with a value of 2.9 ft/s calculated from a published correlation.

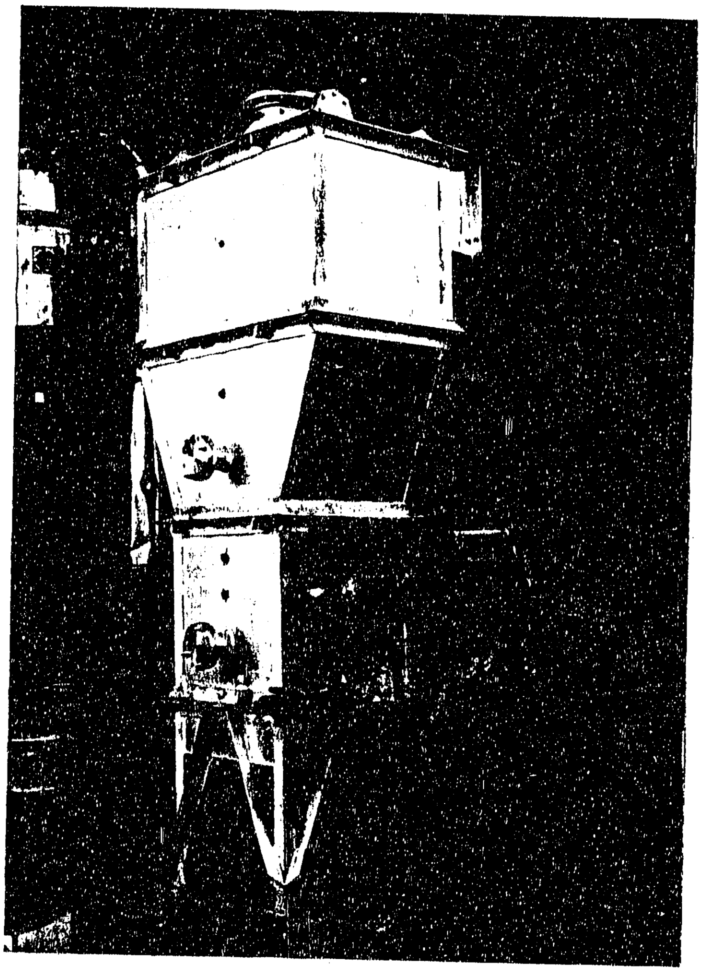


FIGURE 4-18: PHOTOGRAPH OF THE AFBC FURNACE SECTION

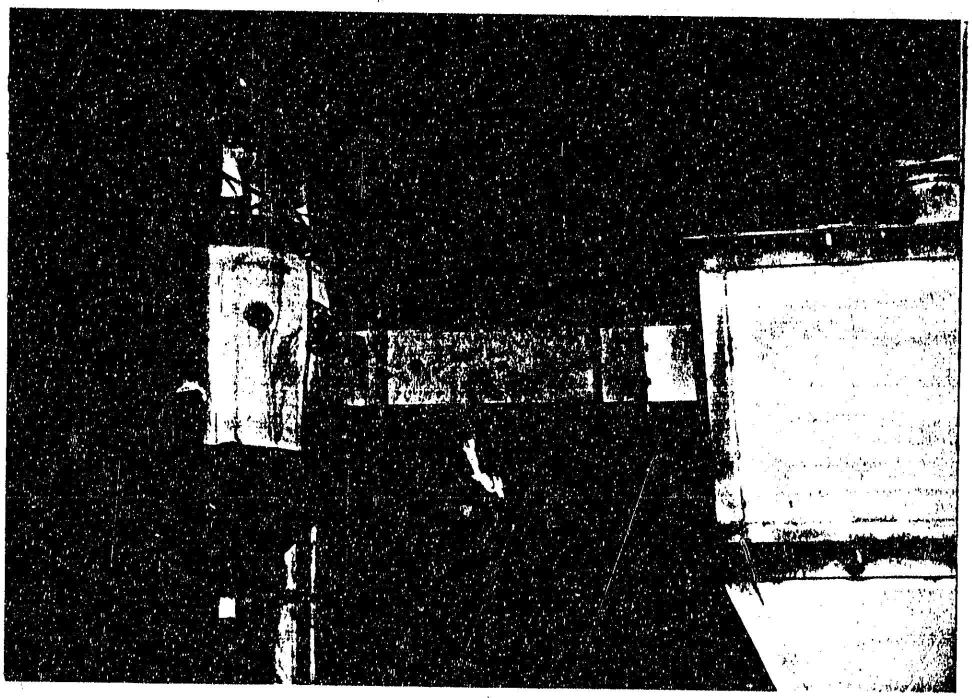


FIGURE 4-19: PHOTOGRAPH OF THE HOT CYCLONE AND THE TRANSITION DUCT THAT CONNECTS THE CYCLONE TO THE AFBC FURNACE

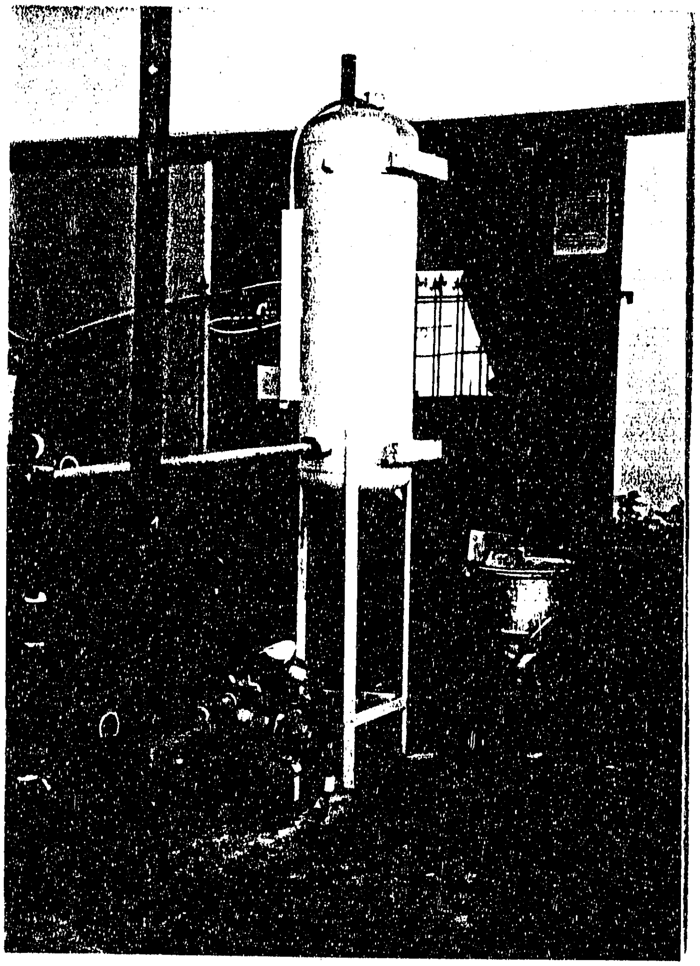


FIGURE 4-20: PHOTOGRAPH OF THE STEAM DRUM

TABLE 4-2: ULTIMATE AND PROXIMATE ANALYSES OF THE TEST COALS

	KENTUCKY NO. 9	PITTSBURGH NO. 8
PROXIMATE (Wt.%)		
Moisture	7.64	5.25
Ash	21.07	9.84
Volatile Matter	31.67	39.80
Fixed Carbon	39.62	45.11
Heating Value (Btu/lb)	10040	12388
ULTIMATE (Wt.%) (DRY BASIS)		
Ash	22.81	10.39
Carbon	60.84	71.61
Hydrogen	4.22	5.02
Nitrogen	1.39	1.33
Sulfur	3.40	4.21
Oxygen By Difference	7.34	7.44

TABLE 4-3: PARTICLE SIZE ANALYSES OF THE TEST COALS

KENTUCKY NO. 9:
KENTUCKY NO. 9 COAL WAS OBTAINED FROM ISLAND CREEK COAL COMPANY FROM ONE OF THEIR COAL PREPARATION PLANTS.

- RAW (UNCRUSHED) -1/2" x 0

PITTSBURGH NO. 8:
PITTSBURGH NO. 8 COAL WAS OBTAINED FROM TRW FROM THEIR EXCESS INVENTORY

(- NOMINALLY 1/4" x 0)

SCREEN MESH NO.	DIAMETER (MICRONS)	WT.% RETAINED KY. #9	WT.% RETAINED PITT. #8
6	3350	24.60	9.06
10	2000	15.66	20.40
14	1400	10.15	15.85
20	850	14.20	20.53
30	600	7.30	8.27
70	212	20.49	23.81
Pan	0	7.60	2.06

TABLE 4-4:

CHEMICAL COMPOSITION OF THE LIMESTONE

CONSTITUENT		WT.%
Calcium Carbonate	$CaCO_3$	98.0%
Magnesium Carbonate	$MgCO_3$	0.6%
Silicon Dioxide	SiO_2	0.2%
Aluminum Oxide	Al_2O_3	0.1%
Ferric Oxide	Fe_2O_3	0.25%

TABLE 4-5:

PARTICLE SIZE ANALYSIS OF THE LIMESTONE

SCREEN SIZE (MESH NO.)	AVERAGE DIAMETER (MICRONS)	% WEIGHT RETAINED ON THE SCREEN
6	3350	0
10	2675	27.31
14	1700	42.99
20	1125	28.90
30	725	0.52
PAN	300	0.27

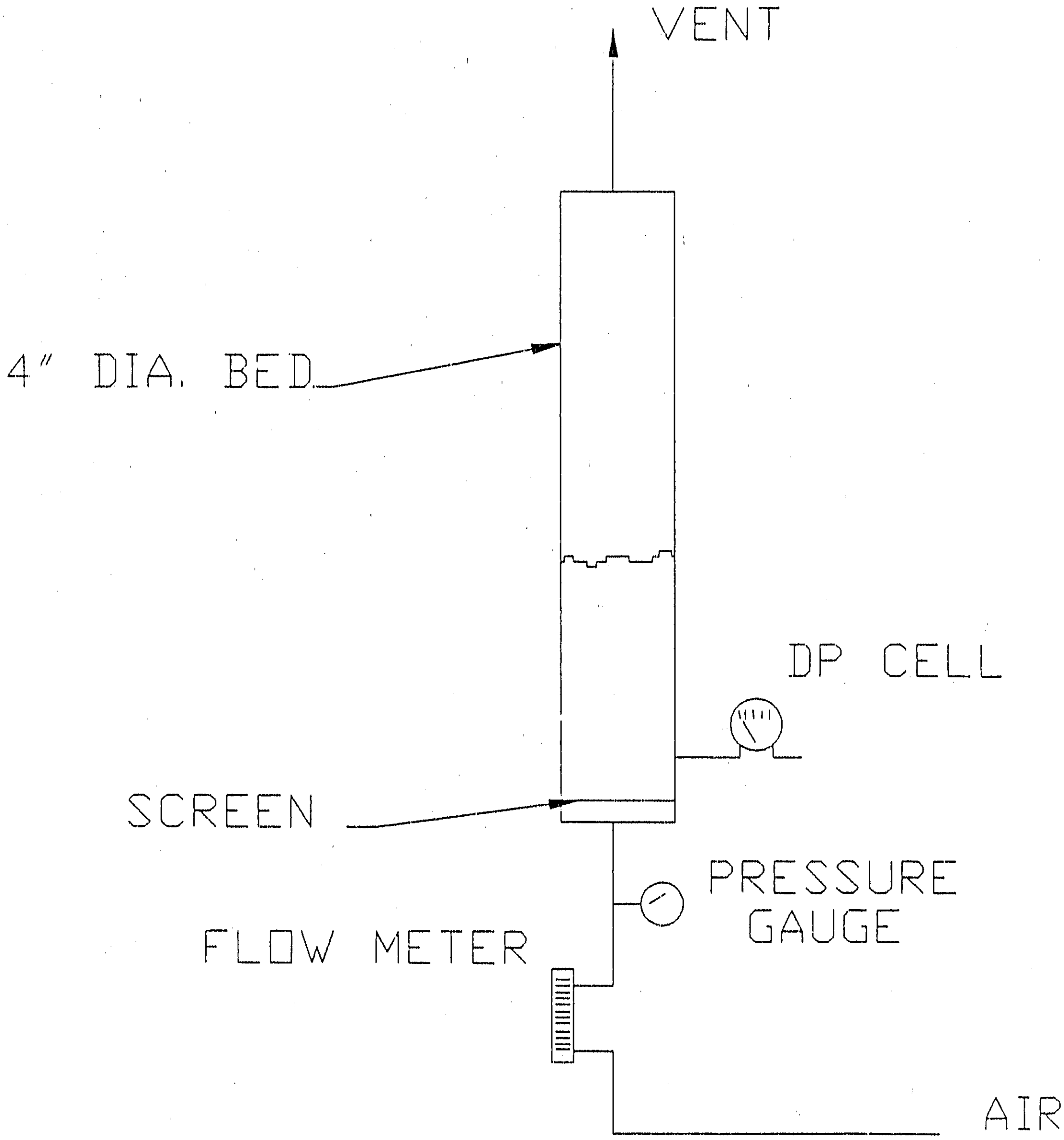


FIGURE 4-21: TEST SET-UP FOR PILOT FLUIDIZATION TEST

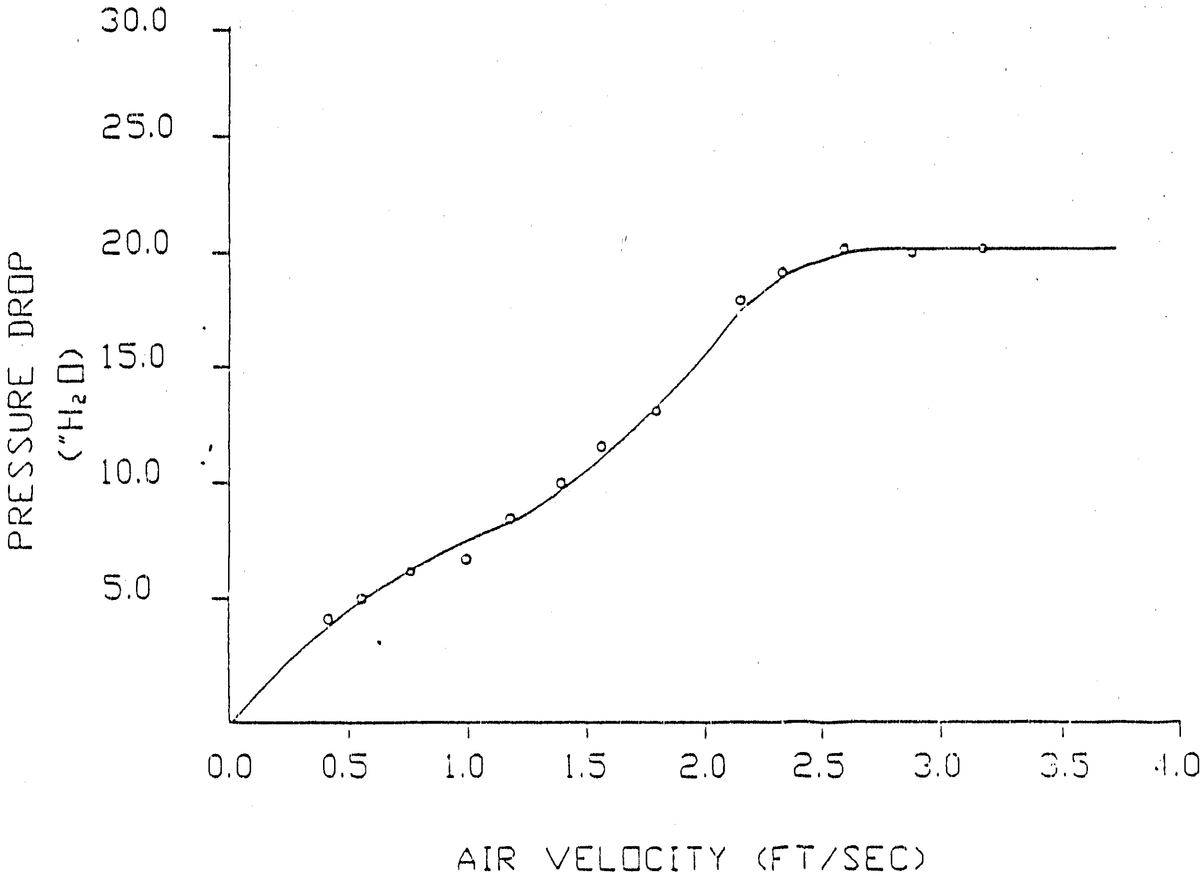


FIGURE 4-22: COLD AIR FLUIDIZATION TEST ON LIMESTONE (AVERAGE DIAMETER, 1.6 MM)

4.3.2 START-UP AND SHAKEDOWN

Main combustion air supplied by the Roots blower is preheated to about 1200°F and introduced into the air distribution pipe grids. Air is preheated by the gas-fired burner located in the main air line which is operated at a firing rate of 500,000 Btu/hr. Starting with a cold bed, the air flow rate is set near the maximum blower capacity of approximately 500 scfm. As the bed temperature increases to about 350 to 400°F, incipient fluidization occurs. As the bed heats further, the air flow rate is adjusted to maintain a superficial air velocity of 4.0 ft/sec through the bed. Pressure taps are located at 1 ft. intervals in the bed section, which allow interpolation of the bed level during the tests. The height of the initial slumped bed is 2 ft. above the air distribution pipe grids. During fluidization, the bed height expands to about 3 ft. which is sufficient to cover all of the steam-generating surfaces contained within the bed. An induced draft fan supplies approximately 1/2-inch H_2O of suction in the freeboard during start-up. The hot flue gases exiting the fluidized bed combustor furnace enter a stainless steel cyclone. The pressure drop through the cyclone is less than 1-inch H_2O. The flue gas exiting the cyclone is then cooled to approxiamtely 150°F as it passes thorugh the water spray quench system before it is vented to the atmosphere.

As the bed temperature approaches 800°F, coal is injected into the fluidized bed combustor using the speed-controlled, overbed screw feeder. The coal feed rate is controlled at approximately 150 lb/hr in order to attain the design firing rate. As the bed temperature reaches the 1550 to 1600°F range, the water flow through the steam generating coils is adjusted to maintain the desired bed temperature.

As many as twelve shakedown tests (Test Nos. A1 to A2) in the AFBC mode were required to rectify mechanical and operational problems and prepare the system to run at steady state conditions. The system run time in the shakedown mode corresponded to about 80 hours. During this stage, different subsystems of the AFBC unit were checked out, problem areas were identified, and quantitative data were generated before and after system modification to facilitate comparison between the two. The major problem areas, along with the modifications carried out therein are detailed below.

- A greater than expected amount of fines carryover in the flue gas was observed during initial shakedown testing. While a large portion of fines was recovered in the cyclone, a significant quantity was seen to escape through the quench system. Since the initial limestone bed material contained only about 1 percent fines, it was believed that high air velocities through the air distributor orifices caused significant attrition and resulted in excessive elutriation. Since high attrition and in turn elutriation rates were anticipated for calcined but not appreciably sulfated limestone, the number of air distributor orifices were increased from a total of 608 to 1216 to prevent jetting and its concomitant effect on elutriation rate. Also, to improve scrubbing efficiency and to reduce fines emissions to the atmosphere, a venturi scrubber was installed downstream of the cyclone. <u>Figure 4-23</u> shows the modified scrubber system. It incorporates water spray nozzles at two elevations. One is placed in the flue gas duct downstream of the cyclone to cool down the flue gas before it enters the venturi section and thereby reduce the pressure drop through the scrubber. The other high pressure water spray nozzle is placed at the throat of the venturi. Water is pumped around the drum-nozzle's loop at a head of about 40 psi and a flow rate of 25 gpm. A demister pad is provided in the flue gas path near the drum outlet to minimize water droplet carryover. The ID fan is mounted on the roof of the building, about 15 feet above the drum outlet. A water level valve regulates the water flow into the drum and maintains a constant water level. A drain line is used to control solids build-up in the recirculating water.

- The pressure taps in the bed were giving inconsistent readings and plugging frequently. the pressure taps were pushed about 1 inch into the bed instead of being flush with the inside furnace wall. Also a critical flow orifice was placed in the line with purge air connection as shown in <u>Figure 4-24</u> to prevent plugging.

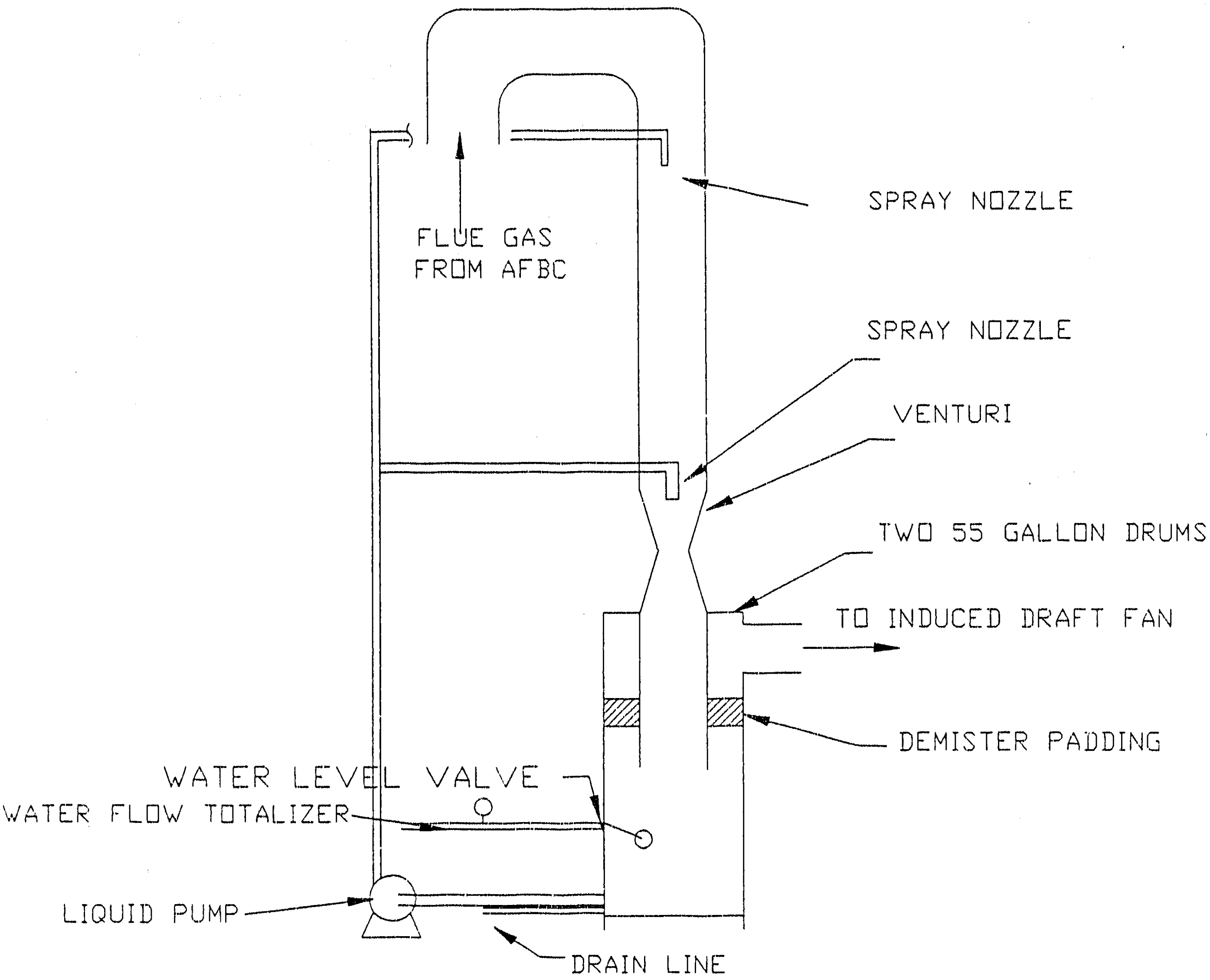


FIGURE 4-23: DIAGRAM OF THE MODIFIED SCRUBBER SYSTEM

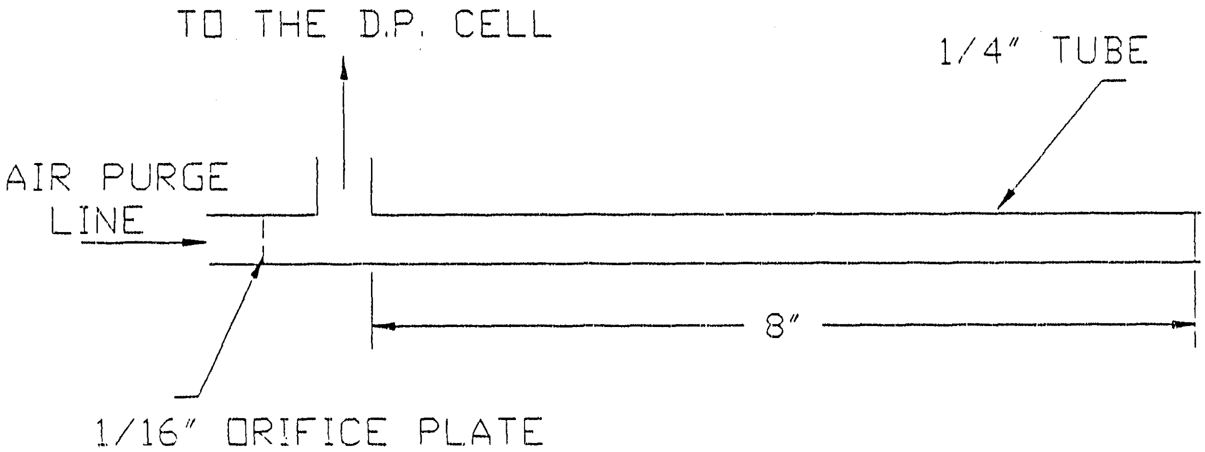


FIGURE 4-24: CONFIGURATION OF THE PRESSURE TAP

- Data from AFBC shakedown Test No. A8 indicated unsteady-state operation by way of changing bed height with time. This resulted from excessive entrainment loss of bed material. For example, the data indicated a net bed weight loss rate of about 98 lb/hr from the AFBC unit for an expanded bed height between 32 and 35 inches and gas velocity of about 5.5 ft/s. This corresponds to a decrease in bed depth of between 6 and 7 inches in the first hour of operation. Note that for steady-state operation, the bed height should not vary and the net bed weight loss rate should be zero. However, for operation in the PAFBC mode and 25 inch bed height (PAFBC shakedown test No. P3 - to be described later in Section 4.5), the net loss rate turned out to be negligible. The pulsations generated due to pulse combustion apparently reduced bed entrainment significantly. In order to verify whether this outcome was due to pulsations or low bed height operation, a test (Test No. A10) was run in the AFBC mode with a 25-inch expanded bed height. The test conditions are specified in Table 4-6. A rather modest rate of loss of bed (10 to 15 lb/hr) was observed.

TABLE 4-6: SUMMARY OF THE AFBC TESTS A10 AND A11

	TEST A10	TEST A11
Test Date	2/9/89	2/16/89
Coal Type	Pittsburgh #8 (Unclassified)	Pittsburgh #8 (Unclassified)
Coal Feed Rate (lb/hr)	100	120
Superficial Gas Velocity (ft/s)	5.5	3 to 6
Limestone Feed Rate (lb/hr)	56	45
Ca:S	4.5	3.0
Bed Temperature (°F)	1550	1550
Bed Height (inches)	25	32
Steam Rate (lb/hr)	600	675

To maximize steam capacity, it was necessary to keep all the four steam coils fully active. This required the AFBC unit to be run at a bed height of 32 inches or more. The next objective, therefore, was to determine the lowest gas velocity at which the AFBC unit could be run under steady-state conditions. Note that the net weight loss rate of bed should be close to zero for steady-state operation. A test was performed on the AFBC unit (AFBC Test A11, Table 4-6) such that the gas velocity ranged between 3 and 6 ft/s. The expanded bed height was maintained at approximately 32 inches and the bed temperature was controlled at about 1500°F. The net weight loss rate of bed determined from this test is plotted versus gas velocity in **Figure 4-25**. It shows an unacceptably high rate of weight loss for the design condition of 4 to 6 ft/s gas velocity. The high bed loss rate was attributed to bubble dynamics, short freeboard, and high velocity entrance effects at the AFBC furnace exit/cyclone inlet section. It was concluded that steady-state operation at design conditions in the AFBC mode was not feasible without either solids recycle or in-furnace solids disengagement.

A companion test in the PAFBC mode (Test No. P7 - to be described later in section 4-5) indicated a net bed weight loss rate of about 60 lb/hr for operation at 6 ft/s gas velocity and an expanded bed height of about 32 inches. This was substantially lower than that obtained in the AFBC mode but still unacceptable from the standpoint of achieving steady-state operation. The data from both the AFBC and PAFBC tests and the requirement for stable bed height resulted in the decision to incorporate an in-furnace solids separator. A schematic of the solids separator that was designed to minimize bed loss is shown in **Figure 4-26**. The initial plan was to run water through the tubes such that the in-furnace separator also functioned as an economizer. Because of space constraints near the furnace exit, it was decided to delete the economizer feature. The separator was fabricated and installed at the furnace exit (5" x 9" opening) that leads into the cyclone.

A test (No. A12) was performed in the AFBC mode to determine the effectiveness of the solids separator. The unit was run at a superficial velocity of 6 ft/s and with Pittsburgh No. 8 coal. The net weight loss rate of bed dropped to less than 10 lb/hr. This is a great improvement in contrast

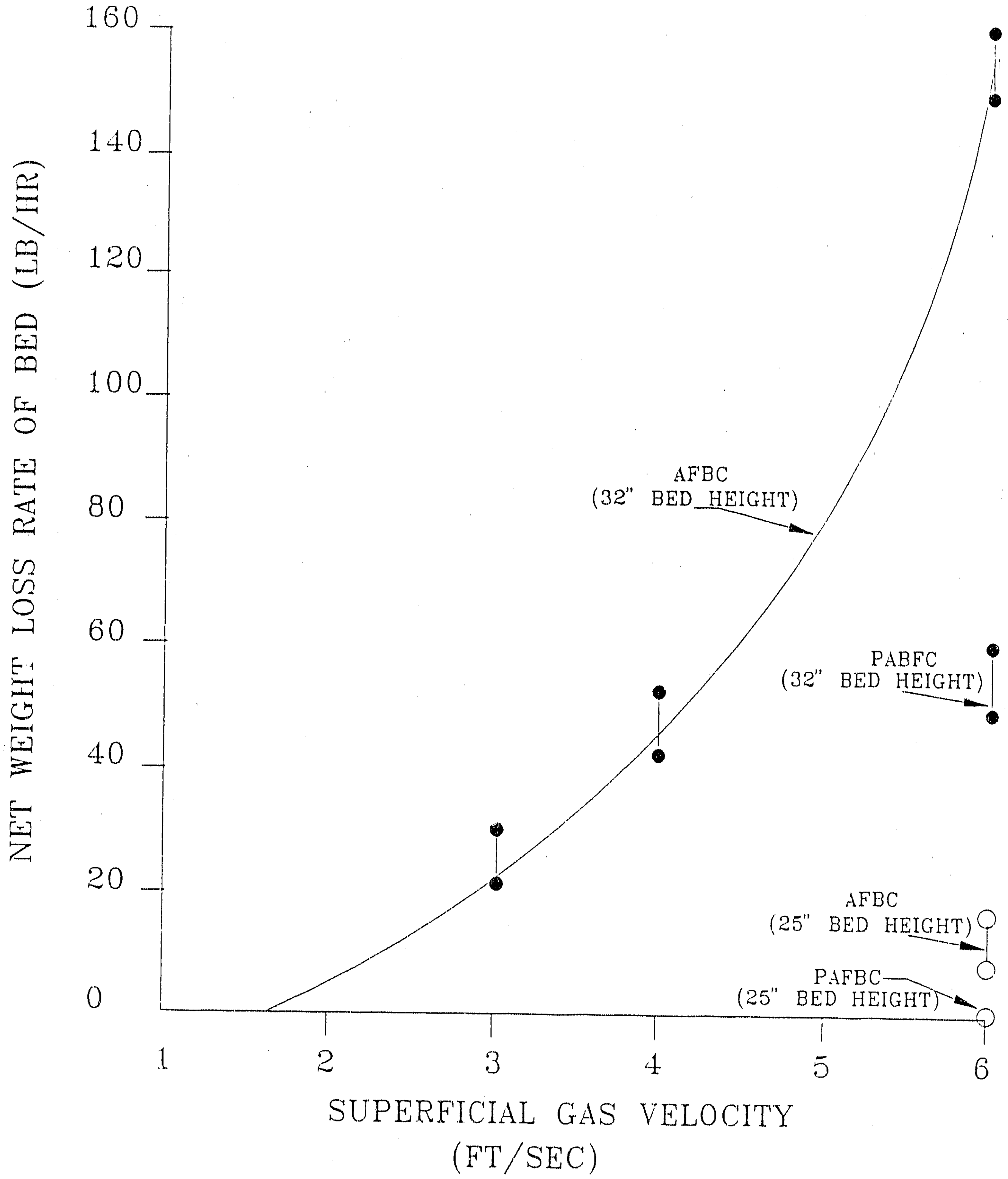


FIGURE 4-25: NET WEIGHT LOSS RATE OF MATERIAL FROM THE BED AT DIFFERENT OPERATING CONDITIONS

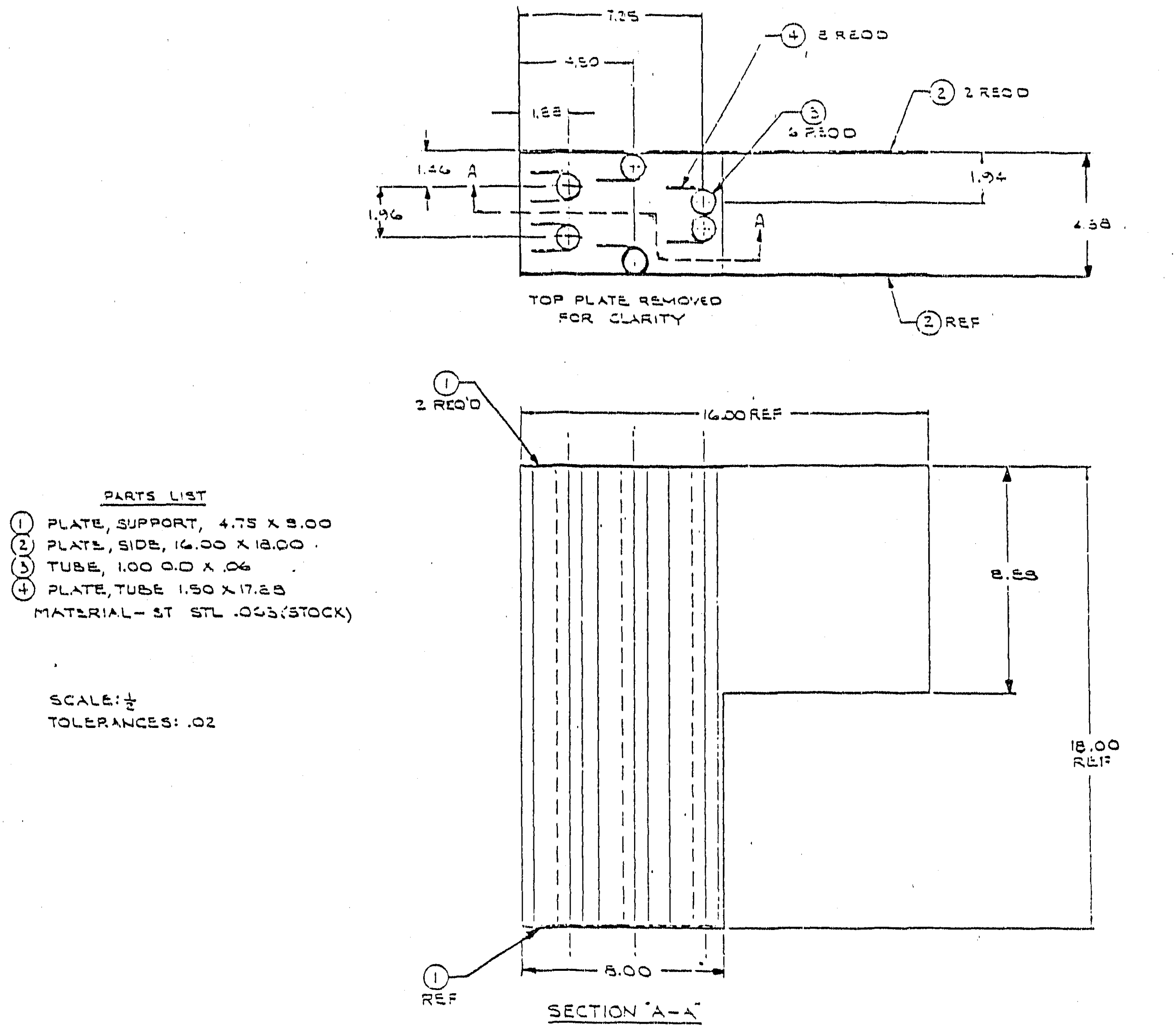


FIGURE 4-26: SCHEMATIC OF THE SOLIDS SEPARATOR FOR THE AFBC UNIT

with the loss rate of 150 to 160 lb/hr experienced in the absence of the separator. Calculations indicate a solids separation efficiency greater than 70 percent. This value is satisfactory considering the space and installation constraints imposed by the system. A later test in the PAFBC mode (Test No. P9) is with the pulse combustor operational, indicated zero net bed weight loss rate.

4.3.3 BASELINE TESTS

Four steady-state tests in the AFBC mode (Test Nos. A13 through A16) were performed to generate baseline data for later comparison with PAFBC test data as well as with published test results from AFBC units at different sites. The test conditions and the performance data are presented in Tables 4-7 through 4-10. The results obtained here were comparable to those observed typically in bubbling bed combustion. Sample profiles of bed temperature and flue gas composition (O_2, SO_2, NO_x and CO) for the steady state period are shown in Figures 4-27 through 4-31. The results will be discussed in detail in Section 4.7.

4.4 MODIFICATION TO A PAFBC SYSTEM

4.4.1 PULSE COMBUSTOR DESIGN AND FABRICATION

The pulse combustor design was based on an estimated load carrying capacity of about one-fourth to one-third that of the total PAFBC System. This corresponded to a firing rate of between 350 and 500 KBtu/hr. The design frequency selected was about 50 Hz. The combustor was intended to run in the non-slagging mode. Three different options were considered for the tailpipe configuration:

- Air shrouded single tailpipe with boost air in the shroud.
- Multiple tailpipes instead of a single tailpipe.
- Water jacketed, single tailpipe with external boost air supply for fluidization.

TABLE 4-7: AFBC BASELINE TEST

TEST #: A13 TEST DATE: 4-6-89 TEST TIME: 18:00-21:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1550.0 DEG F	843.3 DEG C		
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M		
SUPERFICIAL VELOCITY:	5.0 FT/S	1.5 M/S		
CALCIUM-TO-SULFUR RATIO:	2.6			
RECYCLE:	NO			
FUEL FEED RATE TO BED:	120.0 LB/HR		LIMESTONE FEED RATE:	40 LB/HR
FUEL FEED RATE TO PULSE COMBUSTOR:	NONE			

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	21.27	---	27.31	0
14	1400	14.07	---	42.99	2.03
20	850	18.75	---	28.90	8.21
30	600	10.16	---	0.52	5.23
50	300	10.10	---	0.10	10.20
70	212	11.70	---	0.10	24.30
PAN	0	13.95	---	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
PITT. #8	67.85	4.76	3.99	1.26	7.05	9.84	5.25	12388.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	850.0 PPM=	1.7 LB/MMBTU		
NOx FURNACE EXIT:	490.0 PPM=	0.7 LB/MMBTU		
CO FURNACE EXIT:	1600.0 PPM=	1.4 LB/MMBTU		
O2 FURNACE EXIT:	4.5%	CO2 FURNACE EXIT: 15.5%		
CARBON EFFICIENCY:	92.1 %			
COMBUSTION EFFICIENCY:	92.8 %		EXCESS AIR:	20.9 %
STEAM RATE:	500.0 LB/HR			

CARBON MATERIAL BALANCE

TOTAL CARBON IN: 98.8 LB/HR
TOTAL CARBON OUT: 98.1 LB/HR

TABLE 4-8: AFBC BASELINE TEST

TEST #: A14 TEST DATE: 4-7-89 TEST TIME: 17:20-20:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1550.0 DEG F	843.3 DEG C
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M
SUPERFICIAL VELOCITY:	7.0 FT/S	2.1 M/S
CALCIUM-TO-SULFUR RATIO:	2.7	
RECYCLE:	NO	

FUEL FEED RATE TO BED: 160.0 LB/HR LIMESTONE FEED RATE: 54 LB/HR
FUEL FEED RATE TO PULSE COMBUSTOR: NONE

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	25.58	---	27.31	0
14	1400	18.87	---	42.99	2.03
20	850	27.84	---	28.90	8.21
30	600	11.96	---	0.52	5.23
50	300	12.00	---	0.10	10.20
70	212	0.76	---	0.10	24.30
PAN	0	2.98	---	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
PITT. #8	67.85	4.76	3.99	1.26	7.05	9.84	5.25	12300.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	450.0 PPM=	0.9 LB/MMBTU
NOx FURNACE EXIT:	590.0 PPM=	0.8 LB/MMBTU
CO FURNACE EXIT:	1100.0 PPM=	1.0 LB/MMBTU

O2 FURNACE EXIT: 3.8% CO2 FURNACE EXIT: 16.5%
CARBON EFFICIENCY: 90.4 %
COMBUSTION EFFICIENCY: 92.4 % EXCESS AIR: 20.9 %
STEAM RATE: 700.0 LB/HR

CARBON MATERIAL BALANCE

TOTAL CARBON IN: 132.0 LB/HR
TOTAL CARBON OUT: 131.5 LB/HR

TABLE 4-9: AFBC BASELINE TEST

TEST #: A15   TEST DATE: 5-12-89   TEST TIME: 19:00-20:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1585.0 DEG F	862.8 DEG C
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M
SUPERFICIAL VELOCITY:	5.0 FT/S	1.5 M/S
CALCIUM-TO-SULFUR RATIO:	2.6	
RECYCLE:	NO	

FUEL FEED RATE TO BED: 120.0 LB/HR   LIMESTONE FEED RATE: 40 LB/HR
FUEL FEED RATE TO PULSE COMBUSTOR: NONE

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	26.45	---	27.31	0
14	1400	15.78	---	42.99	2.03
20	850	21.46	---	28.90	8.21
30	600	9.51	---	0.52	5.23
50	300	14.62	---	0.10	10.20
70	212	5.42	---	0.10	24.30
PAN	0	6.76	---	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
W. KENTY #11	67.12	4.70	3.22	1.46	9.12	11.36	3.02	12134.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	---	PPM=	---	LB/MMBTU
NOx FURNACE EXIT:	140.0	PPM=	0.2	LB/MMBTU
CO FURNACE EXIT:	400.0	PPM=	0.4	LB/MMBTU
N2O FURNACE EXIT:	75.0	PPM=	0.1	LB/MMBTU

O2 FURNACE EXIT: 4.7%   CO2 FURNACE EXIT: 14.4%

EXCESS AIR: 28.8 %

STEAM RATE: 500.0 LB/HR

TABLE 4-10: AFBC BASELINE TEST

TEST #: A16 TEST DATE: 5-12-89 TEST TIME: 20:00-21:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1600.0 DEG F	871.1 DEG C
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M
SUPERFICIAL VELOCITY:	5.0 FT/S	1.5 M/S
CALCIUM-TO-SULFUR RATIO:	2.6	
RECYCLE:	NO	

FUEL FEED RATE TO BED: 100.0 LB/HR LIMESTONE FEED RATE: 35 LB/HR
FUEL FEED RATE TO PULSE COMBUSTOR: NONE

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	33.03	---	27.31	0
14	1400	40.39	---	42.99	2.03
20	850	23.01	---	28.90	8.21
30	600	0.99	---	0.52	5.23
50	300	0.29	---	0.10	10.20
70	212	0.11	---	0.10	24.30
PAN	0	2.19	---	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
W. KENTY #11	67.12	4.70	3.22	1.46	9.12	11.36	3.02	12134.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	---	PPM=	---	LB/MMBTU
NOx FURNACE EXIT:	143.0	PPM=	0.2	LB/MMBTU
CO FURNACE EXIT:	90.0	PPM=	0.1	LB/MMBTU
N2O FURNACE EXIT:	57.0	PPM=	0.1	LB/MMBTU

O2 FURNACE EXIT: 6.8% CO2 FURNACE EXIT: 12.5%

EXCESS AIR: 49.7 %

STEAM RATE: 500.0 LB/HR

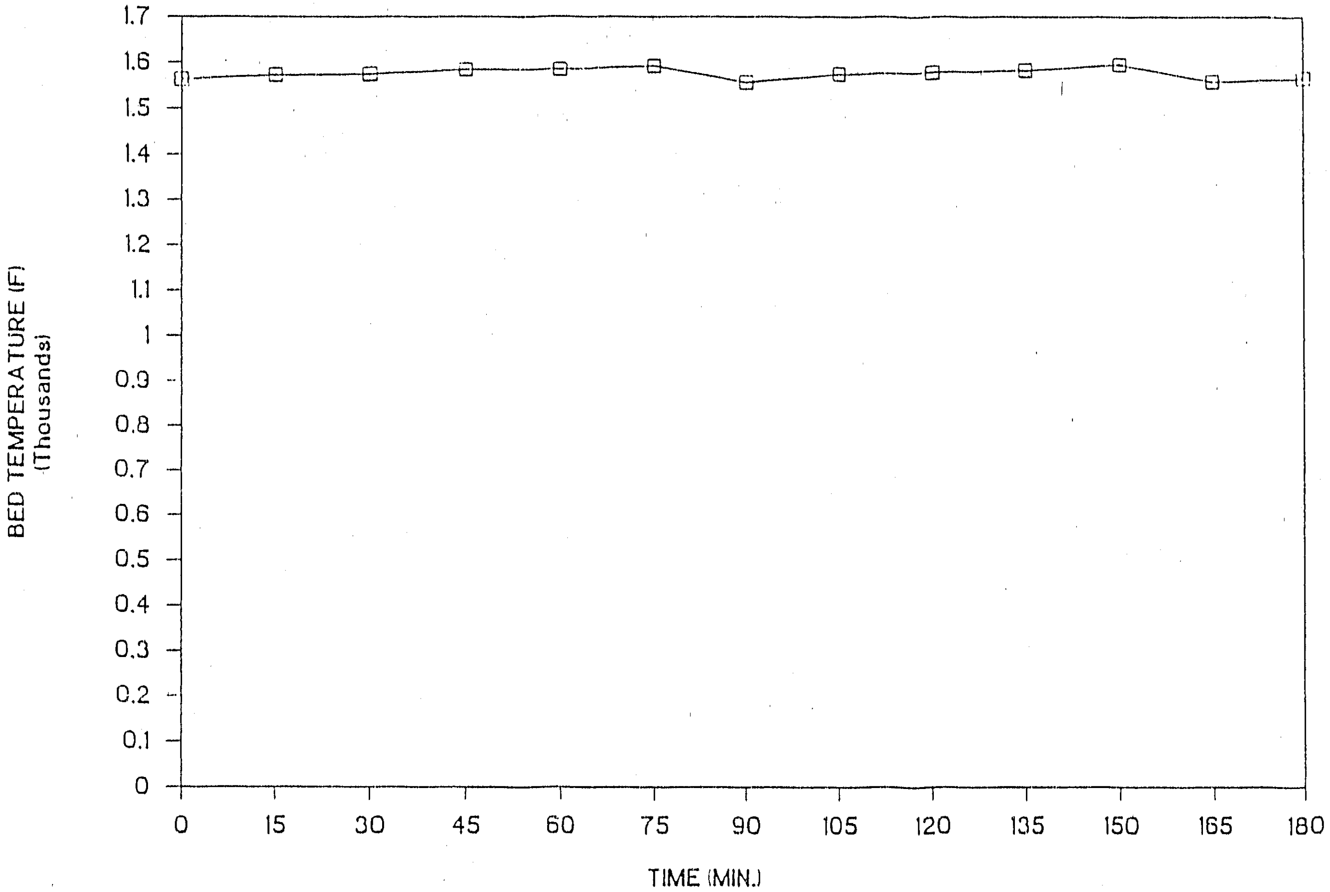


FIGURE 4-27: BED TEMPERATURE PROFILE FOR AFBC BASELINE TEST NO. A13

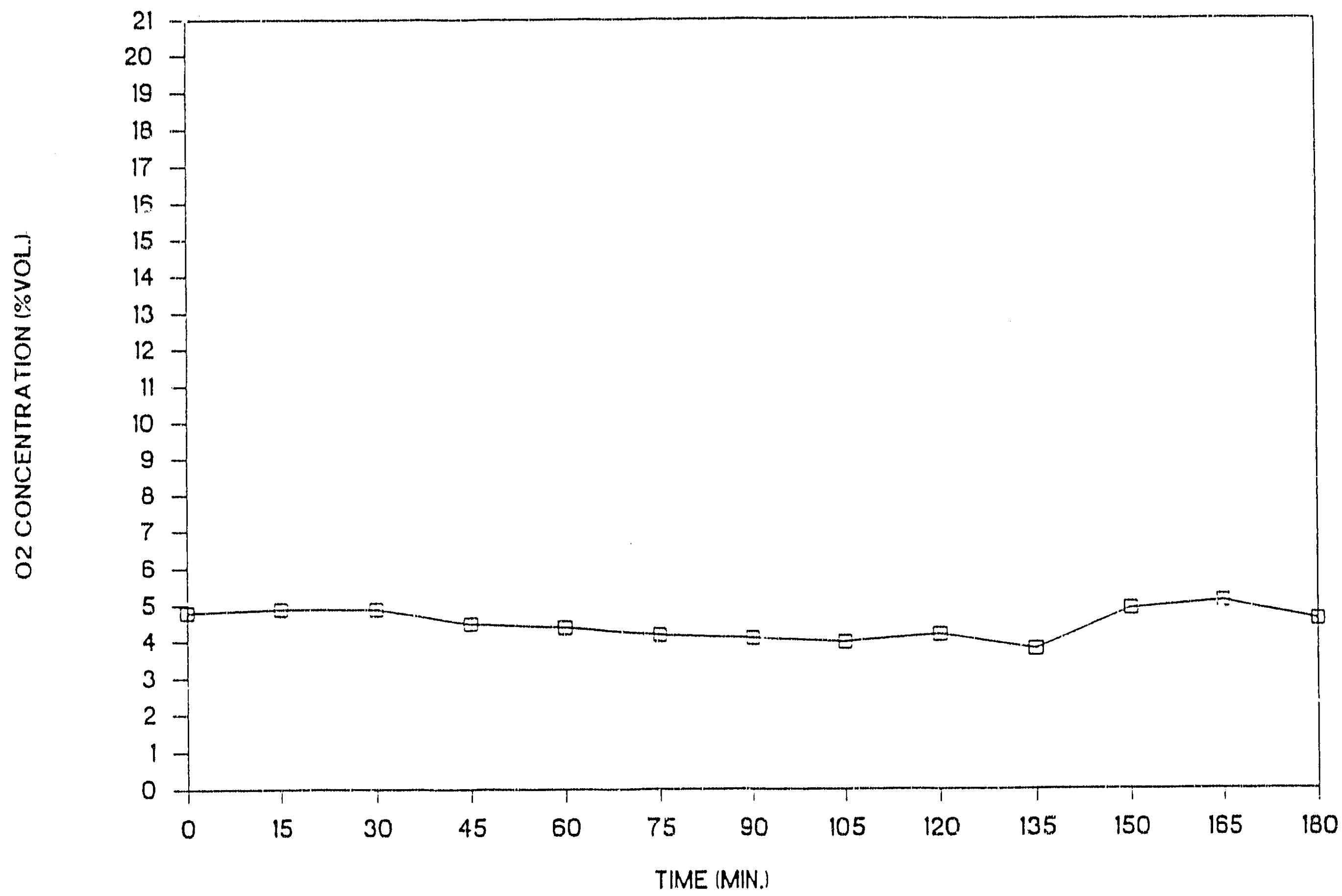


FIGURE 4-28: OXYGEN CONCENTRATION IN FLUE GAS FOR AFBC BASELINE TEST NO. A13

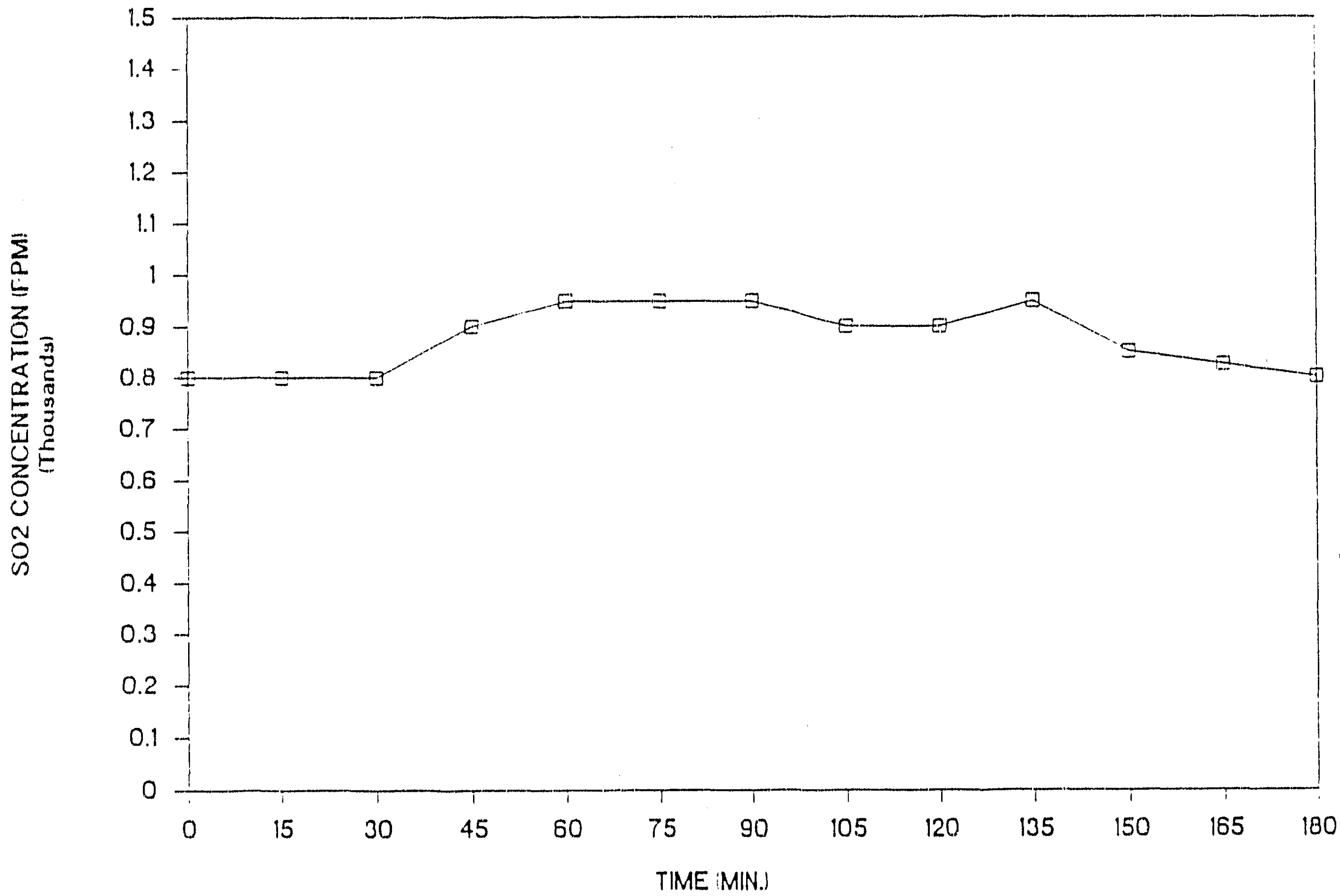


FIGURE 4-29: SO_2 CONCENTRATION IN FLUE GAS FOR AFBC BASELINE TEST NO. A13

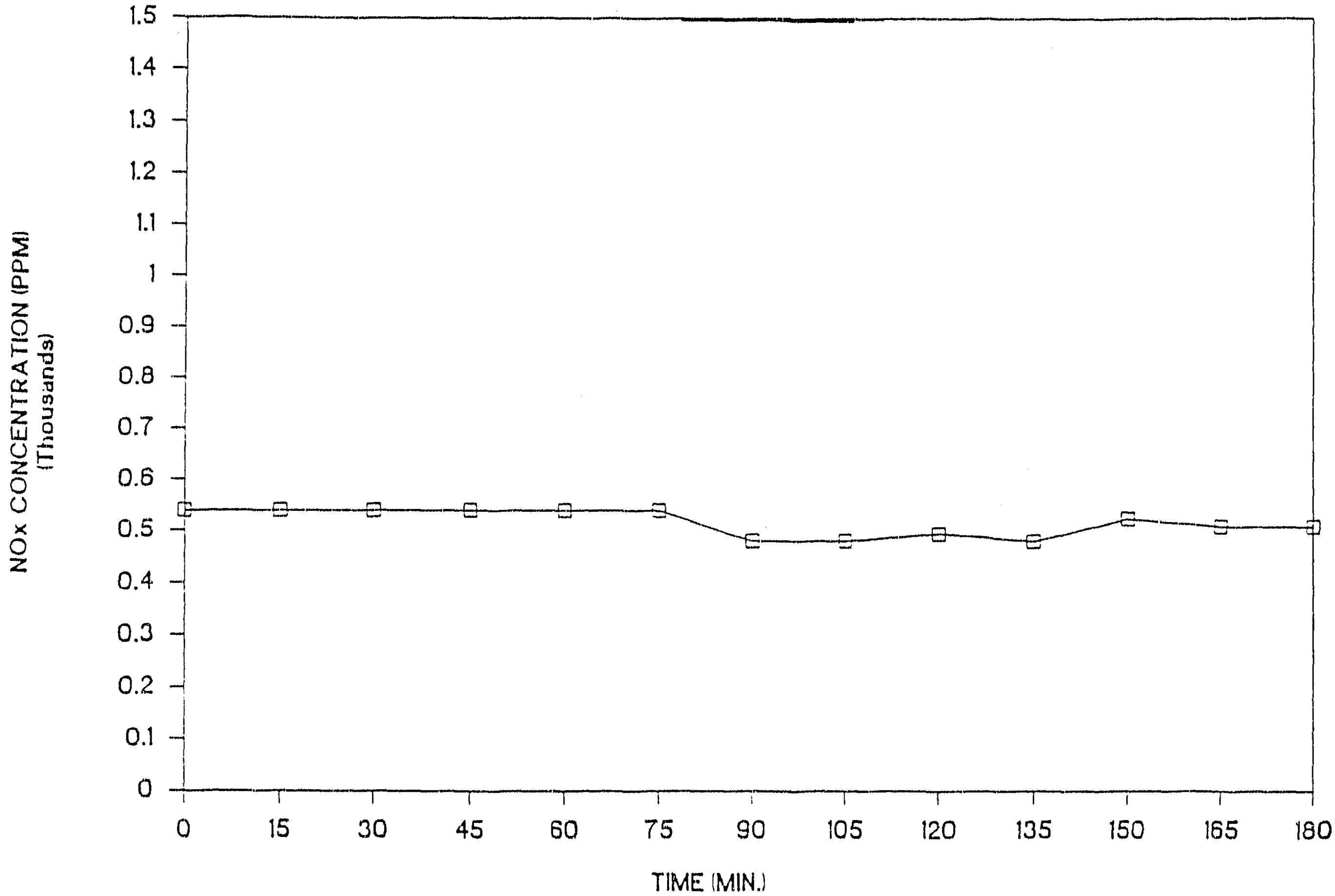


FIGURE 4-30: NO_x CONCENTRATION IN FLUE GAS FOR AFBC BASELINE TEST NO. A13

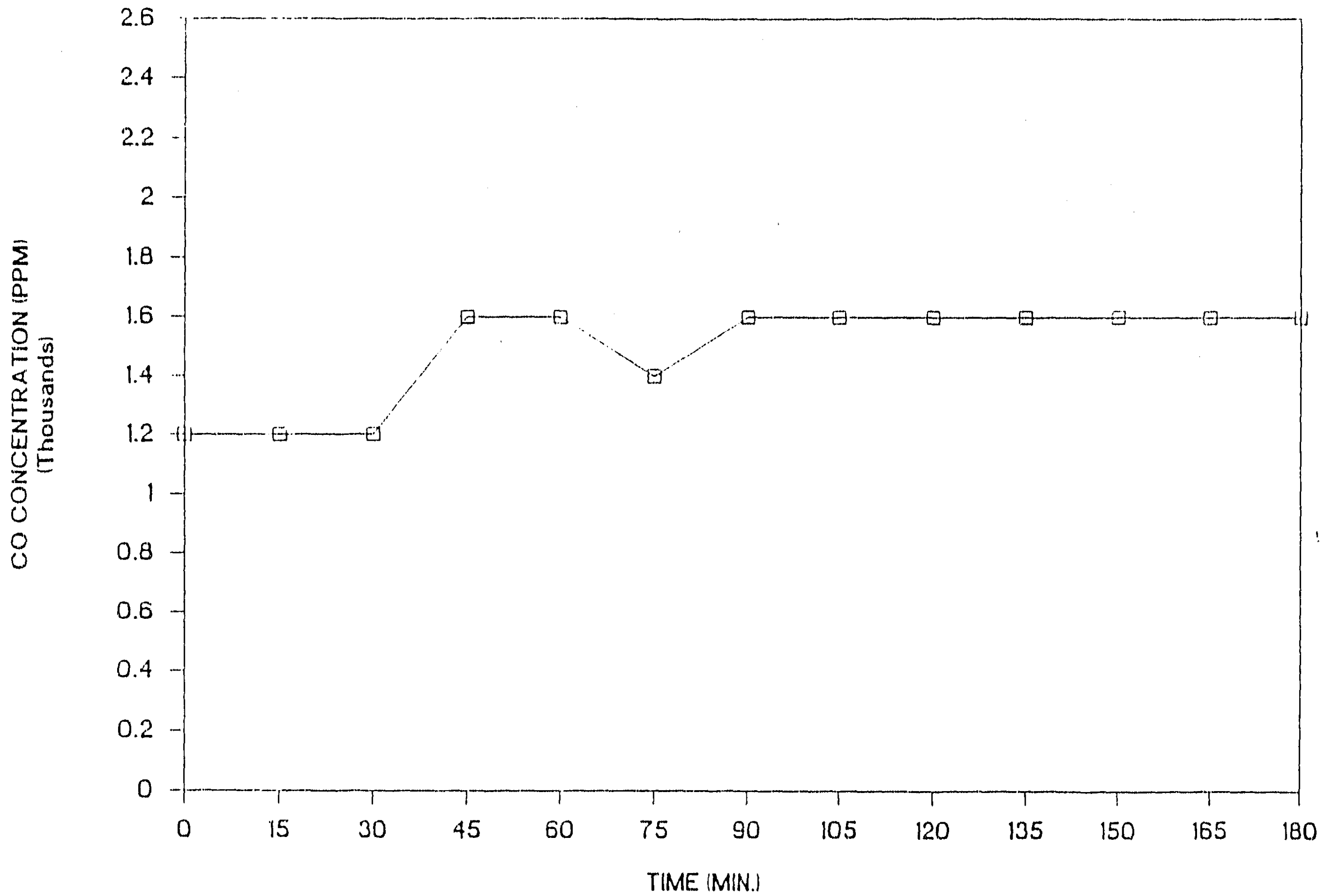


FIGURE 4-31: CO CONCENTRATION IN FLUE GAS FOR AFBC BASELINE TEST NO. A13

Since the freeboard of the AFBC system was refractory-lined and not cooled and additional steam generation was considered important from a boiler design standpoint, the third option of water jacketed tailpipe configuration was selected. This was envisioned to prevent the freeboard from getting very hot (>1600°F) and utilize the high heat transfer coefficient environment prevalent in the tailpipe due to pulsating flow.

Figure 4-32 shows the initial design for the pulse combustor. The combustor comprises an air plenum, thrust augmentor, aerovalve, combustion chamber and a water-cooled tailpipe. The combustion chamber is refractory-lined to control the heat losses and promote rapid combustion. The refractory thickness is optimized to avoid slagging conditions. A thrust augmentor is employed to pump combustion air into the pipe grids to help bed fluidization.

The pulse combustor design was later modified as shown in Figure 4-33. The serpentine water cooling coil design for the tailpipe was changed to a water jacket cooling system to (i) eliminate the possibility of hot spots developing on the tailpipe, (ii) reduce the pressure head required for pumping water, and (iii) increase the heat transferred to the water. The expansion section at the end of the tailpipe is to reduce the flue gas exit velocity and prevent channeling. After the flue gas from the pulse combustor exits the tailpipe, it enters a diffuser section which provides fines re-circulation and increased particle residence time in the bed.

A series of tests were performed at MTCI to verify the operability of pulse combustor with a tailpipe effluent under an imposed static pressure. Figure 4-34 shows the set-up used for these tests. A 100,000 Btu/hr pulse combustor made of S.S. body with a 3/4-inch tailpipe was immersed into a water tank at various depths. The pulse combustor was able to operate with significant static pressures representing a boost ratio of approximately 2 percent. Additional draft requirements necessary for a deep fluid bed will be provided by a forced draft blower. The pulse combustor was fabricated in-house at the MTCI West Coast Laboratory. A photograph of the pulse combustor is shown in Figure 4-35.

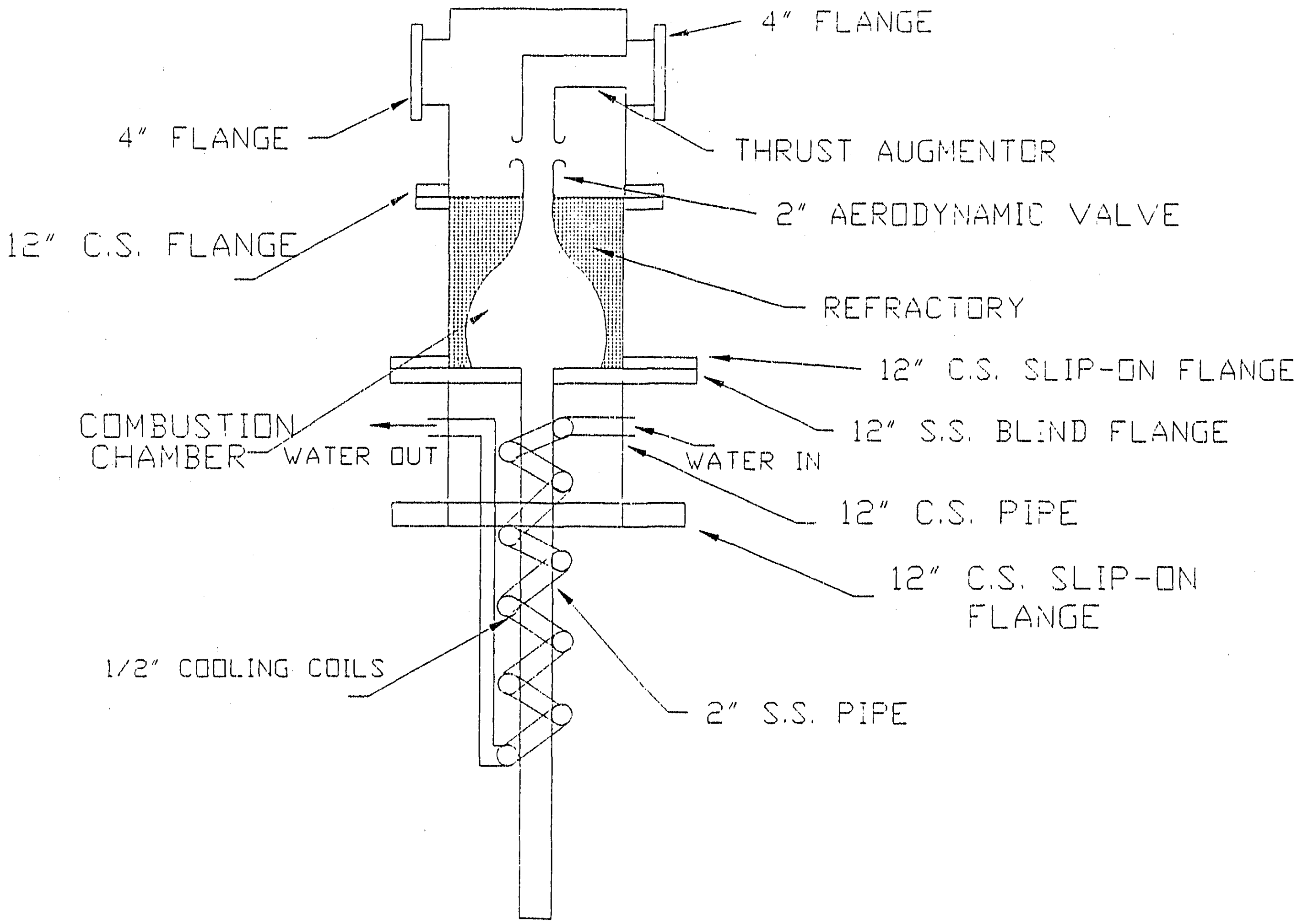


FIGURE 4-32: FIRST-GENERATION PULSE COMBUSTOR DESIGN FOR THE PAFBC SYSTEM

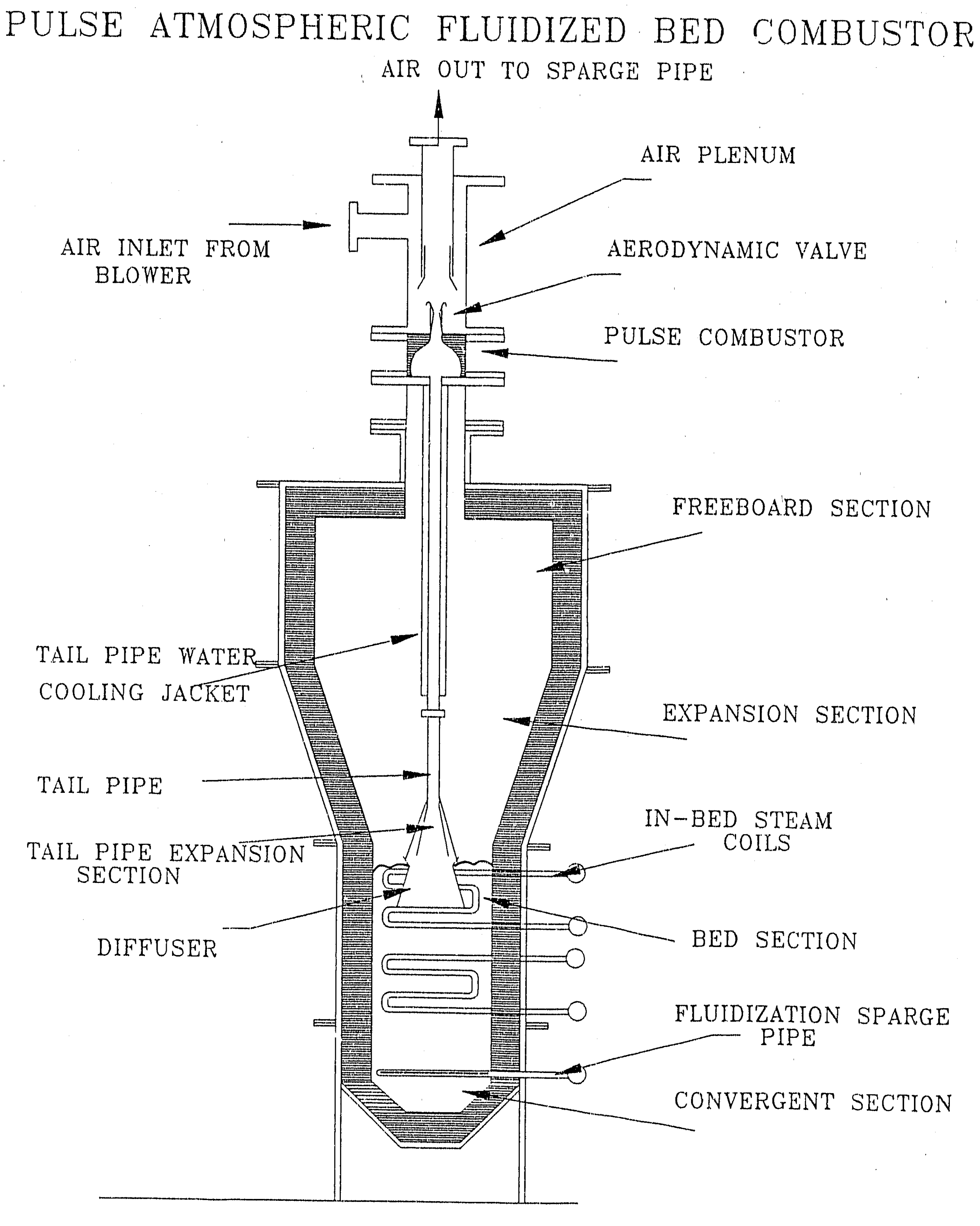


FIGURE 4-33: PULSE COMBUSTOR CONFIGURATION

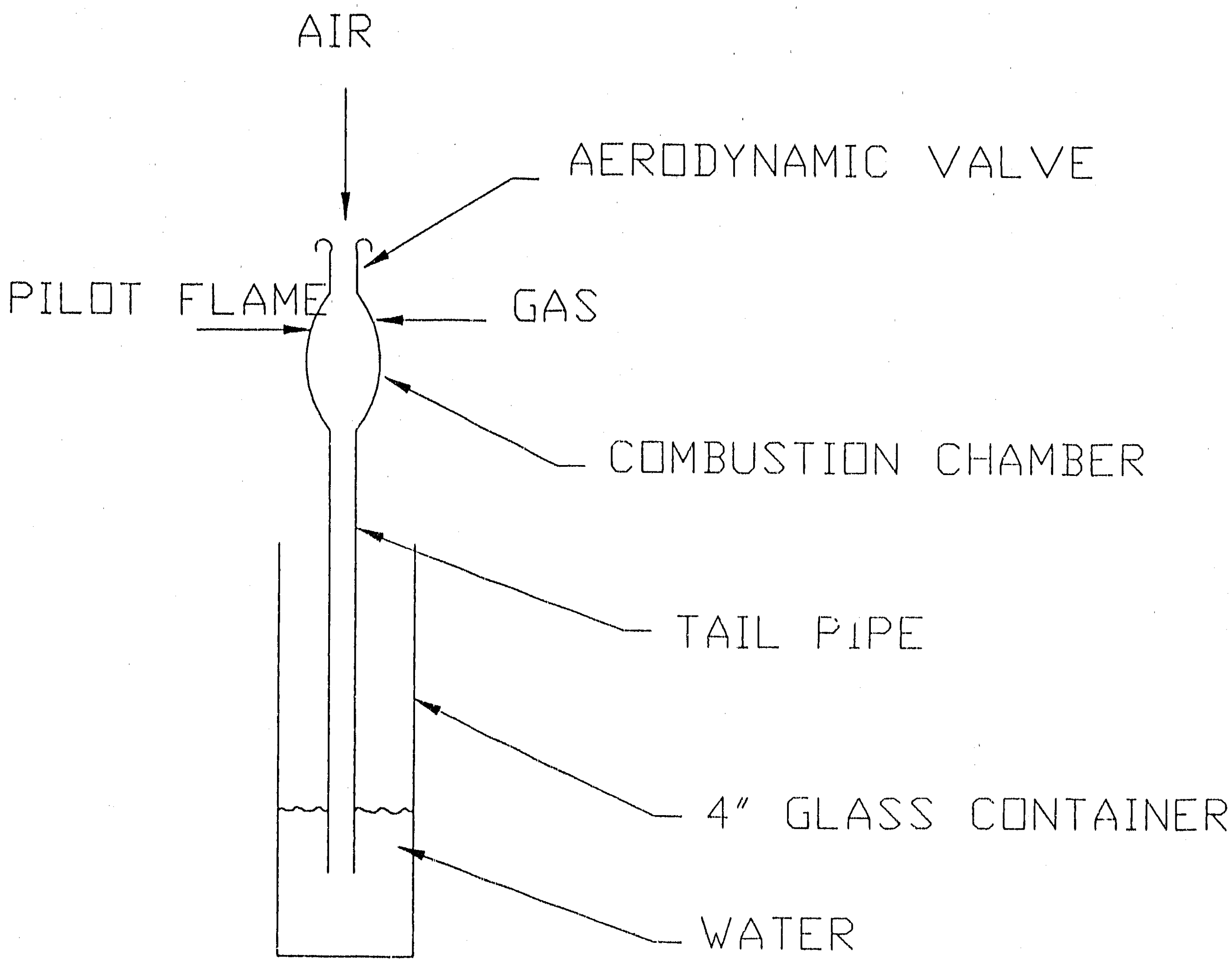


FIGURE 4-34: TEST SETUP USED TO VERIFY THE OPERABILITY OF PULSE COMBUSTOR WITH TAILPIPE UNDER AN IMPOSED STATIC PRESSURE

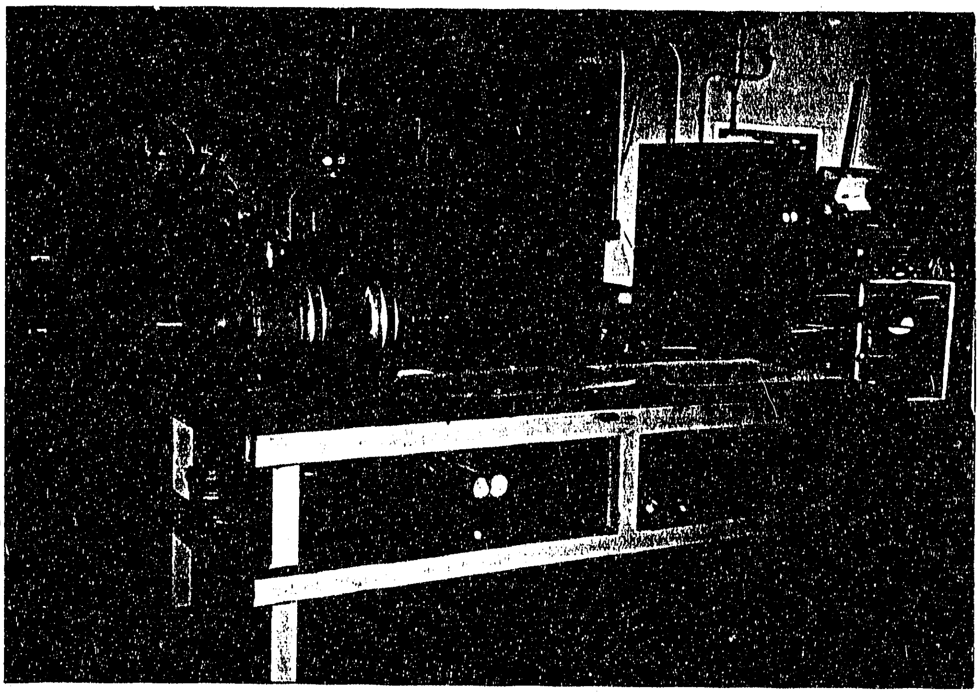


FIGURE 4-35: PHOTOGRAPH OF THE PULSE COMBUSTOR FOR INSTALLATION IN THE PAFBC SYSTEM

4.4.2 Pulse Combustor Integration with AFBC System

A schematic of the PAFBC system layout is shown in Figure 4-36 and a photograph of the system in Figure 4-37. In the PAFBC mode:

- Coarse coal is fed overbed by screw feeders and coal fines (less than 30 sieve or 600 microns) are pneumatically transported into the pulse combustor.

- All the air is routed to the pulse combustor air plenum.

- Based on the aerodynamic valve used, some of the air passed through the pulse combustor and the rest experienced a boost in pressure in the thrust augmentor and flows through the sparge pipes of the fluidized bed. The air plenum of the pulse combustor acts as a windbox at static pressure. The air flow splits between the pulse combustor (aerovalve, combustion chamber, and tailpipe) and the fluidized bed (thrust augmentor, sparge pipes and the dense bed) such that the pressure drops through the two flow paths are equal.

To meet the requirements for classified coal, a classifier was designed and built at MTCI. Figure 4-38 shows the scheme used to separate the fines and coarse particles from the coal feed. This unit was operated in a batch mode for the purposes of this task but the design and construction of a classifier for on-line operation is considered feasible and not difficult.

4.5 PAFBC SYSTEM CHARACTERIZATION TESTS

Nine tests were conducted in the PAFBC mode (Test Nos. P1 to P9) to characterize and debug the PAFBC system. The pulse combustor was initially test-fired on gas after installation in the AFBC unit. The operational characteristics of the pulse combustor are presented in **Table 4-11**. The wave form was near sinusoidal and the pulse combustor operation was robust. It was the first attempt in MTCI's history to run a pulse combustor under an imposed static head and the outcome exceeded all expectations.

V-1	V-2	V-3	V-4	V-5	V-6	V-7	V-8	V-9
STEAM DRUM	COAL & LIME-STONE BIN	BED SOLIDS COLLECTION DRUM	CYCLONE SOLIDS COLLECTION DRUM	WATER DRAIN DRUM	CYCLONE	SILENCER	COAL BIN	PULSE COMBUSTOR

V-10	B-2	B-3	B-4	F-1	P-1	E-1/E-2	S-1
COAL FINES FEEDER	PRIMARY AIR BLOWER	PREHEAT AIR BURNER	PILOT BURNER	INDUCED DRAFT FAN	LIQUID PUMP	FLUID-BED STEAM COIL	SOLIDS DRAIN VALVE

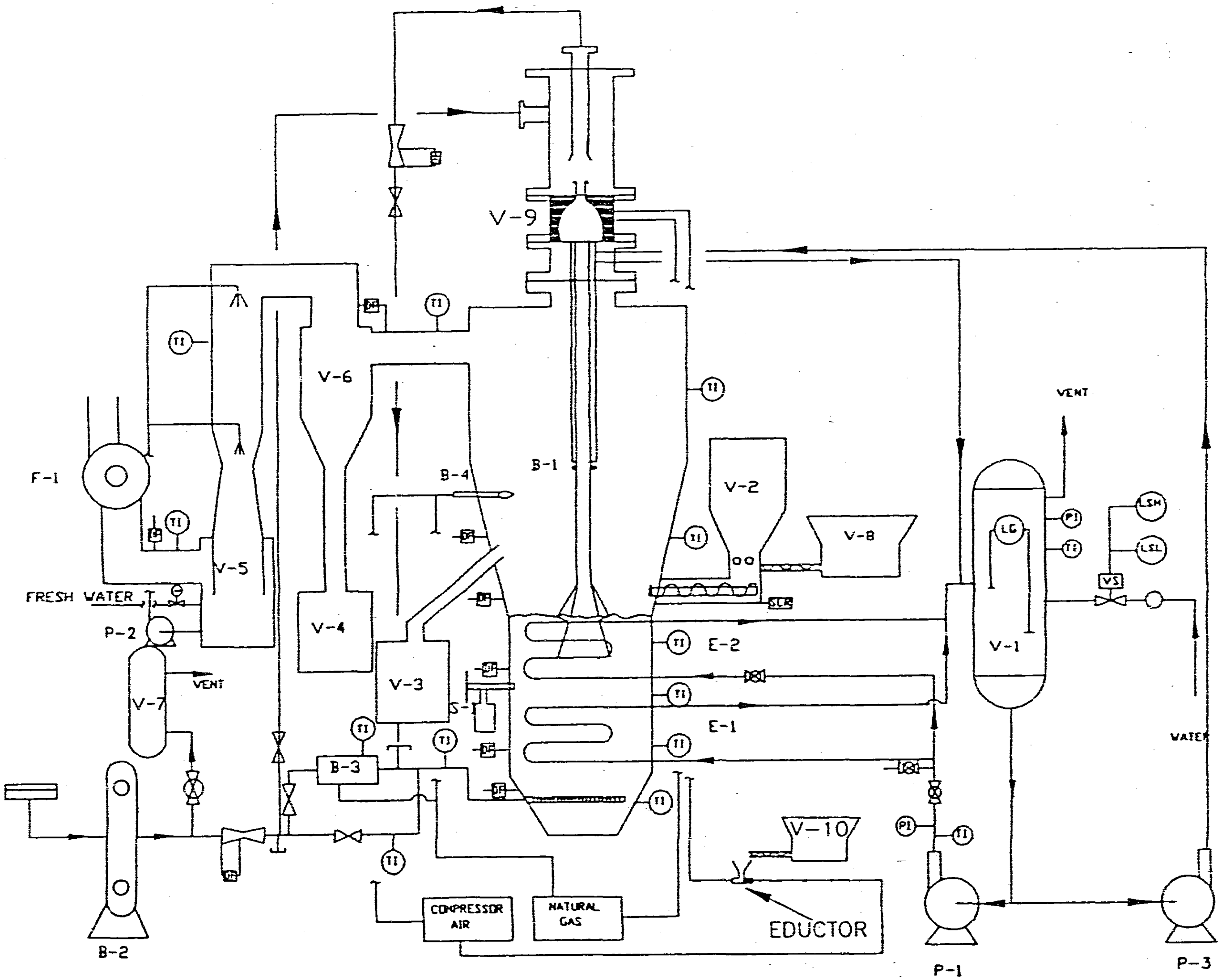


FIGURE 4-36: PAFBC SYSTEM LAYOUT

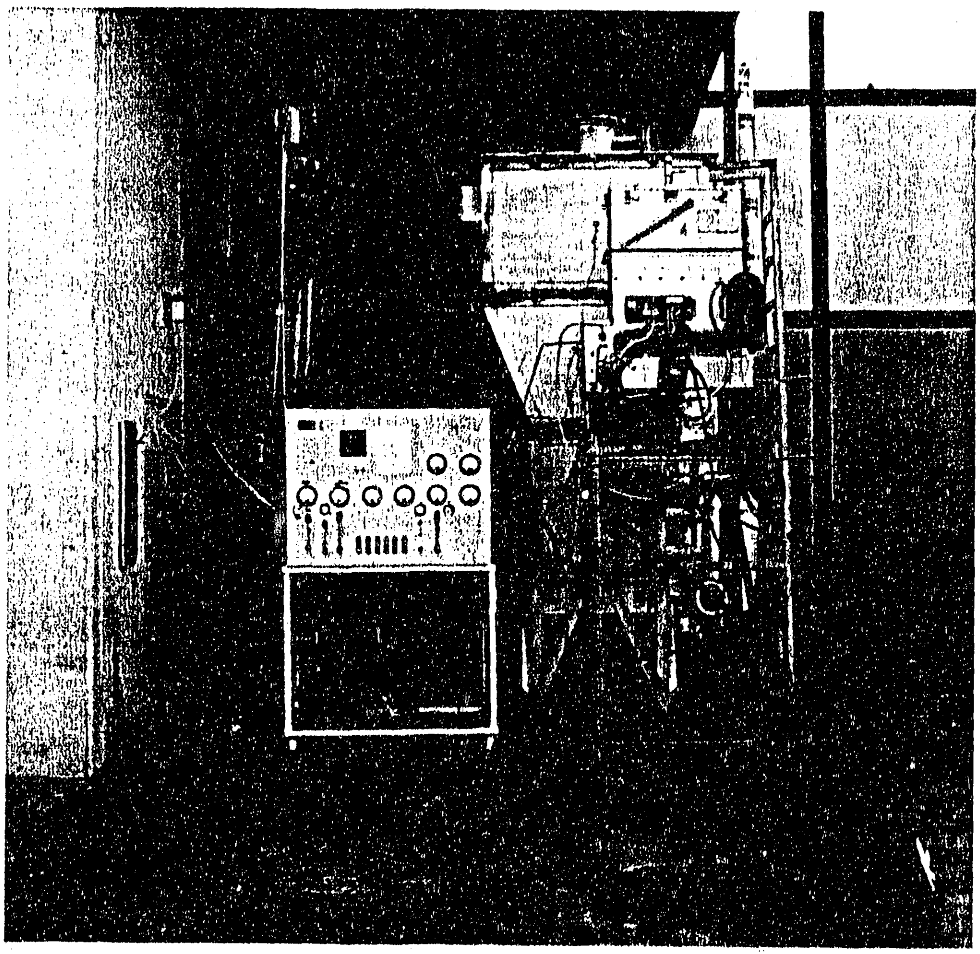


FIGURE 4-37: A PICTURE OF THE PAFBC SYSTEM

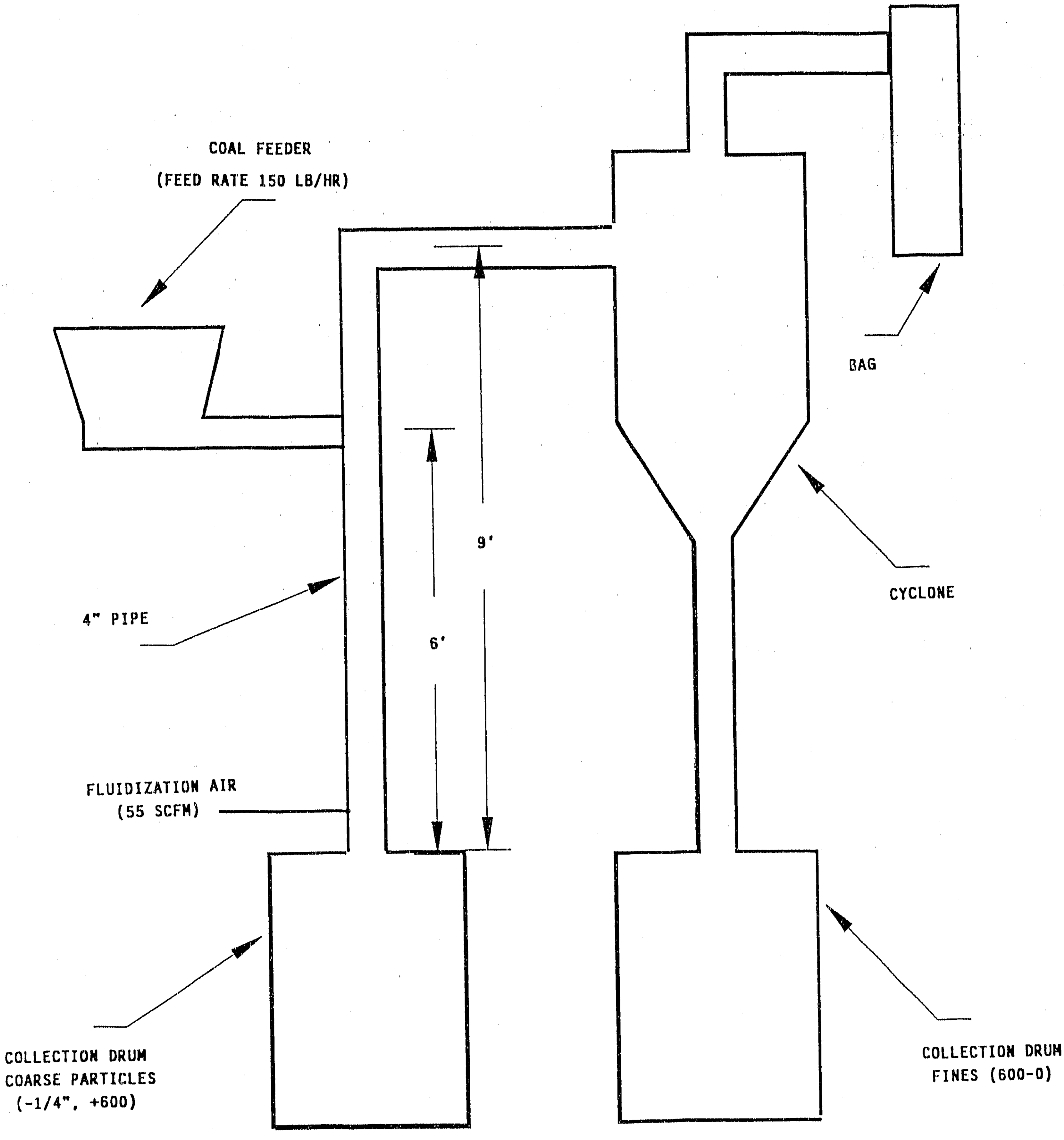


FIGURE 4-38: SCHEMATIC OF THE CLASSIFIER

TABLE 4-11: PULSE COMBUSTOR OPERATIONAL CHARACTERISTICS

Firing rate:	650,000 Btu/hr
Frequency:	50 Hz
Peak-to-Peak Pressure:	14 psi
Boost Pressure:	15 inches of water
Air Plenum Pressure:	42 inches of water
Chamber Temperature:	2000°F
Tailpipe Exit Temperature:	1700°

Tests were then conducted with coal fines injection into the pulse combustor and coarse coal feed into the fluid bed. A summary of the data obtained, problems encountered and the system modifications carried out is given below.

- For operation in the PAFBC mode and 25-inch bed height (Test No. P3), the net bed weight loss rate turned out to be negligible. Therefore, pulsations generated due to pulse combustion seemed to stabilize fluidization dynamics and reduce bed entrainment.

- The expansion bellows incorporated in the tailpipe water jacket ruptured during a shakedown test. This rupture was linked to thermal stress resulting from choked steam flow in the exit line and inadequate water inflow. The cooling water inlet line and steam outlet line were changed from 1/2- to 1-inch tubing and the bellows were taken out from the water-cooling jacket section. Also a separate water pump was installed to circulate water through the pulse combustor water jacket.

- The heat transfer coefficient in the pulse combustor tailpipe was found comparable to that for a tube immersed in the fluidized bed (~40 Btu/hr-ft^2-°F).

- During Test No. P6, the steaming rate exceeded design conditions (>1200 lb/hr) and the water level in the steam drum diminished rapidly, leading to test termination. The problem was traced to water splashing on the water-level control rods in the steam drum and interfering with the operation of the solenoid valve in the make-up water line. An examination of the make-up water supply rate to the steam drum indicated a maximum flow rate of 2 gpm. This translates to a steam rate of 1000 lb/hr. A new water level control system was installed, a manual by-pass line (**Figure 4-39**) for supplying make-up water to the drum in case of level controller malfunction was added, and the water line from the mains to the steam drum was changed from 1/2-inch tube to 3/4-inch pipe. The last modification corresponded to a maximum make-up water flow rate of 6 gpm or 3,000 lb/hr steam production rate. An additional 2-inch steam vent line was also added to the drum to avoid pressure build-up in the steam drum at high steaming rates (>1500 lb/hr).

- Also during test No. P6, it was noticed that pulse combustor start-up required more than the expected amount of natural gas feed rate. Data collected during the test on pressure drop across the venturi in the main air line and thrust augmentor return air line indicated that about 40 percent of the total air flowed through the pulse combustor. This is quite different from the design split of 3 to 1 between the bed and the pulse combustor. This design split had previously been verified in the earlier PAFBC shakedown test (Test No. P3). The change in air split was traced to an increase in bed height from 25 to 35 inches and the corresponding decrease in the pulse combustor tailpipe length. The aerovalve insert was modified from 1-1/4 to 1-inch throat diameter. The pulse combustor was test-fired with gas to verify the air split. It was found that 25 percent of the total air flowed through the pulse combustor and 75 percent through the bed, as desired.

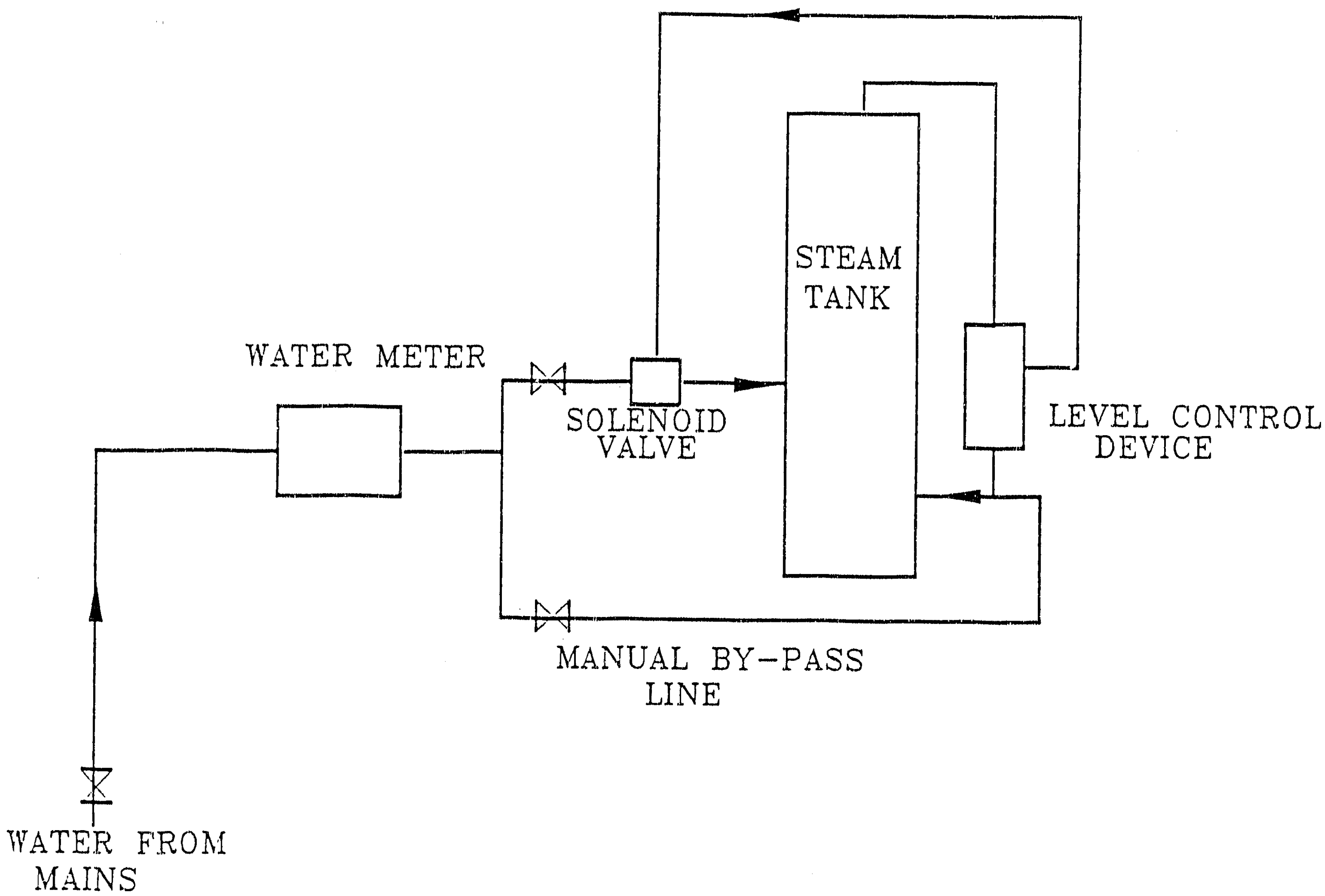


FIGURE 4-39: SCHEMATIC FOR THE NEW WATER-LEVEL CONTROL SYSTEM FOR THE AFBC STEAM TANK

- Test No. P7 was conducted with coarse coal feed to the bed and gas supply to the pulse combustor. The objective was to determine the net bed weight loss rate for operation of the PAFBC at 6 ft/s gas velocity and an expanded bed height of about 32 inches as in the AFBC tests. The unit was started up differently for this test. At start-up the slumped bed was around 20-inches deep. The steam coils in the bed were kept open and water was circulated through the pulse combustor water jacket. Bed depth was built-up by adding bed material as needed to maintain bed temperature at about 1550°F. The net weight loss rate of bed was determined to be about 60 lb/hr. This was substantially lower than that obtained in the AFBC mode (see Figure 4-25) but still unacceptable from the standpoint of achieving steady-state operation. This along with the AFBC shakedown test data (Section 4.3.2) prompted the design and installation of the in-furnace solids separator as discussed in Section 4.3.2.

- A final shakedown test (Test No. P9) indicated zero net bed weight loss rate (Figure 4-25) and confirmed the readiness of the PAFBC system for performance testing.

4.6 COAL COMBUSTION TESTS IN THE PAFBC SYSTEM

Five tests were performed in the PAFBC mode (Test Nos. P10, P11, P13, P14 and P15). Steady-state conditions with regard to combustion, emissions, and steam generation were successfully achieved. Chemical analyses of the streams were performed and the test data and results are presented in Tables 4-12 through 4-16. Sample profiles of bed temperature and flue gas composition (O_2, SO_2, NO_x and CO) for the steady-state period are shown in Figures 4-40 through 4-44.

In summary, a total of 28 tests were performed, including shakedown and debugging tests. The test parameters are given in Table 4-17. The PAFBC system has been on-line for more than 200 hours and combusted nearly 9 tons of coal. A chronology of the tests performed in Subtasks 2-2, 2-4 and 2-5 is given in Table 4-18.

TABLE 4-12: PAFBC SYSTEM TEST

TEST #: P10 TEST DATE: 4-12-89 TEST TIME: 16:00-17:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE: 1550.0 DEG F 843.3 DEG C
BED DEPTH (EXPANDED): 32.0 IN. 0.8 M
SUPERFICIAL VELOCITY: 7.0 FT/S 2.1 M/S
CALCIUM-TO-SULFUR RATIO: 2.6
RECYCLE: NO
FUEL FEED RATE TO BED: 120.0 LB/HR LIMESTONE FEED RATE: 40 LB/HR
FUEL FEED RATE TO PULSE COMBUSTOR: 4.7 CFM NATURAL GAS

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	12.75	---	27.31	0
14	1400	22.98	---	42.99	2.03
20	850	48.22	---	28.90	8.21
30	600	9.59	---	0.52	5.23
50	300	4.67	---	0.10	10.20
70	212	0.68	---	0.10	24.30
PAN	0	1.09	---	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
PITT. #8	67.85	4.76	3.99	1.26	7.05	9.84	5.25	12300.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT: 50.0 PPM= 0.1 LB/MMBTU
NOx FURNACE EXIT: 240.0 PPM= 0.4 LB/MMBTU
CO FURNACE EXIT: 800.0 PPM= 0.9 LB/MMBTU
O2 FURNACE EXIT: 3.9% CO2 FURNACE EXIT: 16.0%
CARBON EFFICIENCY: 98.4 %
COMBUSTION EFFICIENCY: 94.0 %. EXCESS AIR: 22.0 %
STEAM RATE: 817.0 LB/HR

CARBON MATERIAL BALANCE

TOTAL CARBON IN: 118.8 LB/HR
TOTAL CARBON OUT: 118.7 LB/HR

TABLE 4-13: PAFBC SYSTEM TEST

TEST #: P11 TEST DATE: 4-19-85 TEST TIME: 21:30-24:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1550.0 DEG F	843.3 DEG C
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M
SUPERFICIAL VELOCITY:	7.0 FT/S	2.1 M/S
CALCIUM-TO-SULFUR RATIO:	2.6	
RECYCLE:	NO	

FUEL FEED RATE TO BED: 100.0 LB/HR LIMESTONE FEED RATE: 54 LB/HR
FUEL FEED RATE TO PULSE COMBUSTOR: 65.0 LB/HR

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	46.89	0.44	27.31	0
14	1400	31.56	12.49	42.99	2.03
20	850	10.99	17.34	28.90	8.21
30	600	0.87	30.23	0.52	5.23
50	300	0.67	10.83	0.10	10.20
70	212	0.23	16.72	0.10	24.30
PAN	0	0.79	11.94	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
PITT. #8	67.85	4.76	3.99	1.26	7.05	9.84	5.25	12300.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	300.0 PPM=	0.6 LB/MMBTU
NOx FURNACE EXIT:	200.0 PPM=	0.3 LB/MMBTU
CO FURNACE EXIT:	700.0 PPM=	0.6 LB/MMBTU

O2 FURNACE EXIT: 3.5% CO2 FURNACE EXIT: 16.3%
CARBON EFFICIENCY: 98.2 %
COMBUSTION EFFICIENCY: 92.2 % EXCESS AIR: 17.3 %
STEAM RATE: 820.0 LB/HR

CARBON MATERIAL BALANCE

TOTAL CARBON IN: 135.4 LB/HR
TOTAL CARBON OUT: 134.7 LB/HR

TABLE 4-14: PAFBC SYSTEM TEST

TEST #: P13 TEST DATE: 4-28-89 TEST TIME: 10:00-20:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1550.0 DEG F	843.3 DEG C
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M
SUPERFICIAL VELOCITY:	7.0 FT/S	2.1 M/S
CALCIUM-TO-SULFUR RATIO:	2.5	
RECYCLE:	YES	

FUEL FEED RATE TO BED: 100.0 LB/HR LIMESTONE FEED RATE: 45 LB/HR
FUEL FEED RATE TO PULSE COMBUSTOR: 60.0 LB/HR

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	33.03	0.44	27.31	0
14	1400	40.39	12.49	42.99	2.03
20	850	23.01	17.34	28.90	8.21
30	600	0.99	30.23	0.52	5.23
50	300	0.29	10.83	0.10	10.20
70	212	0.11	16.72	0.10	24.30
PAN	0	2.19	11.94	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
TO BED								
W.KENTY.#11	67.12	4.70	3.22	1.46	9.12	11.36	3.02	12134.0
TO P.C.								
PITT. #8	67.85	4.76	3.99	1.26	7.05	9.84	5.25	12388.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	100.0 PPM=	0.2 LB/MMBTU
NOx FURNACE EXIT:	250.0 PPM=	0.4 LB/MMBTU
CO FURNACE EXIT:	260.0 PPM=	0.2 LB/MMBTU

O2 FURNACE EXIT: 4.0% CO2 FURNACE EXIT: 16.0%
CARBON EFFICIENCY: 95.1 %
COMBUSTION EFFICIENCY: 96.4 % EXCESS AIR: 20.9 %
STEAM RATE: 800.0 LB/HR

CARBON MATERIAL BALANCE

TOTAL CARBON IN: 128.1 LB/HR
TOTAL CARBON OUT: 127.8 LB/HR

TABLE 4-15: PAFBC SYSTEM TEST

TEST #: P14 TEST DATE: 5-12-89 TEST TIME: 21:00-22:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1490.0 DEG F	810.0 DEG C
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M
SUPERFICIAL VELOCITY:	5.0 FT/S	1.5 M/S
CALCIUM-TO-SULFUR RATIO:	2.6	
RECYCLE:	NO	

FUEL FEED RATE TO BED: 80.0 LB/HR LIMESTONE FEED RATE: 28 LB/HR

FUEL FEED RATE TO PULSE COMBUSTOR: 8.0 SCFM OF NATURAL GAS

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	33.03	---	27.31	0
14	1400	40.39	---	42.99	2.03
20	850	23.01	---	28.90	8.21
30	600	0.99	---	0.52	5.23
50	300	0.29	---	0.10	10.20
70	212	0.11	---	0.10	24.30
PAN	0	2.19	---	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE: TO BED	CARBON	HYDROGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
W. KENTY.#11	67.12	4.70	3.22	1.46	9.12	11.36	3.02	12134.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	--	PPM=	--	LB/MMBTU
NOx FURNACE EXIT:	117.0	PPM=	0.1	LB/MMBTU
CO FURNACE EXIT:	180.0	PPM=	0.2	LB/MMBTU
N2O FURNACE EXIT:	59.0	PPM=	0.1	LB/MMBTU

O2 FURNACE EXIT: 6.0% CO2 FURNACE EXIT: 11.6%

EXCESS AIR: 40.0%

STEAM RATE: 500.0 LB/HR

TABLE 4-16: PAFBC SYSTEM TEST

TEST #: P15 TEST DATE: 5-12-89 TEST TIME: 23:00-24:00

SUMMARY OF TEST CONDITIONS

BED TEMPERATURE:	1550.0 DEG F	843.3 DEG C
BED DEPTH (EXPANDED):	32.0 IN.	0.8 M
SUPERFICIAL VELOCITY:	7.0 FT/S	2.1 M/S
CALCIUM-TO-SULFUR RATIO:	2.5	
RECYCLE:	NO	

FUEL FEED RATE TO BED: 80.0 LB/HR LIMESTONE FEED RATE: 45 LB/HR

FUEL FEED RATE TO PULSE COMBUSTOR: 60.0 LB/HR

SIZE ANALYSIS- WT% RETAINED ON THE SCREEN

MESH #	MICRON	COAL TO BED	COAL TO P.C.	LIMESTONE	CYCLONE CATCH
10	2000	33.03	0.44	27.31	0
14	1400	40.39	12.49	42.99	2.03
20	850	23.01	17.34	28.90	8.21
30	600	0.99	30.23	0.52	5.23
50	300	0.29	10.83	0.10	10.20
70	212	0.11	16.72	0.10	24.30
PAN	0	2.19	11.94	0.07	50.12

CHEMICAL ANALYSIS, PERCENTAGES BY WEIGHT

COAL TYPE:	CARBON	HYDORGEN	SULFUR	NITROGEN	OXYGEN	ASH	MOISTURE	BTU/LB
TO BED								
W.KENTY.#11	67.12	4.70	3.22	1.46	9.12	11.36	3.02	12134.0
TO P.C.								
PITT. #8	67.85	4.76	3.99	1.26	7.05	9.84	5.25	12388.0

LIMESTONE TYPE:	CACO3	MgCO3	SiO2	Al2O3	Fe2O3	LOSS ON IGNITION
SHASTA	98.0	0.6	0.2	0.1	0.025	43.4

SUMMARY OF RESULTS

SO2 FURNACE EXIT:	--	PPM=	--	LB/MMBTU
NOx FURNACE EXIT:	95.0	PPM=	0.1	LB/MMBTU
CO FURNACE EXIT:	525.0	PPM=	0.5	LB/MMBTU
N2O FURNACE EXIT:	85.0	PPM=	0.1	LB/MMBTU

O2 FURNACE EXIT: 5.4% CO2 FURNACE EXIT: 13.0%

EXCESS AIR: 35.1 %

STEAM RATE: 500.0 LB/HR

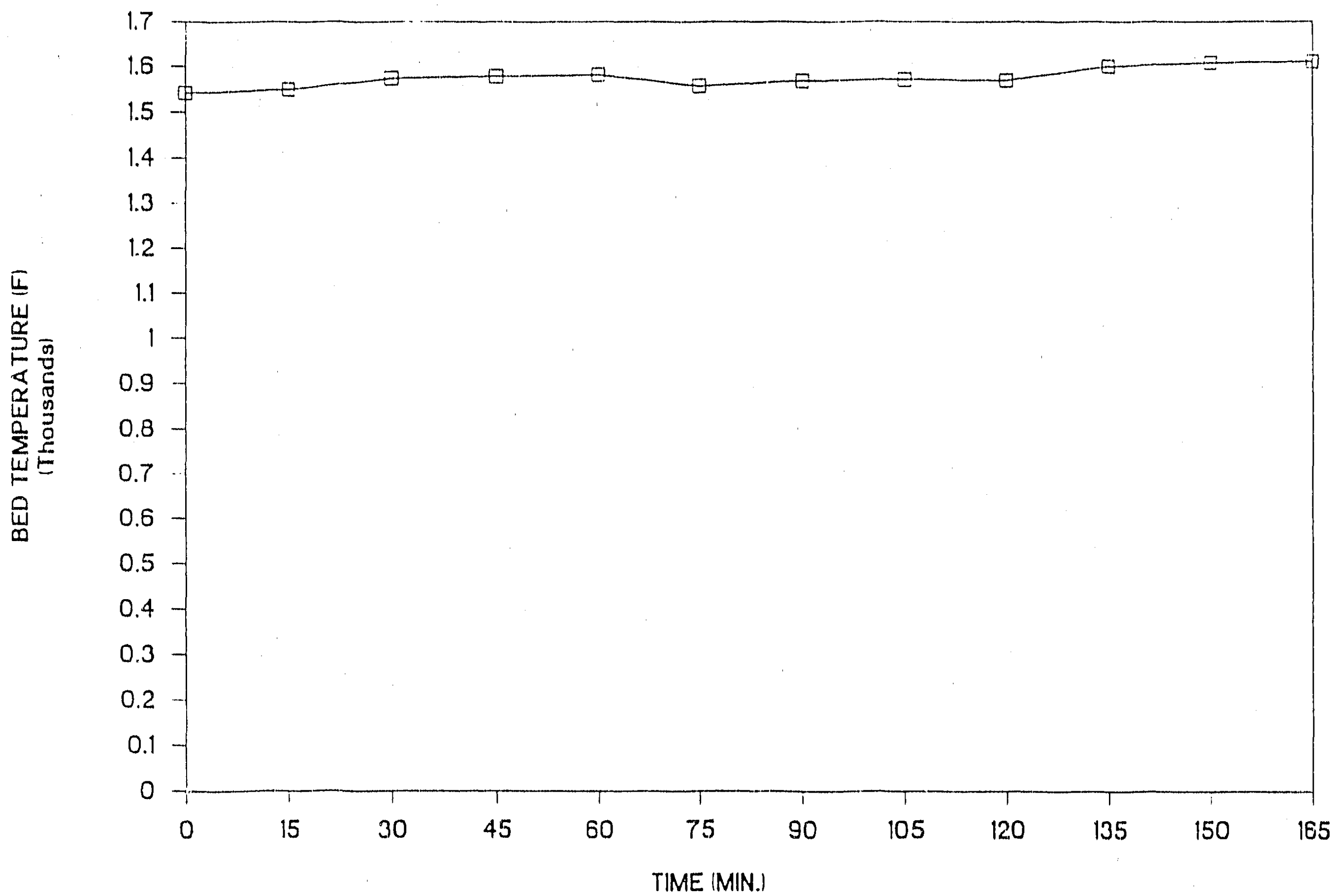


FIGURE 4-40: BED TEMPERATURE PROFILE FOR PAFBC SYSTEM TEST NO. P11

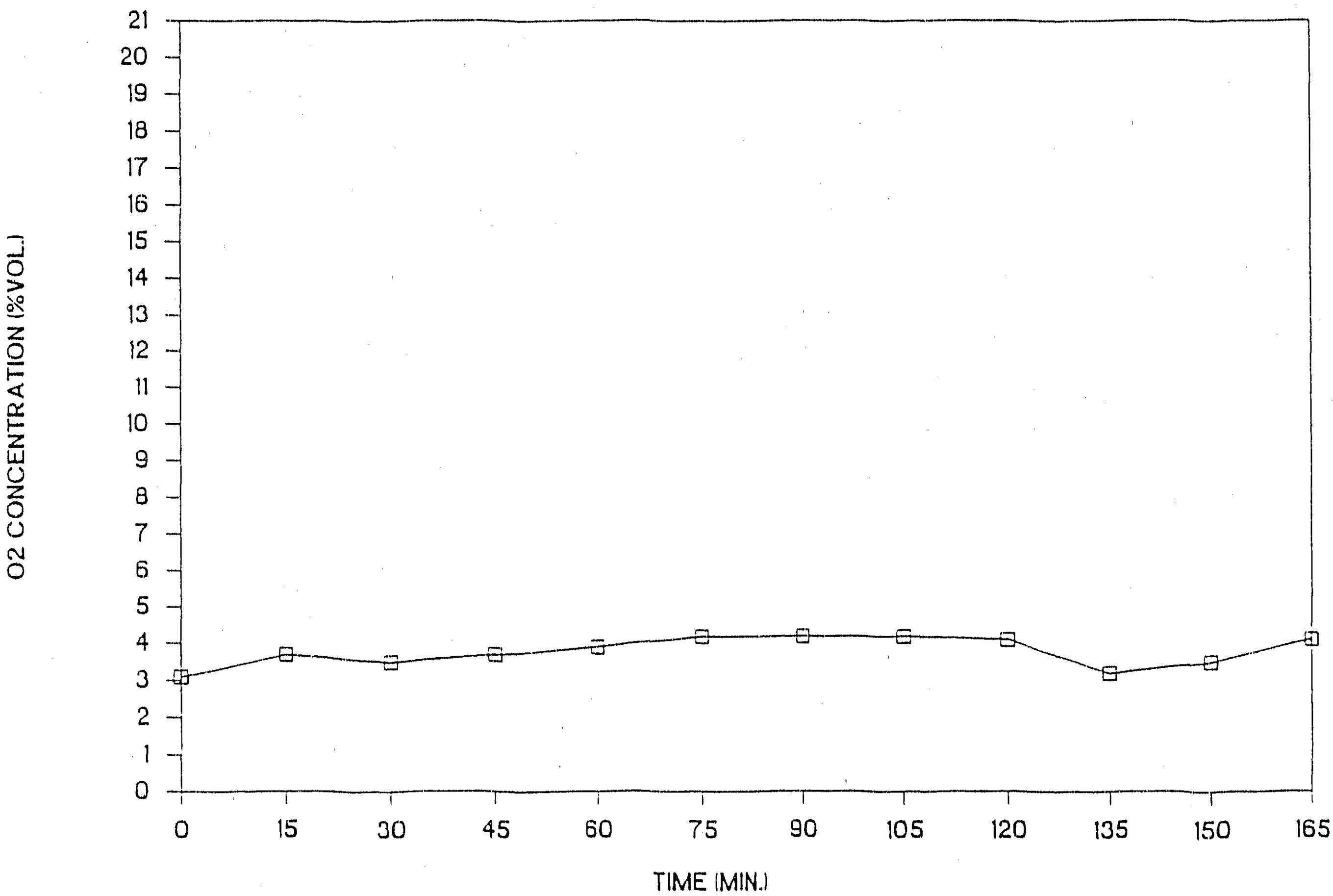


FIGURE 4-41: OXYGEN CONCENTRATION IN FLUE GAS FOR PAFBC SYSTEM TEST NO. P11

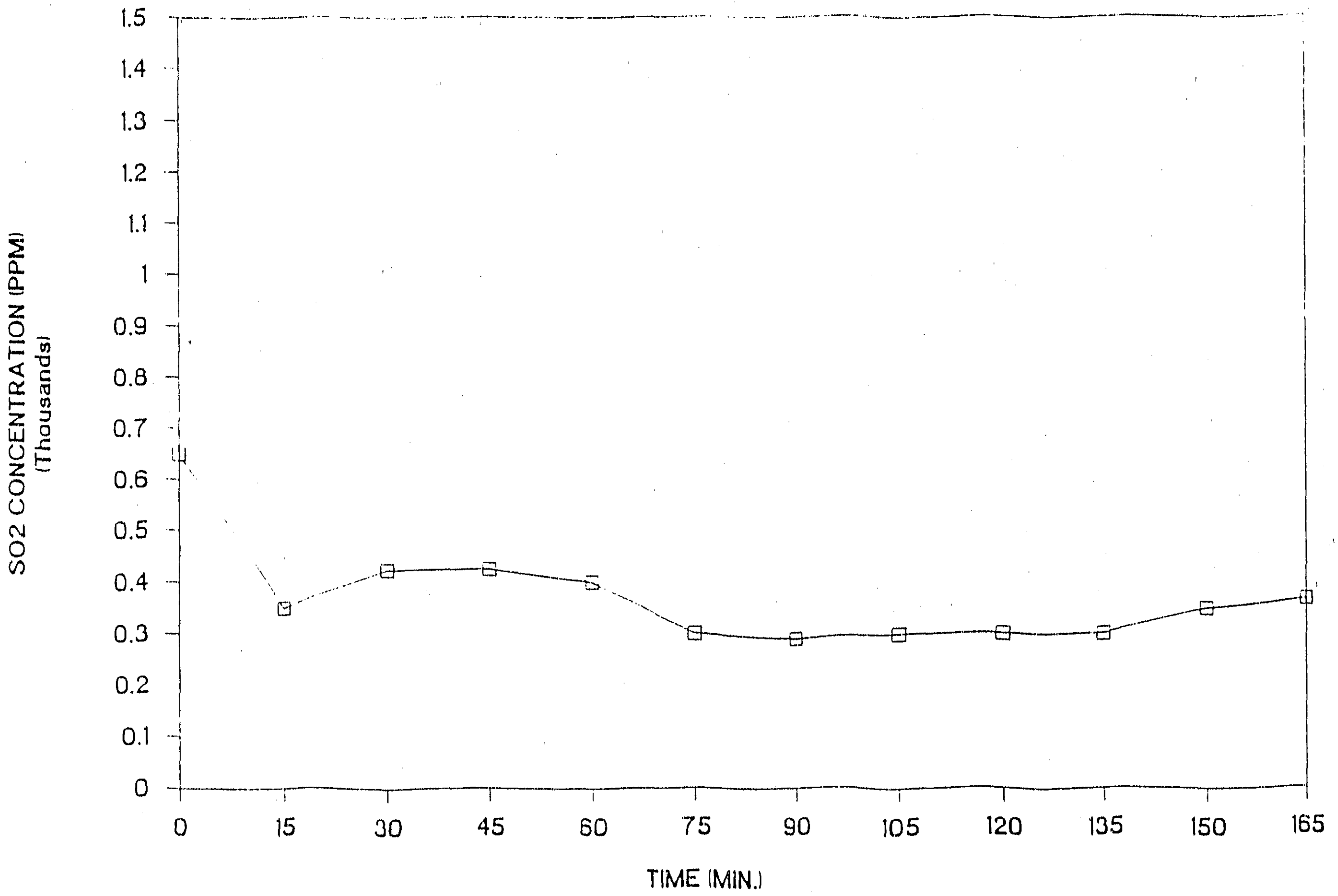


FIGURE 4-42: SO_2 CONCENTRATION IN FLUE GAS FOR PAFBC SYSTEM TEST NO. P11

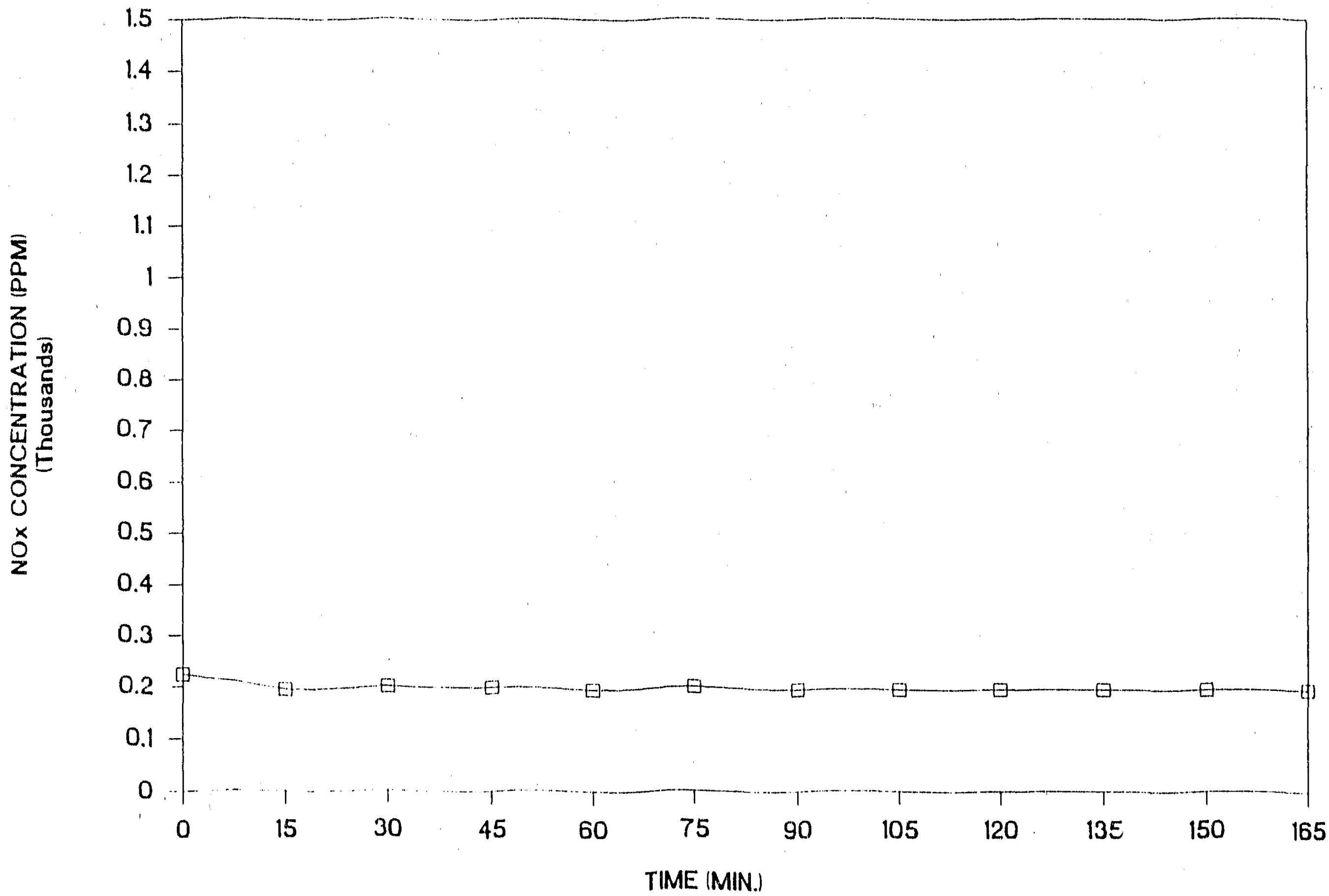


FIGURE 4-43: NO_X CONCENTRATION IN FLUE GAS FOR PAFBC SYSTEM TEST NO. P11

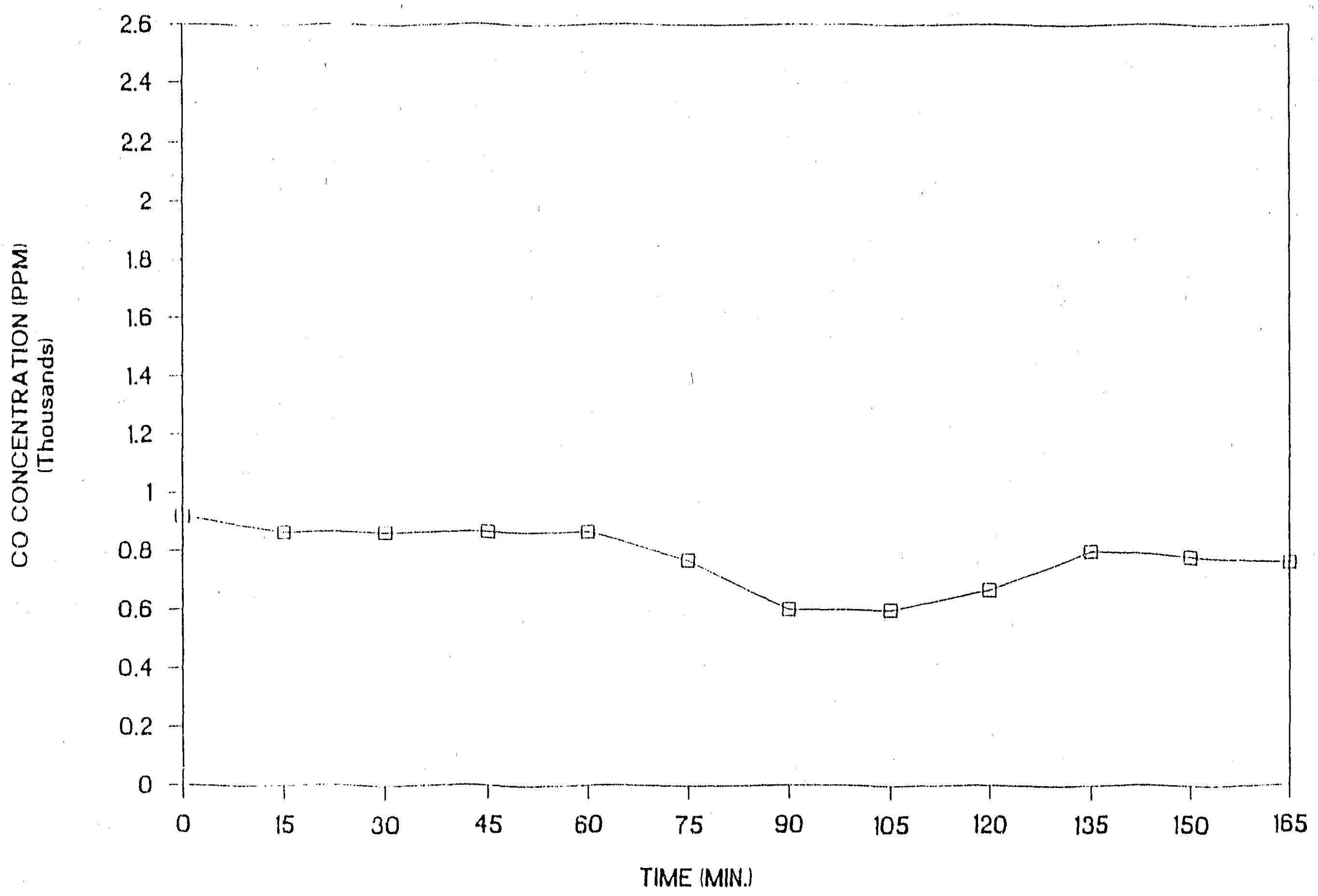


FIGURE 4-44: CO CONCENTRATION IN FLUE GAS FOR PAFBC SYSTEM TEST NO. P11

TABLE 4-17: TEST PARAMETERS

Mode:	AFBC, PAFBC
Coal Type:	Pittsburgh No. 8, W. Kentucky No. 11, W. Kentucky No.9
Coal Size Distribution:	3/8" by 0 with 15 - 40% fines by wt.
Limestone:	Shasta
Limestone Size Distribution:	1/8" by 0
Superficial Gas Velocity:	5 - 7 ft/sec
Bed Temperature:	1500 - 1600°F
Ca/S Ratio:	2.5 - 2.7
Bed Area	2' x 2'
Furnace Height:	10'
Pulse Combustor Fuel:	Coal, Gas

TABLE 4-18: TASK 2 - TEST CHRONOLOGY

TEST NO.	TEST DATE	MODE OF OPERATION	TEST DURATION (HR)	COAL FED (LB)	FUEL TYPE	COMMENTS
A1	12-02-88	AFBC	7	100	W. KENTY #9	SHAKEDOWN
A2	12-06-88	AFBC	10.5	500	W. KENTY #9	SHAKEDOWN
A3	12-09-88	AFBC	8	960	W. KENTY #9	SHAKEDOWN
A4	12-20-88	AFBC	6	500	W. KENTY #9	SHAKEDOWN
A5	12-28-88	AFBC	4	300	W. KENTY #9	SHAKEDOWN
A6	01-04-89	AFBC	6	640	W. KENTY #9	SHAKEDOWN
A7	01-06-89	AFBC	7.5	600	W. KENTY #9	SHAKEDOWN
A8	01-12-89	AFBC	7	450	PITT. #8	SHAKEDOWN
P1	01-21-89	PAFBC	1	---	GAS	CHARACTERIZATION
P2	01-23-89	PAFBC	1.5	---	GAS	CHARACTERIZATION
P3	01-24-89	PAFBC	5.5	300	PITT. #8	CHARACTERIZATION
P4	01-26-89	PAFBC	4	200	PITT. #8	SHAKEDOWN
A9	02-03-89	AFBC	4.5	450	PITT. #8	SHAKEDOWN
A10	02-09-89	AFBC	6	820	PITT. #8	SHAKEDOWN
A11	02-16-89	AFBC	15	1820	PITT. #8	SHAKEDOWN
P5	02-24-89	PAFBC	2	100	PITT. #8	SHAKEDOWN
P6	02-27-89	PAFBC	4	100	PITT. #8	SHAKEDOWN
P7	03-02-89	PAFBC	9	720	PITT. #8	SHAKEDOWN
A12	04-04-89	AFBC	5.5	600	PITT. #8	SHAKEDOWN
A13	04-06-89	AFBC	14	2000	PITT. #8	BASELINE TEST
P8	04-07-89	PAFBC	4.5	450	PITT. #8	SHAKEDOWN
A14	04-07-89	AFBC	5	700	PITT. #8	BASELINE TEST
P9	04-11-89	PAFBC	3	200	PITT. #8	SHAKEDOWN
P10	04-12-89	PAFBC	10	1080	PITT. #8	SYSTEM TEST
P11	04-19-89	PAFBC	15	800	PITT. #8	SYSTEM TEST
P12	04-27-89	PAFBC	8.5	550	W. KENTY #11	SHAKEDOWN
P13	04-28-89	PAFBC	14	1285	W. KENTY #11 & PITT. #8	SYSTEM TEST
A15	05-12-89	AFBC	5	250	W. KENTY #11	BASELINE TEST
A16	05-12-89	AFBC	4	250	W. KENTY #11	BASELINE TEST
P14	05-12-89	PAFBC	4	250	W. KENTY #11	SYSTEM TEST
P15	05-12-89	PAFBC	4	250	W. KENTY #11 & PITT. #8	SYSTEM TEST

4.7 RESULTS AND DISCUSSION

The values obtained for the overall combustion efficiency are compared with bubbling fluidized bed combustion (BFBC) data from Babcock & Wilcox (B&W) and Tennessee Valley Authority (TVA) units[21] in **Figure 4-45**. The BFBC data correspond to the zero fly ash recycle case. Combustion efficiency decreases with an increase in superficial gas velocity. This decrease is attributed to greater carbon loss resulting from higher attrition and elutriation of char, and shorter carbon residence time. Lignites and sub-bituminous coals perform better than bituminous coals mainly due to their higher reactivity. The data from the 2′ x 2′ MTCI unit for the AFBC mode of operation are in general agreement with those from BFBC units. This provides support for the short but expanded freeboard coupled with in-furnace solids disengagement. Typically, combustion efficiency in the PAFBC mode is higher than in the AFBC mode for bituminous coal and tends to approach the values obtained in BFBC for lignites and sub-bituminous coals.

Figure 4-46 illustrates the effect of calcium to sulfur molar feed ratio on sulfur capture efficiency. As expected, sulfur capture improves with increasing Ca/S ratio for all fuels tested. Again, the MTCI AFBC mode data are in general agreement with those from the 1′ x 1′ BFBC unit at B&W[21]. Also, the sulfur capture efficiency in the PAFBC mode is 5 to 30 percent better than those in the AFBC mode. For a Ca/S ratio between 2.5 and 2.6, the sulfur capture efficiency exceeds 90 percent. The superior sulfur capture in the PAFBC mode could be due to one or more of the following:

- Acoustic enhancement of the mass transfer process,
- Fines recirculation arising from the draft tube design,
- Greater proportion of sulfur release in the bed due to pulse combustor effluxing into the fluid bed.

The NO_x emissions obtained in this program are compared with those from the 1′ x 1′ BFBC unit[21] in **Figure 4-47**. The emissions are higher than the current EPA limit of 0.6 lb/MKB for the AFBC mode of operation and Pittsburgh

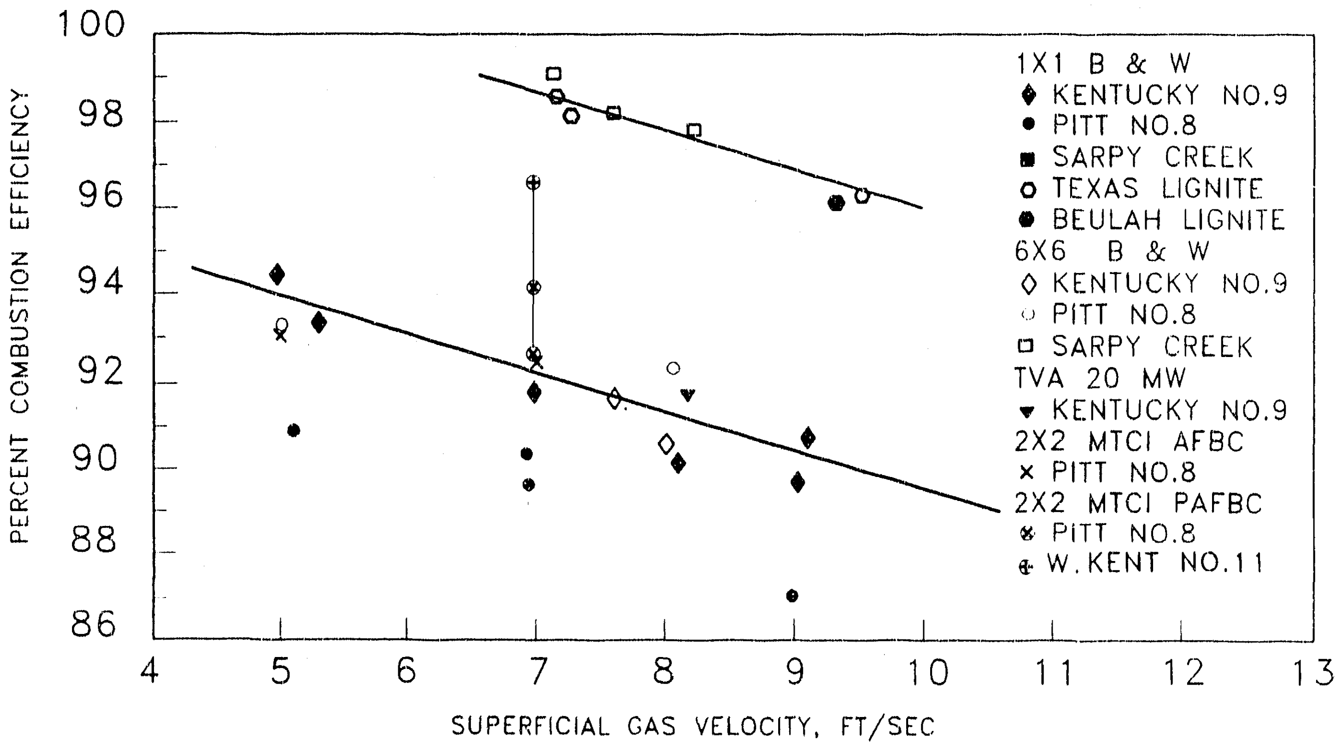


FIGURE 4-45: COMPARISON OF PAFBC OVERALL COMBUSTION EFFICIENCY DATA WITH BFBC DATA

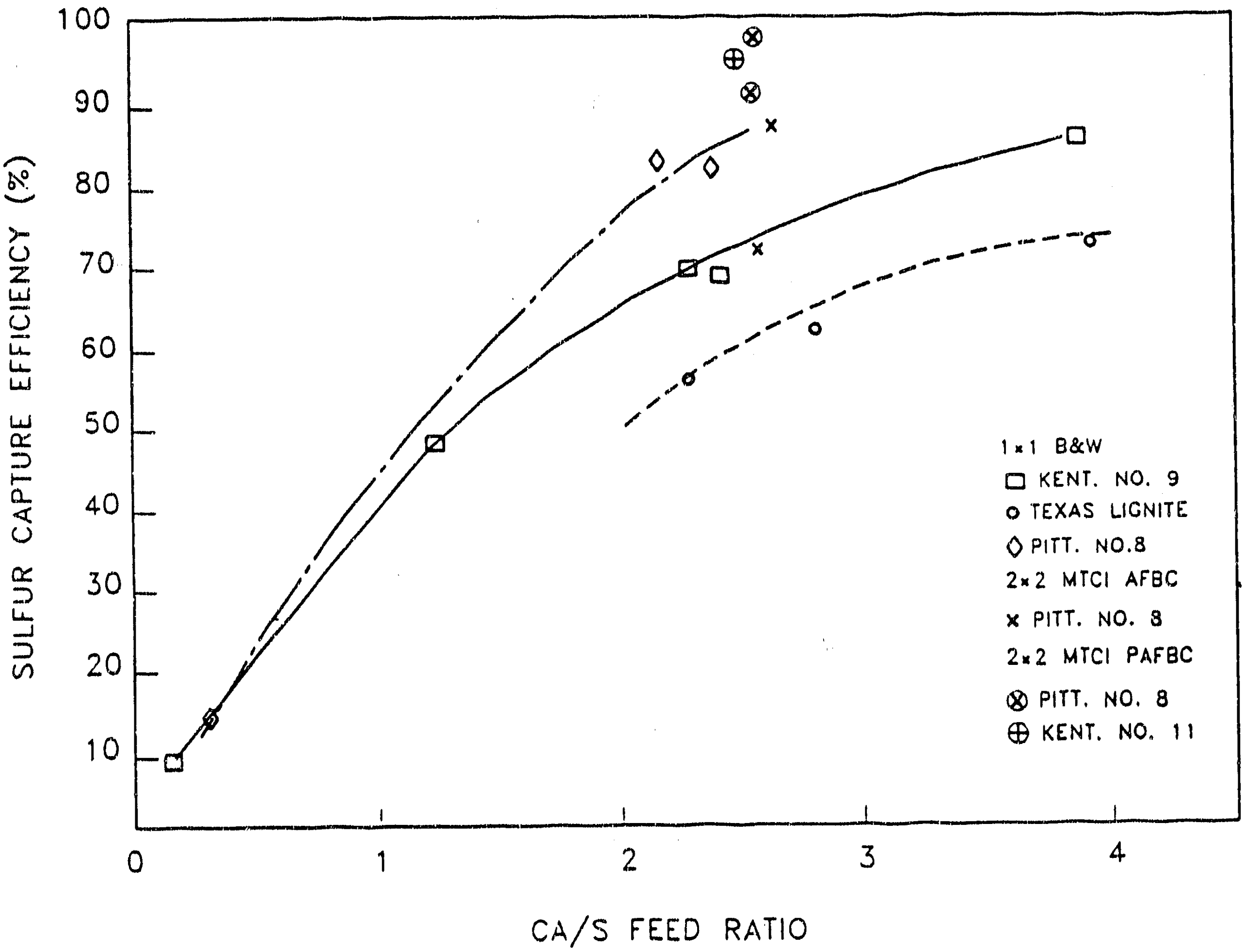


FIGURE 4-46: COMPARISON OF PAFBC SULFUR CAPTURE EFFICIENCY WITH BFBC DATA

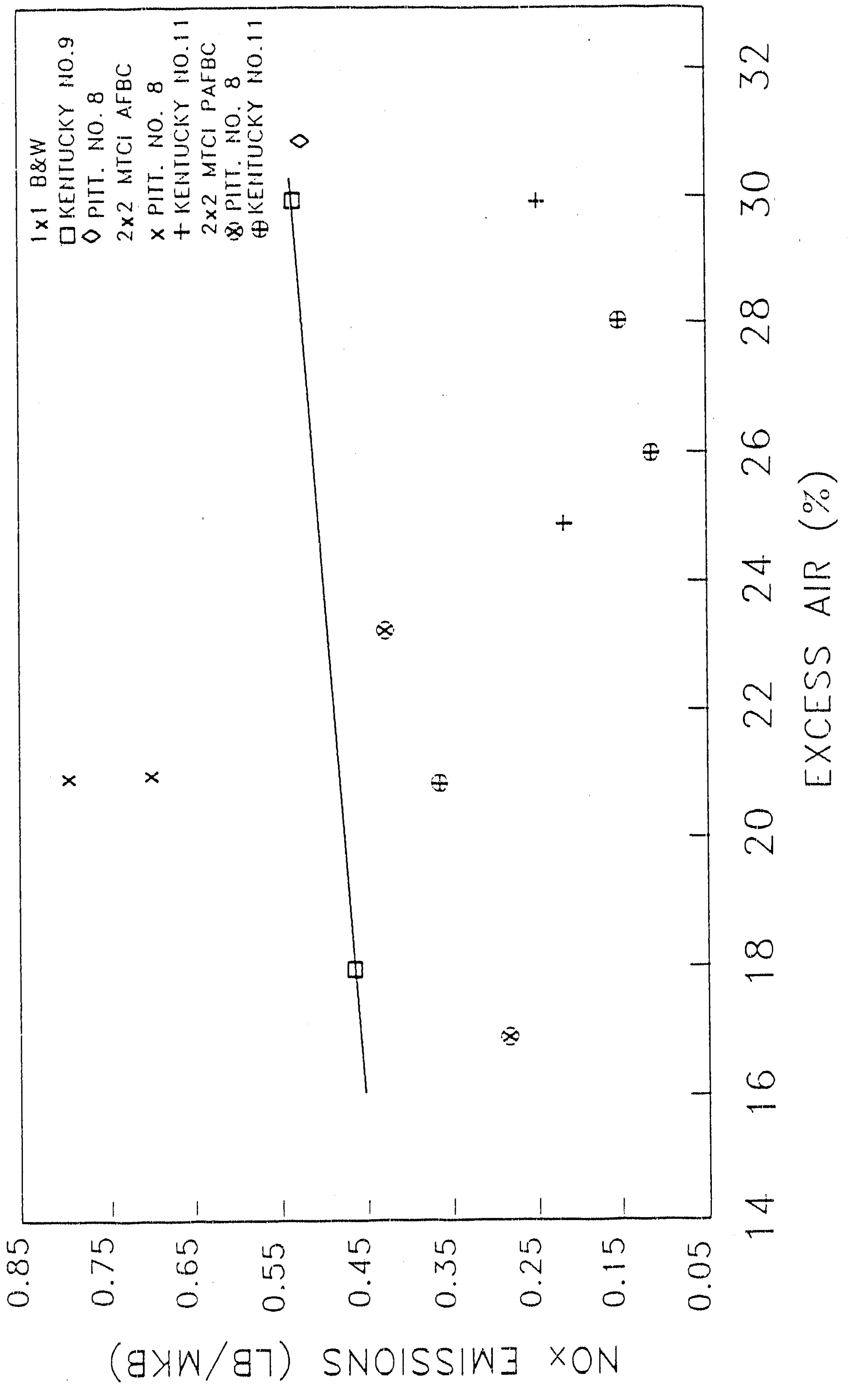


FIGURE 4-47: NO_x EMISSIONS FROM THE PAFBC UNIT

No. 8 coal. However, the emissions are significantly lower for the Kentucky No. 11 coal in both the AFBC and PAFBC modes. The NO_x levels in the PAFBC mode are generally lower than those obtained in BFBC and meet the New Source Performance Standards (NSPS).

A recent publication[22] as well as measurements made at MTCI point out that N_2O emissions from fluidized bed boilers are not insignificant but are comparable to NO_x emissions. The test conditions and the results are given in **Table 4-19**. Actual furnace exit measurements are shown as well as the NO_x and N_2O values corrected to 3 percent O_2 at the exit. The corrected values will now on be termed as normalized values. The results from tests A15, A16, P14, and P15 indicate the following:

- AFBC mode - In switching from unclassified to classified coal feed, the NO_x emission increases while N_2O emission decreases. The increase in NO_x due to classified coal feed is attributed to higher NO_x formation (as a result of lower carbon loading and CO level in the freeboard). The decrease in N_2O due to classified coal feed is probably because of a reduction in the freeboard devolatilzation of fines (as a result of lower fines content in the feed).

- PAFBC mode - With a gas-fired pulse combustor and the fluidized bed burning coarse coal, the normalized NO_x drops to 140 ppm from 181 ppm obtained in Test A16. The decrease in NO_x is attributed to pulse operation, lower bed temperature, and lower coal feed rate (Required for similar overall firing rate). The N_2O emission is almost invariant due to a combination of lower bed temperature (which tends to increase emissions as per Amand and Andersson (1989)[3] and lower coal feed rate (which lessens N_2O formation). Upon switching the pulse combustor fuel from gas to Pittsburgh No. 8 coal fines, the normalized NO_x drops to 110 ppm while normalized N_2O increases to 98 ppm. The decrease in NO_x is attributed to pulsed operation and higher level of NO_x destruction (as a result of higher carbon loading and CO level in the freeboard). Note that the pulse operation essentially is tantamount to air staging in that primary air flows

TABLE 4-19: TEST CONDITIONS AND EMISSIONS DATA

TEST NUMBER (MODE)	FUEL TYPE TO BED	FUEL TO PULSE	FIRING RATE (MMBtu/hr)	BED TEMP. (°F)	SUP. GAS VEL. (FT/SEC)	CO (PPM)	NO_x (PPM)	N_2O (PPM)	NO_x* (PPM)	N_2O* (PPM)
A15 (AFBC)	W. Kentucky #11 Unclassified (27% Fines)**	None	1.46	1585	5	400	140	75	155	83
A16 (AFBC)	W. Kentucky #11 Cassified (3% Fines)	None	1.21	1600	5	90	143	57	181	72
P14 (PAFBC)	Same as in Test A16	Gas	1.46	1490	5	180	117	59	140	71
P15 (PAFBC)	Same as in Test A16	Pitts. #8 (Fines)	1.67	1550	5	525	95	85	110	98
A13 (AFBC)	Pittsburgh #8 Unclassified (40% Fines)	None	1.47	1500	5	1600	490	--	534	--
A14 (AFBC)	Pittsburgh #8 Classified (15% Fines)	None	1.98	1500	7	1100	590	--	617	--
P10 (PAFBC)	Pittsburgh #8 Classified (5% Fines)	Gas	1.89	1500	7	800	240	--	253	--
P11 (PAFBC)	Pittsburgh #8 Classified (3% Fines)	Pitts. #8 (Fines)	2.19	1570	7	700	200	--	208	--
P13 (PAFBC)	W. Kentucky #11 Classified (3% Fines)	Pitts. #8 (Fines)	2.12	1500	7	260	250	--	265	--

* Corrected to 3% O_2 at the stack.
** Fines less than 30 mesh.

through the distributor and the oxygen-rich flue gas from the pulse combustor provides secondary air in the upper part of the bed. This helps reduce NO_X. The N_2O is higher than those in tests A15, A16, and P14 presumably because of firing a different fuel viz. Pittsburgh No. 8 fines. The measurement of Amand and Andersson (1989)[22] support this reasoning in that the N_2O emissions exhibited a variation with fuel.

The normalized NO_x emissions range from 110 to 181 ppm while N_2O (normalized) emissions vary from 71 to 98 ppm in these tests. Previous data from this program (Test Nos. A13, A14, P10, P11, and P13) indicated substantially higher NO_x emissions (530 to 620 ppm under AFBC mode and 205 to 265 ppm under PAFBC mode at 3 percent O_2 at the furnace exit); N_2O was not measured. The differences in NO_x emissions between the current and the previous test series are probably due to differences in fuel and some operating conditions (bed temperature, gas velocity, etc.). In contrast, Amand and Andersson (1989) report NO emissions (normalized) ranging from 10 to 100 ppm and N_2O emissions (normalized) ranging from 20 to 200 ppm.

Therefore, with regard to nitrogenous species emissions, the following observations can be made:

- N_2O emissions from fluidized bed boilers are not insignificant but are comparable to NO_x emissions.

- NO_x emissions are significantly lower (25 to 60 percent less) under PAFBC operation as compared to those under AFBC mode.

- The mode of operation (AFBC or PAFBC) does not have much influence on N_2O emissions.

- NO_x and N_2O emissions vary with fuel.

- It is not known whether sorbent and char influence N_2O formation and destruction reactions as they do in the case of NO_x.

Table 4-19 also furnishes data on CO emissions. The emissions depend on the mode of operation (AFBC or PAFBC), fuel type, weight percent fines in the coal feed to the fluidized bed, superficial gas velocity, and the excess air level. Typically, the CO emissions were lower in the PAFBC mode than those under AFBC mode.

Under comparable operating conditions, the steam generation rate turned out to be abut 20 percent higher in the PAFBC mode than in the AFBC mode. For example, at a superficial gas velocity of about 7 ft/s, the steam production rate was 700 lb/hr in the AFBC mode and was between 800 and 820 lb/hr in the PAFBC mode. The improvement is attributed to the pulse combustion of fines, water jacketing of the tailpipe and the high heat transfer coefficient in the tailpipe (as high as in the fluidized bed) due to pulsating flow. This outcome translates into a reduction in the freeboard/convective section heat exchange surface where heat transfer coefficients are substantially lower than those in the bed (1/10 to 1/8) and a consequent decrease in capital cost.

4.8 TECHNICAL, ENVIRONMENTAL AND ECONOMIC ASSESSMENT

A summary comparison of the performance and emissions data from the MTCI 2′ x 2′ facility (AFBC and PAFBC modes) with those from conventional BFBC (taller freeboard and recycle operation) and circulating fluidized bed combustion (CFBC) units is given in <u>Table 4-20</u>. The comparison is for typical high-volatile bituminous coals and sorbents of average reactivity. The values indicated for BFBC and CFBC are based on published information.[2,23-29] It is seen that the PAFBC mode exhibits superior performance in relation to AFBC mode. The higher combustion efficiency translates into reduced coal consumption and lower system operating cost; the improvement in sulfur capture implies less sorbent requirement and waste generation and in turn lower operating cost; lower NO_x and CO emissions mean ease of siting; and greater steam-generation rate translates into less heat exchange surface area and reduced capital cost. Also, the PAFBC performance generally (i) surpasses those of conventional BFBC, (ii) is comparable to CFBC in combustion and NO_x emissions, and (iii) is better than CFBC in sulfur capture and CO emissions.

TABLE 4-20: PERFORMANCE CHARACTERISTICS

	AFBC	PAFBC	BFBC*	CFBC*
Combustion Efficiency (%)	89-93	92-97	90-97	93-99
SO_2 Capture (%)	70-85	90-98	70-85	75-95
NO_x Emissions (ppm)	115-620	110-265	400-500	100-300
CO Emissions (ppm)	400-1600	180-800	400-1200	500-1500
Steam Rate (lb/hr)	500-700	800-820		

TEST PARAMETERS

Bed Temperature	1500-1600°F
Ca/S Ratio	2.5 - 2.7
Coal	Bituminous (high volatile)

*Based on literature data.

These factors render the PAFBC to be an attractive option at any scale. The fact that it is impractical and expensive to scale-down CFBC to the 1,000 - 50,000 PPH steam equivalent range makes the PAFBC a clear contender for the small-scale boiler market sector.

After the completion of Subtask 2.5 and more than 200 hours of operation, the PAFBC system was partially dismantled to assess the integrity of the unit and conduct materials evaluation. The diffuser section connected to the pulse combustor tailpipe was observed to have fallen off into the fluid bed due to fracture of holding/support rods. The failure is attributed to thermal stress. Incorporation of water-cooled support rods is expected to solve this problem. An examination of the furnace internals and the pulse combustor indicated that the refractory linings had minor surface cracks and erosion was not evident. In conclusion, the PAFBC system seemed to be generally in good condition.

A cost analysis was performed to estimate the capital cost of a 1000 lb/hr PAFBC steam generator based on the configuration investigated in Task 2. Convective section and baghouse were included and the scrubber was deleted. The cost of one-of-a kind system (not the mass produced version) was estimated to be about $52,000. The cost breakdown is given in **Table 4-21**. This figure is somewhat higher than the target capital cost goal (between $45,000 and $50,000) derived from the steam production cost model outlined in ection 3.3.5. A packaged PAFBC boiler however, is anticipated to meet the target capital cost goal and compete favorably with a natural gas- or oil-fired system. The projected steam cost is about $7/1000 lb, as pointed out in Section 3.3.5. Since the steam cost is very sensitive to capacity factor, applications/markets with high capacity factors (>60%) provide the best targets for the initial entry of this advanced coal-fired technology. Also, due to economy of scale - smaller surface area per unit volume and lower marginal investment in subcomponent cost with increase in unit size - PAFBC boilers in the 10,000 to 50,000 PPH steam range provide a keener competitive edge for replacing oil- and gas-fired units.

MTCI has successfully demonstrated the feasibility of a PAFBC technology. The performance of the laboratory-scale system exceeded the expectations of both MTCI and DOE. The integration of a pulse combustor with a fluidized bed combustor has produced the following benefits:

- The oscillating flow field imposed by the introduction of pulse combustor exit gas into the fluid bed helps stabilize fluidization dynamics, reduce particle entrainment, improve interphase heat and mass transfer, enhance sulfur capture and reduce solid waste volume.

- The fines burned in the pulse combustor generate pressure boost for fluidization and/or air staging thereby reducing air moving equipment requirements and cost.

- The furnace height requirement is lowered due to pulse combustor integration, freeboard expansion and in-furnace solids disengagement. The pulse combustor integration decreases carbon loading in

TABLE 4-26:
COST BREAKDOWN FOR A PAFBC (1000 PPH STEAM) BOILER

MATERIAL/PURCHASED ITEMS

	ESTIMATE
Coal Bunker	$ 3,000
Variable-Speed Screw Meter	2,000
Limestone Bunker	1,500
Variable-Speed Screw Meter	2,000
Classifier	1,000
Steam Drum	2,500
Circulation Pump	500
Feedwater Pump	1,500
Bed Steam Coils	1,000
Convection Coil	3,375
Fluid Bed & Freeboard Structural Steel & Refractory	3,000
Pulse Combustor	5,000
Baghouse	10,000
Cyclone	5,000
Primary Air Fan	2,000
Forced Draft Air Fan	2,000
Induced Draft Fan	2,000
Instruments	5,000
SUBTOTAL	$52,375

LABOR HOURS @ $13.00/hr

	HOURS	
Coal Bunker	80	$ 1,040
Limestone Bunker	80	1,040
Fluid Bed	280	3,640
Complete System Mechanical	120	1,560
Complete System Electrical	80	1,040
Complete System Instrument	80	1,040
Site Installation	40	520
Site Testing	40	520
SUBTOTAL	200	$10,400
TOTAL*		$62,775

*First unit costs based on material and labor estimates with field support.

the freeboard. The freeboard expansion helps decrease gas velocity, increase gas residence time and decrease solids elutriation. The in-furnace solids disengagement improves combustion and sulfur capture performance and decreases particle carryover with flue gas.

- The heat exchange surface area requirement is greatly reduced by efficient heat transfer both in the fluidized dense bed and the pulse combustor tailpipe.

- The high combustion intensity (2 to 5 $MMBtu/hr/ft^3$) and fast response of the pulse combustor facilitate rapid system start-up and load-following.

- The draft tube configuration employed at the end of the pulse combustor tailpipe provides fines recirculation and increased particle residence time in the bed for enhanced combustion and sulfur capture.

- It is possible to incorporate multiple air staging in the freeboard to achieve even lower NO_x emissions.

- The system affords the potential for co-incineration of wastes of various types - hospital waste, hazardous waste, coal pond waste, coal tailings etc. - in an efficient, environmentally acceptable and economical manner.

Due to the advantages cited above, a number of end-users such as Baltimore Thermal Energy Corporation, Island Creek Corporation, and Cleveland Thermal Energy Corporation have expressed great interest in this technology and have offered participation in field testing the PAFBC system.

SECTION 5.0

PRELIMINARY DESIGN FOR THE INTEGRATED SYSTEM

The technical merit and commercial potential of the pulsed fluid-bed technology has been established at the low end of the market sector for which it was originally intended (1,000 - 10,000 PPH). The performance of the experimental PAFBC unit actually surpassed that of conventional bubbling and circulating fluidized bed combustion units and exceeded the initial expectations for the novel and innovative technology. Even at this first level of development, the project provided experimental data in combustion, sulfur capture emissions control and enhanced heat transfer to the degree that a number of potential end-users are interested in participating in the next phases of technology development, offering siting for field test trials for their system's application. The preliminary designs were therefore focused upon two different applications, one for drying and the other for steam generation.

The first application for coal drying has been proposed by Island Creek Corporation. The second application involves steam generation for district heating with steam generated fed to the steam distribution lines of the Baltimore Thermal Energy Corporation.

For each of these applications, several different design configurations were formulated and evaluated in order to arrive at an acceptable design for each integrated system. The preliminary designs for each of the two applications are discussed in Section 5.2.

5.1 MARKET PENETRATION

As of 1987, there were 56 industrial fluid-bed combustors (FBC) on-line in the United States. The sizes ranged from approximately 10 to 600 thousand pounds of steam per hour. Of these, only one was in the range of interest (1-10 thousand PPH). Figure 5-1 shows the distribution by size of these industrial boilers and Figure 5-2 indicates the year of initiation of on-line

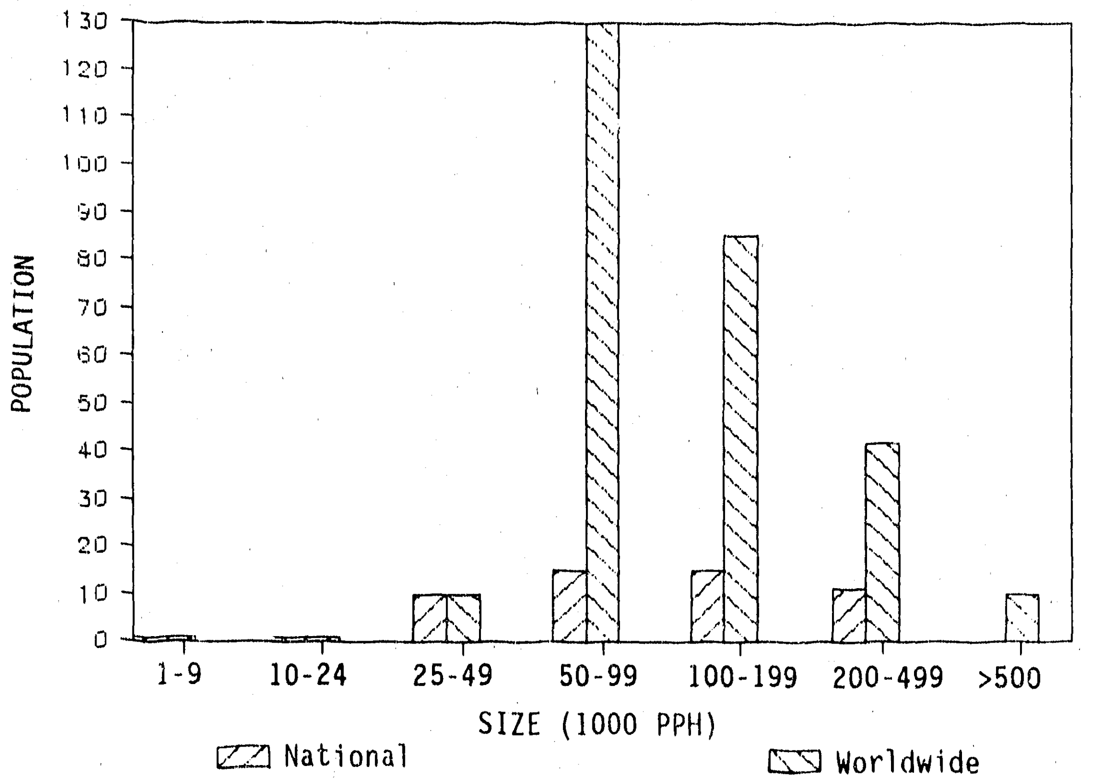


FIGURE 5-1: DISTRIBUTION OF OPERATING UNITS BY SIZE

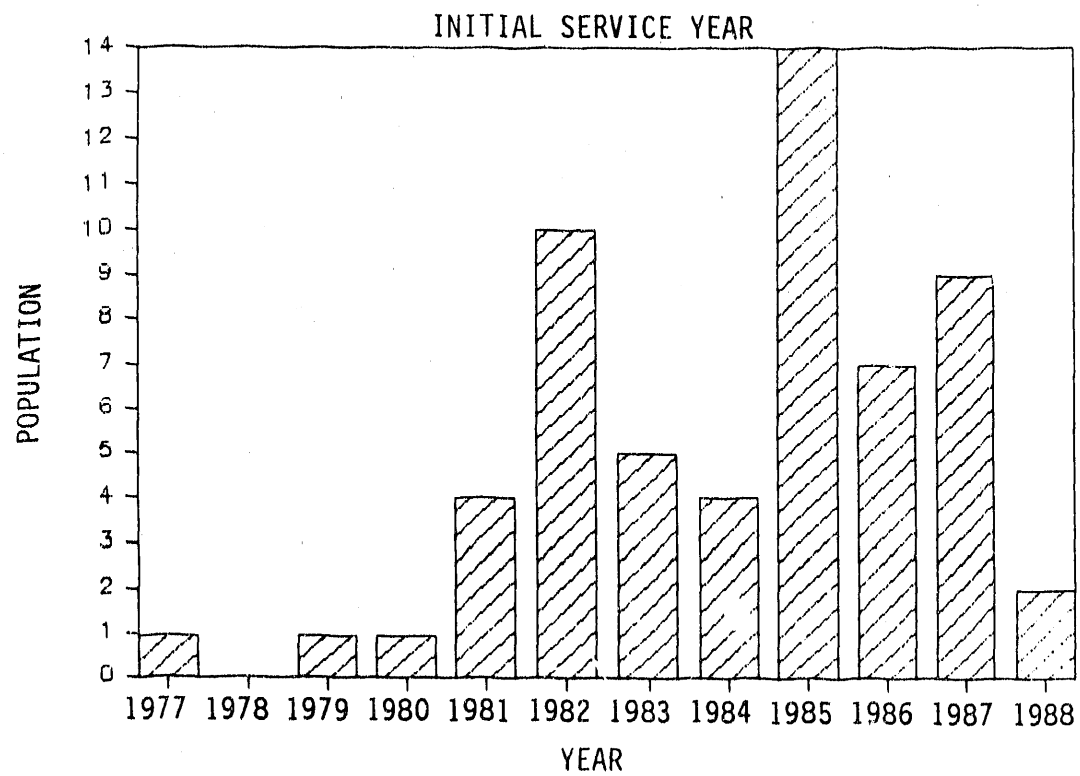


FIGURE 5-2: DISTRIBUTION OF OPERATING UNITS

operations. Two additional units (at 110 PPH each) were projected to come on-line in 1988 (Stearns Catalytic Corporation, 1986).

Worldwide, excluding the Soviet and Eastern block nations and the People's Republic of China, the number of boiler units including utility units either on-line or projected to come on-line through 1988 are also provided in Figure 5-1. The number of units in the Soviet Union and Eastern block nations, as well as the People's Republic of China (PRC), are uncertain, although the PRC has reported well over 2,000 units (Zhang). A size definition and annual distribution of on-line units is not available, although it appears there are some units at the 8,000 - 20,000 PPH level.

The implications from this size distribution are perhaps two-fold. The units cluster at the 50-500 thousand PPH level, an indication that the technology and market for units in this size have reached a mature commercial level. Scale-up to units greater than 500 thousand PPH appears to present little technical difficulty and is probably more a matter of market penetration, especially within the utility sector.

Scale-down and operating experience from 1,000 - 50,000 PPH at the less than 10,000 PPH is almost non-existent at the low end and quite sparse at the upper end. This indicates that in spite of the availability of a significant market, the state-of-the-art technology for smaller units is insufficient to provide either operating experience or economic incentives. The conclusion that can be reached is that innovative and/or creative additions to the technology base is a mandatory prerequisite for expansion to these levels of application.

A more practical definition of unit size was based on discussions with a local boiler manufacturer (Mr. Dixon, President of Dixon Boiler Works, Los Angeles, California), a boiler size of 10,000 PPH steam equivalent is the one considered most suitable for market penetration. This is because this size is in great demand, there is a large inventory of boilers in the market, and the boiler owner is better able to absorb the capital cost differential between an oil-/gas-fired and alternate fuel-fired unit. Therefore, the design steam capacity for the integrated facility is selected to be 10,000 PPH at 150 psi and saturation condition. This would correspond to a 10:1 scale-up from the Task 2 laboratory test unit and would provide a measure of the scaleability of the PAFBC concept.

Numerous variants exist in relation to the geometry, construction, and means of heat removal in fluidized bed combustors. The arrangements commonly employed include:

- Horizontal fire tube
- Vertical fire tube
- Water-walled combustor with water-tube convective pass
- Refractory-lined combustor with immersed water-tube banks and water-tube convective pass.

These designs were reviewed separately at first and then together with Mr. Dixon.

5.2 DISTRICT HEATING APPLICATION

The objective is to develop a flexible design that would permit limited studies on boiler optimization while evaluating the performance, reliability, maintainability, controllability, operability, fuel flexibility, cost effectiveness, environmental compliance, and safety of the system. Some of the considerations for design include:

- System should incorporate simple modular construction. For example, the integrated test facility could be divided into multiple subsystems. Each subsystem would then be delivered on an individual pallet and a minimum degree of interconnection would be necessary at the end-user's site. Here the user has the flexibility to locate the individual pallets in a manner which makes the best use of the existing site space. Also, the user has the option of mixing and matching different size subsystems to achieve performance and reliability goals at less cost in comparison to multiple fully packaged systems.

- Unit should be capable of shop fabrication and truck transportation to the greatest extent possible. This generally limits the pallet dimensions to 30′ x 10′ x 13′.

- Assembled system height should not exceed about 20 feet since vertical space in the small-scale boiler market sector is generally limited.

- Particulate collection should be localized at a minimum number of points.

- Unit should be flexible to allow a high turndown ratio (~ 5:1).

- System should incorporate automatic controls and require minimal operator attention.

- Subsystems should be accessible for routine inspections and maintenance as required.

- Boiler should require normal water treatment or conditioning system.

- Erosion, fouling and deposition problems should be minimized.

The pertinent facts are as follows:

Fire-tube designs are commonly limited to relatively low steam pressure ranges (up to 150 psi) due to mechanical constraints. Also, there is an upper limit on steam capacity due to shell size restrictions. Although the horizontal fire-tube boiler offers a familiar and proven design for natural gas-, oil-, and coal-fired stoker service, the geometry of the furnace tube is less than ideal for fluidized bed applications. By nature, fluidized beds which are incorporated into these designs must be quite shallow. Although a more extensive vertical appendage could be added at the bottom of the shell to accommodate deeper beds, this results in an awkward design which compromises the simplicity of the boiler and requires a significantly more extensive structural support system. In the original configuration, heat removal from the bed is difficult. For instance, if the lower half of the furnace tube is used to cool the bed, then fluidization must occur in a semi-circular sectional area using horizontal sparge pipes to carry the fluidization air. In addition, the freeboard height is limited to approximately two-thirds of the furnace tube diameter. The available space is clearly insufficient for optimal carbon burnout and particle disengagement. Typically, a bed retaining wall constructed from refractory brick defines the end of the bed. Since the combustion gases pass over the top of this wall at high velocity, particle carryover is a serious problem and necessitates virtually continuous bed solids replenishment. Furthermore, installation of a pulse combustor in a horizontal shell design would be difficult. Therefore, the horizontal fire-tube design is considered inappropriate for the present application.

The vertical fire-tube design by nature seems to be more suitable for conversion to an FBC boiler. However, this design is not commonplace in the market and, when available, occurs in small capacity sizes. The fire-tube diameter and height are very limited for FBC application and therefore design and fabrication of a brand new boiler rather than the modification of an existing design is called for. Since in vertical fire-tube design:

- the fire tubes could get oxidized, pit, and corrode if air is present in steam due to dissolution in water and the top portion of the tubes get exposed to air; and

- the freeboard could quench combustion if not refractory lined; alternately, the water column surrounding the freeboard is almost unutilized if the freeboard is refractory lined.

Consequently, it was decided to drop the fire-tube concept.

The water-tube design is preferable from the standpoint of scale-up in steam capacity and steam pressure. It is capable of a faster response rate than that of a fire-tube design. Also, the failure of a small water tube is less catastrophic than that of a large shell in a fire-tube boiler. Since erosion of tubes immersed in fluidized beds is as yet an unresolved issue and the water-wall concept permits a more compact design for a given boiler capacity, it was decided to employ a water-wall design for the dense bed portion of the FBC.

Preliminary design calculations indicated that for a 10,000 PPH steam generation rate, under nominal PAFBC operating conditions (1550°F bed temperature, 7 ft/s superficial gas velocity, 3 foot bed height, and bituminous coal), a bed area of about 28 sq. ft. would be required. This translates approximately into a plan cross-section of 5 x 5 feet. Heat transfer calculations for the water wall indicated that a 3 x 3 feet bed could be maintained at about 1550°F but not a 5 x 5 feet bed. Therefore, it was decided to employ a water-cooled distributor plate as well. A schematic of the conceptual design proposed for the PAFBC boiler is shown in **Figure 5-3**. The design incorporates:

- a 3- to 4-inch wide plate type (for ease of cleaning), water-wall design in the dense bed region of the fluidized bed,
- a refractory-lined freeboard to promote complete combustion,
- a two-drum (steam and mud drums) concept to avoid elaborate water treatment,
- natural circulation with downcomers and risers to avoid using water circulation pumps that are prone to failure,
- an inertial solids separator-cum-steam generator for in-furnace solids disengagement such that high-temperature material is not required for fabrication,
- an air-shrouded pulse combustor tailpipe to increase the residence time in the high-temperature zone for enhanced combustion of fines, to provide multiple air staging for NO_x control, to facilitate furnace start-up without an auxiliary start-up burner, and to provide boost pressure to the shroud air for mixing enhancement,

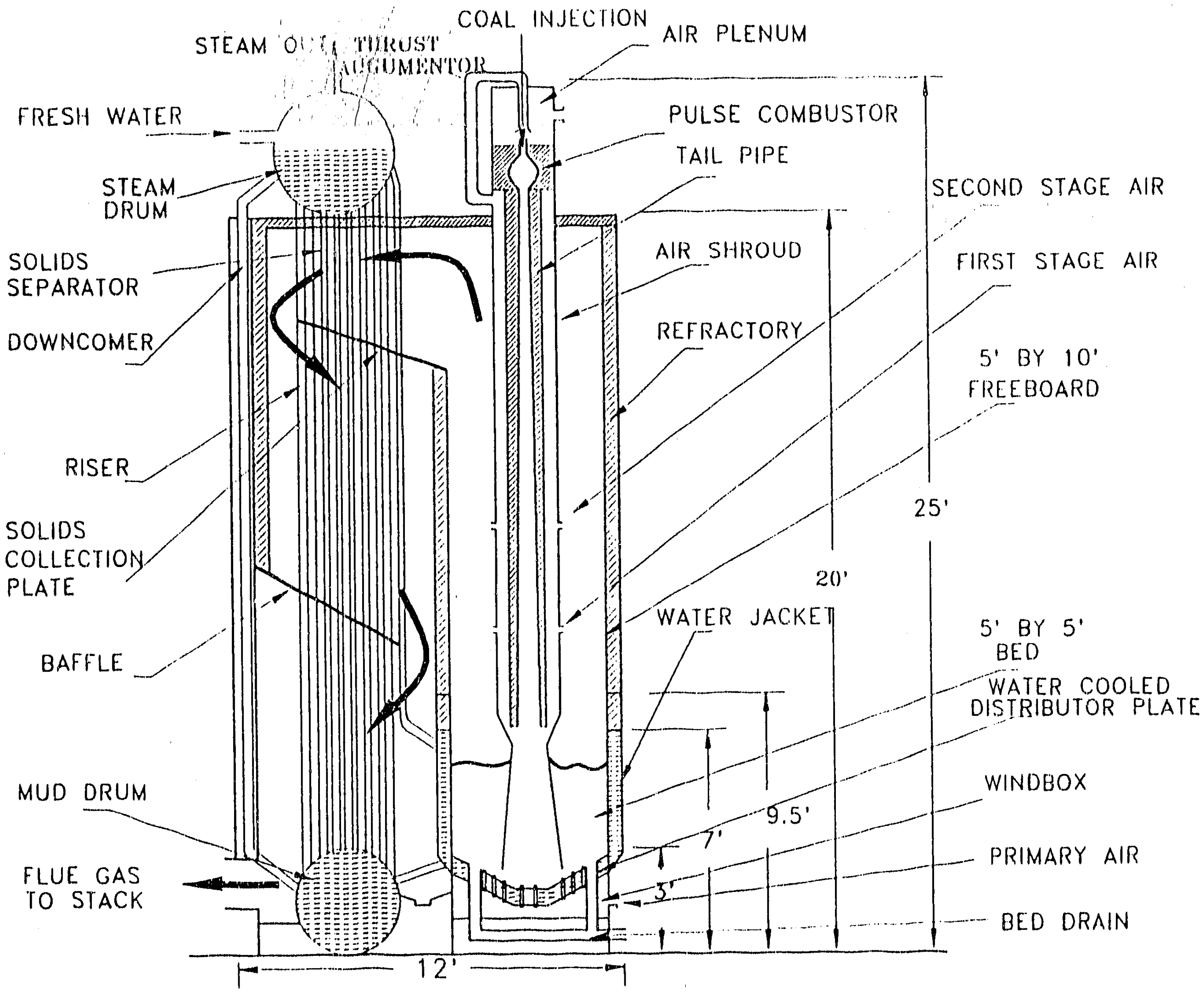


FIGURE 5-3: CONCEPTUAL DESIGN FOR THE PAFBC BOILER

- baffles in the convective pass to decrease gas bypassing,

- a bed drain to facilitate rock removal,

- an expanded freeboard section to decrease gas velocity, increase gas residence time and decrease elutriation,

- a water-cooled distributor plate to control bed temperature as well as to reduce thermal stresses; a sloping design to prevent solid dead zones, and

- a tight arrangement so that the boiler subsystem is compact and the pallet dimensions of about 20′ x 12′ x 10′ permit shop fabrication, truck transportation and installation within the vertical space usually available in boiler rooms.

A preliminary conceptual process and instrumentation diagram is shown in <u>Figure 5-4</u>. It includes the usual complement of FD fan, ID fan, coal and sorbent bins, baghouse, feedwater pump, screw feeders, bed removal conveyor, bed drain and fly ash collection drums, and also a coal classifier. The coal is first introduced into a standpipe type classifier. Here, air supplied from a fan entrains the fines for injection into the pulse combustor and the coarse coal falls into a hopper. The coarse coal is then mixed with limestone and fed overbed into the fluid bed using a screw injector. The coal feed rate is regulated by the coal metering screw based on the steam demand signal from the steam drum pressure controller. The limestone metering screw is ratio-controlled against the coal feed rate. City water is pumped into the steam drum through a water-treatment module. A level control is used to regulate the water in-flow to the drum. Bed drain is accomplished by means of a water-cooled screw conveyor and the drain rate is controlled based on bed pressure drop.

Data points comprise water/steam side and fire-side flows, pressures, temperatures, compositions, and loads. These are input to a data acquisition computer for scanning, data analysis, data storage, and activation of control

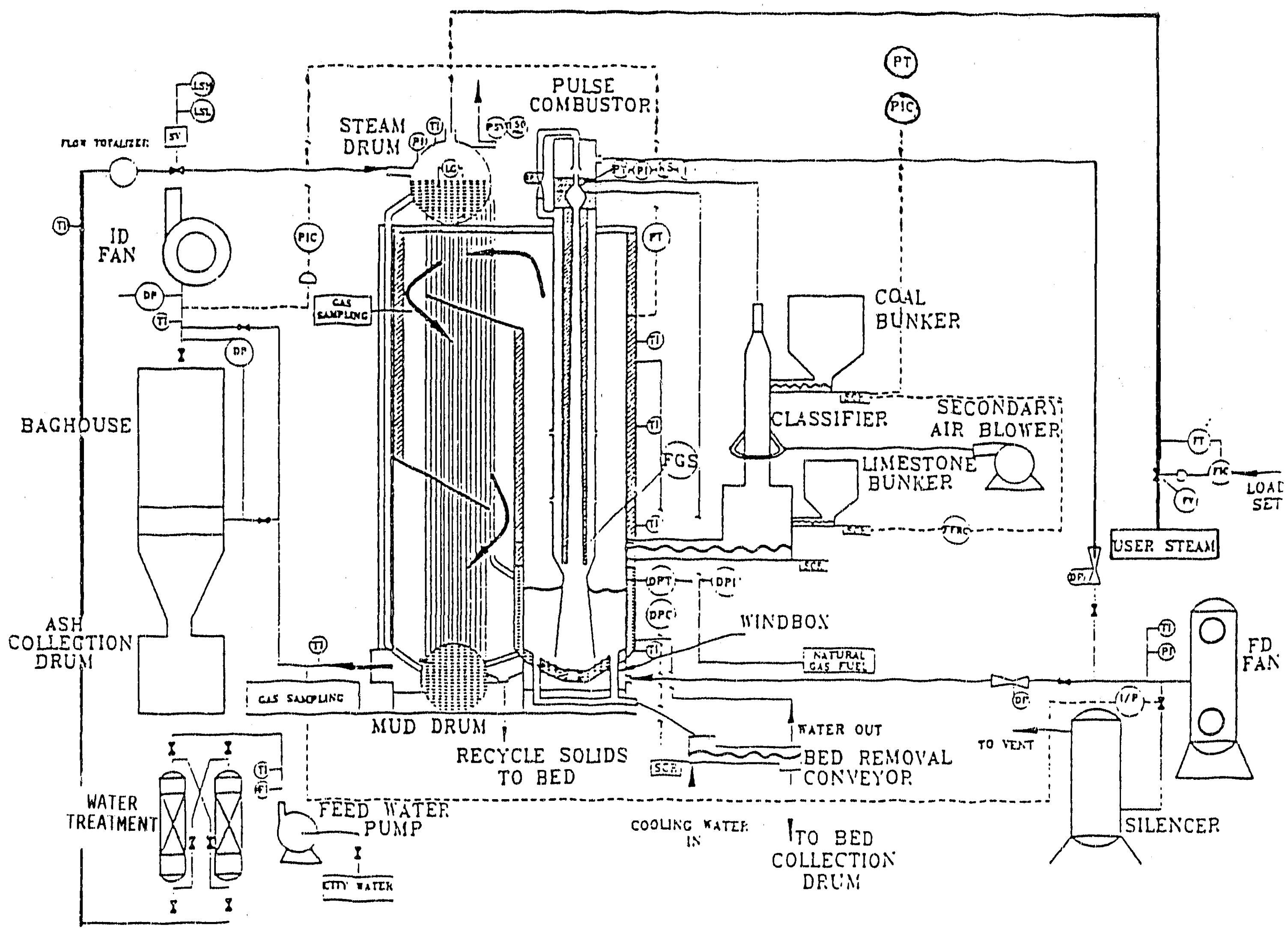


FIGURE 5-4: CONCEPTUAL PAFBC UNIT P&ID

systems. Performance calculation programs will be developed to provide on-line monitoring and evaluation capability. Control systems will be designed and tested for automatic, reliable, and operator-free operation.

A preliminary listing of the nominal facility design parameters and selected equipment specifications is given in **Table 5-1**.

5.3 COAL DRYING APPLICATION

The objective is to develop an adiabatic PAFBC design for integration into a coal-drying operation and evaluate the performance, reliability, maintainability, controllability, operability, cost effectiveness, environmental compliance, and safety of the PAFBC system.

The PAFBC system is to be sited in a coal preparation plant operated by Island Creek Corporation (ICC). The plant uses a Heyl Patterson (H&P) fluid-bed dryer for thermally drying coal. The H&P dryer operates under negative pressure, in which drying gases are drawn from a heat source through a fluidized drying chamber and a primary dust collector to the induced draft fan. The induced draft fan discharges into a wet scrubber for cleaning the exhaust gases. The heat source is a coal-fired stoker unit. The dryer is rated at 20 TPH evaporation and the stoker is rated at 75 MMBtu/hr. It is proposed to partially retrofit the stoker air heater with a 15 MMBtu/hr PAFBC air heater (~ 10,000 PPH steam equivalent). The PAFBC configuration provides the following advantages:

- does not require highly beneficiated coal to meet environmental regulations,
- can use unbeneficiated, crushed, refuse coal in the fluid bed and refuse coal fines headed for the coal pond in the pulse combustor,
- high combustion and sulfur capture efficiencies,
- low NO_x and CO emissions,

TABLE 5-1: NOMINAL FACILITY DESIGN PARAMETERS AND SELECTED EQUIPMENT SPECIFICATIONS FOR PAFBC BOILER APPLICATION

Bed Area:	25 feet^2 (5′ x 5′)
Bed Height:	36 inches
Furnace Height:	16 feet
Total Test Facility Height:	20 feet
Steam Rate:	10,000 lb/hr
Steam Condition:	Saturated @ 150 psig
Coal Feed Rate:	1200 lb/hr
Limestone Feed Rate:	360 lb/hr
Superficial Velocity:	7 ft/s
Bed Temperature:	1550°F
Furnace Outlet Temperature:	~ 375°F
Oxygen in Flue Gas at Furnace Outlet:	~ 3%
Forced Draft Fan Rating:	3,000 SCFM @ 75" WC
Induced Draft Fan Rating:	4,500 SCFM @ 30" WC
Coal Feeder Rating:	2,000 lb/hr
Limestone Feeder Rating:	500 lb/hr
Bed Ash Conveyor Rating:	750 lb/hr
Feedwater Pump Rating:	25 gpm @ 200 psig
Furnace Water Wall Surface Area:	~ 100 ft^2
Coal Feed Size:	~ 1/2" x 0
Limestone Feed Size:	~ 1/8" x 0
Pulse Combustor Firing Rate:	~ 4 MMBtu/hr
Classifier:	1/2" x 30 mesh coarse, 30 mesh x 0 fines

- fuels flexible,

- low capital and operating costs, and

- rapid start-up and load following.

Three different configurations for the dense fluidized bed portion of the PAFBC were examined:

- water-jacketed fluidized bed,
- air-cooled tubes embedded in the fluidized bed,
- adiabatic fluidized bed.

All three configurations were to employ overbed feed of coarse coal into the fluidized bed and fine coal-fired pulse combustor.

Configuration 1 involves a steam circuit, Configuration 2 involves a compressed air circuit, and Configuration 3 deals with the use of high excess air level to operate the fluidized bed in an almost adiabatic mode. Based on an evaluation of the three configurations, it was decided to select the third configuration. The advantages of the adiabatic configuration (Figure 5-5) are:

- Simple design, fabrication and installation - no steam circuit and no compressor circuit.

- Minimum modification of the dryer system required for PAFBC retrofit.

- Lower capital and O&M costs than those of Configurations 1 and 2.

The disadvantages of this option are:

- Bulkier PAFBC unit - larger footprint or cross-sectional area required to operate at nominal (~ 7 ft/s) superficial gas velocity in the bed.

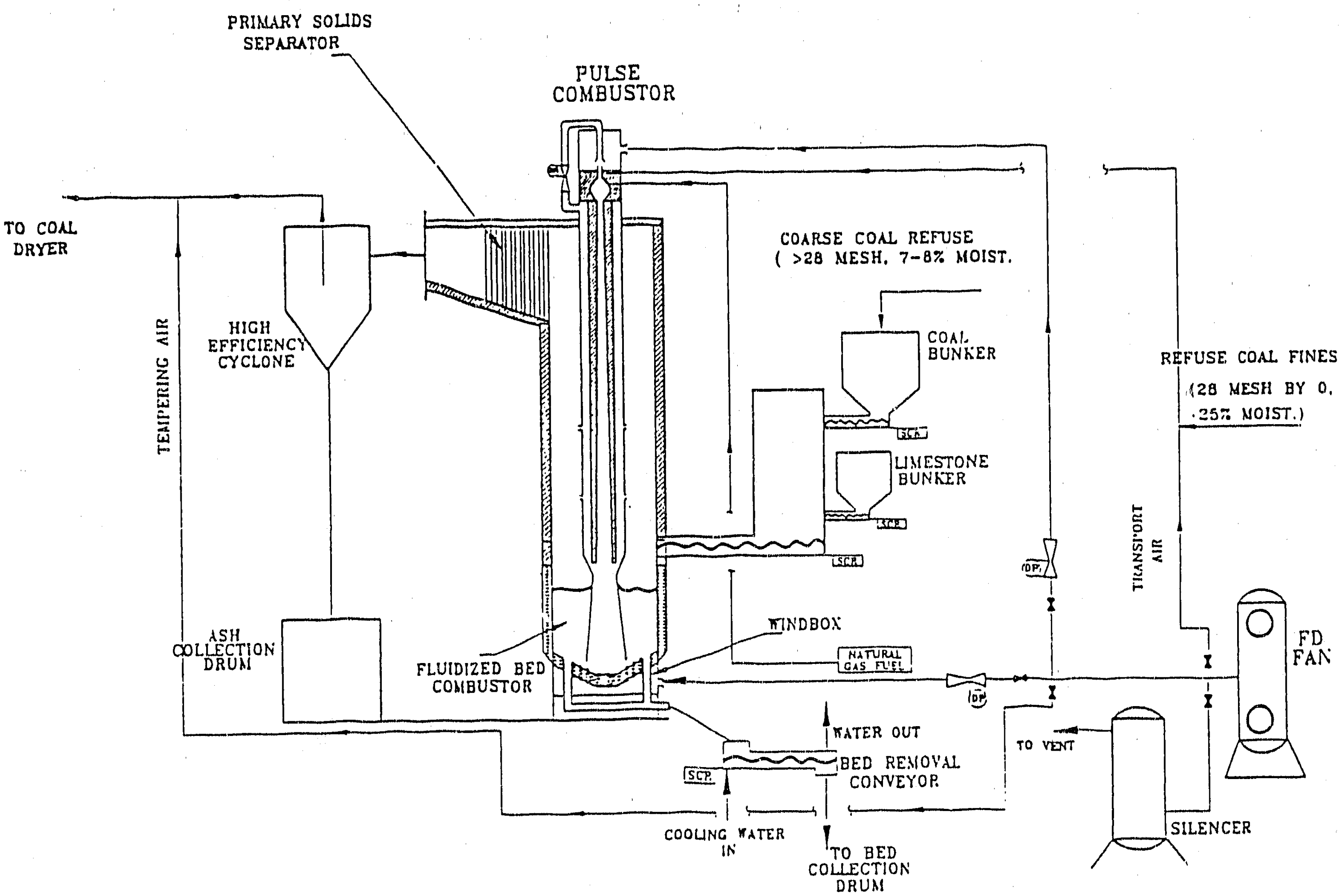


FIGURE 5-5: CONCEPTUAL PAFBC UNIT CONFIGURATION #3 FOR COAL DRYING

- Higher excess air level operation could translate into higher emissions (gaseous and particulate) levels.

Preliminary design calculations indicated that for a 15 MMBtu/hr firing rate, under nominal PAFBC operating conditions (1550°F bed temperature, 7 ft/s superficial gas velocity, 3-foot bed height, and bituminous coal), a bed area of about 61 sq. ft. would be required. This translates approximately into a plan cross-section of 8 x 8 feet or a furnace shell diameter of 9 feet. From a fabrication and cost standpoint, the circular geometry is considered superior and is therefore selected here. A schematic of the conceptual design for the PAFBC air heater is shown in **Figure 5-6**. The design incorporates:

- A refractory-lined furnace shell to minimize heat loss.
- An expanded freeboard section to decrease gas velocity, increase gas residence time and decrease elutriation.
- An air-shrouded pulse combustor tailpipe to increase the residence time in the high-temperature zone for enhanced combustion of fines, to provide multiple air staging for NO_x control, to facilitate furnace start-up without an auxiliary start-up burner, and to provide boost pressure to the shroud air for mixing enhancement.
- An inertial solids separator for in-furnace solids disengagement.
- A sloping distributor design to prevent solid dead zones.
- A bed drain to facilitate rock removal.

The PAFBC system (Figure 5-5) includes the usual complement of FD fan, coal and sorbent bunkers, screw feeders, bed drain and fly ash collection drums, bed removal conveyor, and a high efficiency cyclone. The control system proposed comprises furnace temperature controllers, individual dryer temperature controllers, and dampers in flue gas duct to adjust the heat input to match the evaporative load changes.

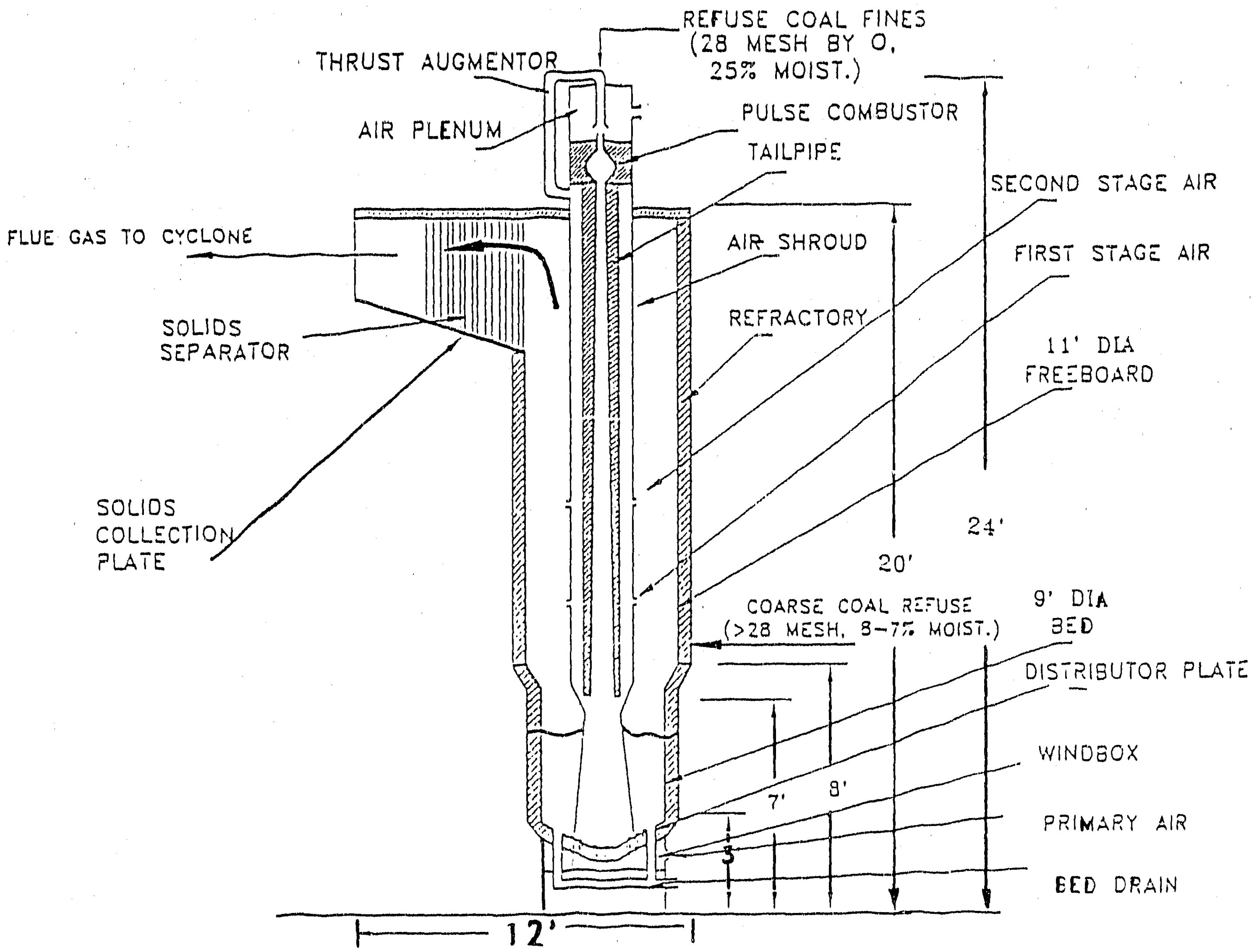


FIGURE 5-6: CONCEPTUAL DESIGN FOR THE PAFBC COAL-DRYING OPERATION

The PAFBC system (Figure 5-5) includes the usual complement of FD fan, coal and sorbent bunkers, screw feeders, bed drain and fly ash collection drums, bed removal conveyor, and a high efficiency cyclone. The control system proposed comprises furnace temperature controllers, individual dryer temperature controllers, and dampers in flue gas duct to adjust the heat input to match the evaporative load changes.

The dryer inlet temperature is controlled by dampers in the tempering air and PAFBC flue gas ducts. This control is actuated by a thermocouple at the dryer outlet. The temperature leaving the dryer is set to give the desired final surface moisture and then produces it automatically. The coal feed rate is regulated by the coal metering screw based on the PAFBC flue gas temperature controller. The limestone metering screw is ratio-controlled against the coal feed rate. Bed drain rate is controlled based on bed pressure drop.

Data points comprise fire-side and tempering air flows, pressures, temperatures, compositions, and loads. These are input to a data acquisition computer for scanning, data analysis, data storage, and activation of control systems. Performance calculation software will be developed to provide on-line monitoring and evaluation capability. Control systems will be designed and tested for automatic, reliable, and operator-free operation.

A preliminary listing of the nominal facility design parameters and selected equipment specifications is given in **Table 5-2**.

TABLE 5-2:
NOMINAL FACILITY DESIGN PARAMETERS
AND SELECTED EQUIPMENT SPECIFICATIONS
FOR COAL-DRYING APPLICATION

Bed Diameter:	9 feet
Bed Height:	36 inches
Freeboard Diameter:	11 feet
Furnace Height:	20 feet
Total Test Facility Height:	24 feet
Coal Feed Rate:	1200 lb/hr
Limestone Feed Rate:	360 lb/hr
Superficial Velocity:	7 ft/s
Bed Temperature:	1550°F
Furnace Outlet Temperature:	1550°F
Temperature After Tempering:	850 - 1050°F
Oxygen in Flue Gas at Furnace Outlet:	~ 3%
Forced Draft Fan Rating:	13,000 SCFM @ 75" WC
Coarse Coal Feeder Rating:	1,500 lb/hr
Limestone Feeder Rating:	500 lb/hr
Bed Ash Conveyor Rating:	750 lb/hr
Coal Feed Size:	> 28 mesh and 28 mesh x 0
Limestone Feed Size:	~ 1/8" x 0
Pulse Combustor Firing Rate:	~ 4 MMBtu/hr
Fine Coal Feeder Rating:	500 lb/hr
Cyclone Efficiency:	> 50% for 4 μm cut size

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