FE-1726-17A
Distribution Category UC-90e

ENGINEER, DESIGN, CONSTRUCT, TEST AND EVALUATE A PRESSURIZED FLUIDIZED BED PILOT PLANT USING HIGH SULFUR COAL FOR PRODUCTION OF ELECTRIC POWER

PHASE I - PRELIMINARY ENGINEERING

ANNUAL REPORT

MARCH 1, 1976 THROUGH FEBRUARY 28, 1977

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Power Systems Division
Wood-Ridge, New Jersey 07075

March 15, 1977

Prepared for the United States
Energy Research and Development Administration

Under Contract No. EX-76-C-01-1726

ABSTRACT

Work performed from March 1, 1976 to February 28, 1977 to Engineer and Design a Pressurized, Fluidized Bed Pilot Plant using high sulfur coal for production of electric power is summarized. A conceptual design of a 500 MW commercial power plant is described. Plant efficiencies of 40% are projected. The preliminary performance and design arrangement of the PFB Pilot Plant are presented, with comparisons tabulated between the latter and the commercial plant. Also described are supporting technological test programs and results, covering heat exchanger performance and corrosion/erosion resistance of candidate materials for heat exchanger and turbine application. Design was completed and construction begun for the Small Gas Turbine/Pressurized Fluidized Bed (SGT/PFB) operating parameters rig which fully simulates the pilot plant operating environment. Fabrication of heat exchanger tubes, and SGT/PFB components is described.

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Section 1.0

INTRODUCTION AND EXECUTIVE SUMMARY

1.1 INTRODUCTION

Production of clean, cost-competitive electric power from coal requires advances in combustion and power conversion technology. One promising approach to improved power cycle efficiency involves application of a Pressurized Fluidized-Bed (PFB) Combustor for combustion of high sulfur coal in the presence of a sulfur sorbent material. Bed temperature is controlled to remain below 1750°F by removing heat from the PFB with heat exchanger tubes using a portion of incoming compressed air as coolant, while the balance of compressed air is used for combustion. The coolant air is heated close to bed gas temperature and mixes with the products of combustion after they are cleaned of particulates but prior to entering the gas turbine expander. The reduced percentage of turbine gas directly involved in coal combustion results in substantially less gas to be cleaned of particulates.

The most obvious application of the PFB combustor to commercial, base load power production is in a combined-cycle system. The PFB combustor, in this concept, will supply energy to a gas turbine-generation unit, and a waste heat boiler at the exit of the gas turbine system will generate steam for a steam turbine-generator unit. A simplified flow diagram for the air-cooled PFB combined cycle system is shown in Figure 1.1.

The main objective of this program is to evaluate the commercial potential of a power generating concept that includes the pressurized, fluidized-bed combustion of coal in conjunction with a combined gas-steam turbine cycle. The capability to burn high-sulfur coal in an environmentally acceptable manner is also a major objective. The program involves conceptual commercial design, supporting experimental work, and the design, construction and operation of a PFB pilot plant which can be used to evaluate the commercial concept.

The pilot plant will be located at Wood-Ridge, New Jersey and will utilize the existing MOD POD 8 Total Energy Power Generating Station. Where applicable, existing systems and equipment for materials receiving, laboratories and facilities will be used for the pilot plant program.

The major tasks of the program are summarized as follows:

a. Execute a conceptual design for a central station power plant consisting of a PFB combustor with a combined cycle power conversion system.

b. Complete a preliminary design of a pilot plant suitable for simulating and evaluating the central station design concept. Supporting experiments to provide technical data for the pilot plant design will be conducted.

c. Design and construct the PFB pilot plant.

COMBINED CYCLE PILOT PLANT SIMPLIFIED FLOW DIAGRAM

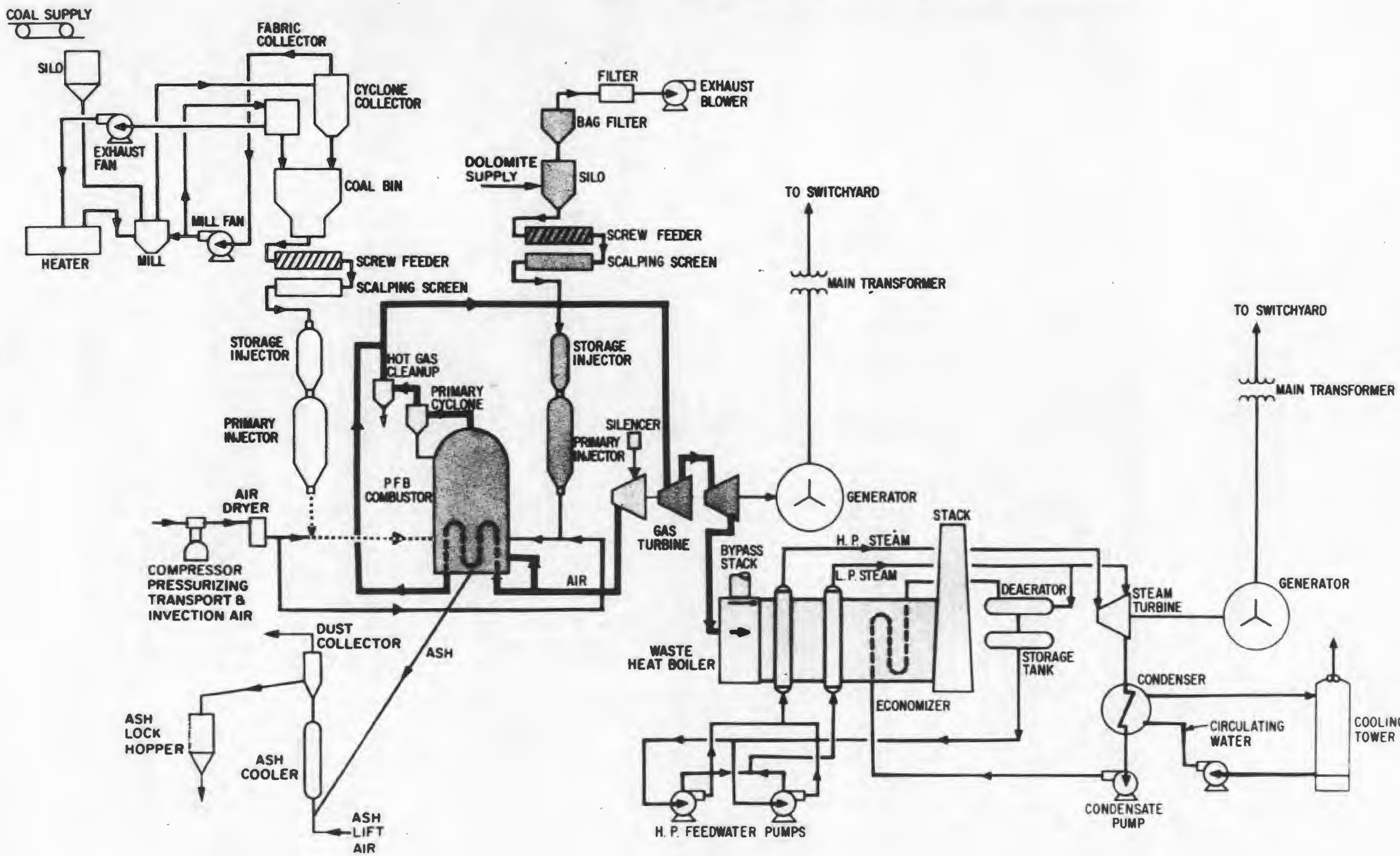


Figure 1.1

d. Conduct a test program with the pilot plant to assess the validity of full-scale design concept, to identify design or component characteristics, to establish operating characteristics under nominal and off-design running conditions, and to provide a firm engineering base for full-scale plant development decisions.

e. Provide engineering assessments of the commercial potential of the PFB concept for central station electric power production and major design specifications for a plant using high-sulfur (>3 percent by weight as received) coal while meeting applicable environmental standards.

1.2 EXECUTIVE SUMMARY

A comprehensive program to perform engineering analyses and design evaluations of both commercial and pilot PFB power plants, conduct related technology support experiments and design, construct and operate a PFB pilot plant using high sulfur coal for the generation of electric power was initiated in March 1976 under support of the Energy Research and Development Administration. The work is being performed by Curtiss-Wright Corporation, Power Systems Division, Wood-Ridge, N.J., with major supporting studies being supplied by Dorr-Oliver Corporation, Stamford, Connecticut and Stone and Webster Engineering Corporation, Boston, Mass. Progress during Phase I-Preliminary Engineering is reported herein, involving performance of conceptual design, analytical evaluation of commercial and pilot PFB power plants and execution of technology support experiments.

This report summarizes the activities of the five technical tasks of Phase I during the annual reporting period.

The power plant configuration selected for the application of the pressurized fluidized bed (PFB) process for direct combustion of high sulfur coal ($>3\%$) in a combined gas turbine/steam turbine cycle includes:

a. gas turbines to provide compressed air for coal combustion (1/3 of the airflow) and air cooling in the PFB heat exchanger ($\sim 2/3$ of the airflow).

b. recombination of the total compressor airflow after heating for expansion in the compressor drive turbine and further expansion in a power turbine which drives an alternator.

c. gas turbine waste heat recovery in a steam boiler which powers a steam turbine/alternator.

The selected power plant configuration limits the hot gas flow which must be passed through a particulate clean-up system to approximately 1/3 of the total gas turbine flow and reduces the concentration of corrosive combustion products in the recombined turbine gas stream to 1/3 of the concentration which exists in the combustion gas exiting the PFB.

Performance analysis and conceptual design of a 500 MW commercial power plant have identified a modularized plant arrangement with three pairs of gas turbines, each pair driving a 100 MW alternator for a total of 300 megawatts (MW). Six waste heat boilers (one for each individual gas turbine) produce steam which drives one 200 MW turbine/alternator. The modularized arrangement provides low plant heat rate over a broad output range (below 50%) and high proportion of plant power availability during major component scheduled or unscheduled maintenance.

Conceptual designs are presented for major plant components including PFB combustor and heat exchanger, gas turbines, particulate removal system, materials handling systems (coal, sulfur sorbent, ash), steam system and control system.

PFB Pilot Plant preliminary performance and design arrangement are presented. Relationship of the pilot plant to the commercial plant is discussed.

The Site Evaluation for the Pilot Plant has been completed, covering the following areas:

Real Estate

Site Master Plan

Climatological, Meteorological Data

Foundation Investigation and Soil Analysis

Site Survey and Local Resources Survey

Site Transportation Study

A real estate report prepared for the proposed site contains a description of property, arrangements made for services, entry permits to perform site investigations, outstanding encumbrances, (i.e. liens of easements) and ownership.

A site master plan was developed showing the areas to be used for construction, availability of utility services, temporary routing of utilities, temporary roads and storage area.

Tables have been prepared on a number of important climatological parameters based on 20 - 40 years of available data. They include normals and extremes of temperature, precipitation and snow, averages of relative humidity, wind speed frequency distribution, wind speed extremes, precipitation amounts for storms of various durations, design dry bulb and wet bulb temperatures, etc.

Soil geotechnical investigation including test borings was completed to determine soil characteristics and location of water table, and to provide a basis for the types of support for the major structures and equipment in the pilot plant.

A topographic survey was made to establish baselines and benchmarks to be used for construction of the pilot plant. The existing railroads, roads and utilities were investigated to determine their capacities and conditions, and what arrangements are to be made regarding permits, licenses, etc.

A study was made to determine the adequacy of local transportation systems - trucking, railroads, etc.

Technology support tests are planned to evaluate PFB air-cooled heat exchanger performance, heat exchanger turbine materials; corrosion and erosion resistance in simulated PFB systems environments, and small gas turbine/pressured fluidized bed (SGT/PFB) test rig operating parameters.

Initial effort to fabricate PFB heat exchanger tube specimens and bundles led to successful development of brazed and cast finned tube exchangers and suitable NDT inspection techniques to facilitate tube manufacture.

Tube specimens of varying external fin density were tested for heat transfer performance in an existing coal fired AFB at Dorr-Oliver Corporation over a range of test parameters and preliminary results are presented. A heat exchanger tube bundle was designed and manufactured for later installation and test in the NRDC PFB Combustor at Leatherhead, England, for heat transfer and system performance evaluation.

Test loops including several tubes of different materials were manufactured for later installation in Dorr-Oliver client operated fluid beds with bed media and operating conditions, from erosion and corrosion consideration, spanning the PFB operating environment. Materials erosion and corrosion screening tests were performed on existing test rigs to evaluate relative performance of selected PFB tube materials and turbine materials.

Progress was made in the design and fabrication of a SGT/PFB operating parameters rig to evaluate PFB combustor/heat exchanger performance at full simulated pilot plant operating conditions and to evaluate PFB combustor coal and sorbent injection and ash discharger characteristics, particulate removal efficiency in the 1st and 2nd stage clean-up, gas turbine erosion characteristics and operating parameters under simulated pilot plant control conditions, including plant start-up and shutdown.

Section 2.0

TASK 1 - PRELIMINARY ENGINEERING

2.1 COMMERCIAL PLANT CONCEPTUAL DESIGN

2.1.1 Plant Cycle Selection and Performance

2.1.1.1 Cycle Selection

The power plant configuration chosen for commercial utility application of the pressurized fluidized bed process for direct combustion of high sulfur coal in a gas turbine is a combined cycle in which sixty percent of the electrical power is generated by gas turbines and the remainder by a waste heat recovery steam turbine system. Schematically this process is described in Figure 1.1. Air is delivered by the gas turbine driven compressors to the PFB combustors where one third flows through the distributor plate tuyeres for combustion and two-thirds flows through cooling tubes in the beds to hold the bed temperature at the design value, initially selected as 1650°F. Coal and a sulfur sorbent, dolomite, are fed to the beds by air injection guns in proportions selected to achieve the required level of sulfur retention. Flue gas from the combustors is passed through particulate removal systems for cleanup, then mixed with the heated air from the bed cooling tubes for delivery to the compressor drive turbines. After expansion through the compressor drive turbines and the power turbines which drive the generators, the exhaust gas flows through waste heat recovery boilers which produce steam for a conventional steam turbine driving another generator.

Design parameters for the system resulted from initial studies of parametric cycle analyses, and of the relative impact on cost and dependability of gas turbine pressure ratio, control flexibility, and overall system complexity. An excerpt of the cycle analyses, Figure 2.1 shows the effects of fluidized bed temperature on thermal efficiency and specific power output at two levels of PFB pressure for a steam cooled bed system as used in the ECAS studies and the selected air cooled bed system. An efficiency advantage is shown for the air cooled concept, increasing as the turbine inlet temperature is raised by operating the PFB at a higher combustion temperature. There is a small difference in heat rate between seven atmospheres and ten atmospheres pressure which was weighed against the greater complexity of ten to one pressure ratio gas turbines. It was decided to use a single spool gas generator of seven pressure ratio which does not require variable geometry blading or air bleed to start and accelerate to design speed and load. This design also is less expensive and more reliable because of fewer stages of blading and reduced starting power. A slightly higher power level results from the lower pressure ratio, but this is a small advantage which would have an insignificant effect on cost.

For the same power output, the plant with air cooled beds uses more than three times as much air as that with steam cooled beds and produces the bulk of its power from the gas turbines rather than the steam system. The fuel consumed by both plants is nearly the same, however, so the air which must be used for combustion is also nearly equal. The air cooled bed design takes advantage of this relationship by segregating the two flows, combustion air and coolant, before the PFB and mixing the combustion product gas after cleanup and the heated air to supply the turbines. In this arrangement the levels of corrosive and

COMBINED CYCLE ANALYSIS
FOR
PRESSURIZED FLUIDIZED BED COMBUSTION

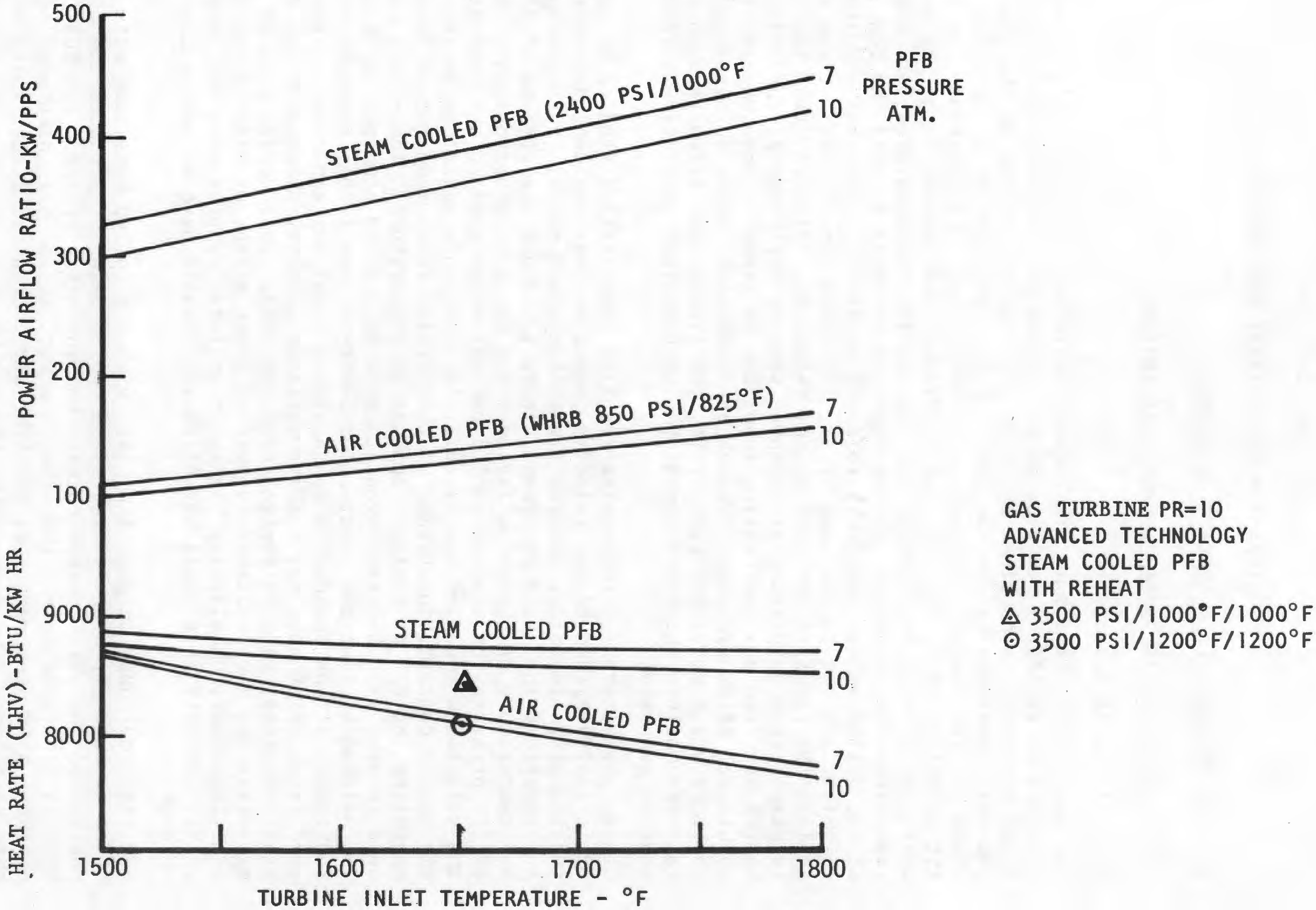


Figure 2.1

erosive elements in the turbine gas stream for the same gas cleanup method are reduced by a factor of three, at least, thus assuring substantially longer operating life for the gas turbine units.

Another item of selection affecting cost is the use of free power turbines. Because these turbines are not mechanically connected to the compressor drive turbines, they can be made to rotate in either direction, clockwise or counterclockwise, such that two can be connected to a single generator for twice the output. They are also adaptable to other services, such as 50 Hz electrical power generation, and, because of their mechanical independence, they and the generators they drive do not add to the system starting load.

2.1.1.2 Overall Performance

The commercial plant was designed to produce approximately 500 MW total plant output. In this power class electrical generators are generally available in two pole configurations which operate at 3600 rpm for 60 Hz. Direct drive power turbines at that speed are limited by structural and gas leaving velocity requirements to about eight feet last wheel diameter, which, at temperatures available from the PFB combustion process, results in a power output per turbine of about 50 MW. To achieve the desired total plant output a modular concept was employed, using three gas turbine modules, each of which consisted of a 100 MW generator driven in double-ended arrangement by two gas turbines. Each gas turbine has its own PFB combustor and waste heat recovery boiler and can be operated independently. All steam generated is delivered to a single steam turbine generator unit which develops forty percent of the total plant power. The gas turbines have single spool heavy duty industrial type gas generators with two stage free power turbines. The fluidized beds operate at seven atmospheres pressure and a constant bed temperature of 1650°F. Design temperature at first turbine inlet is 1600°F. The design heat and material balance is shown diagrammatically in Figure 2.2 and tabulated in Table 2.1. By virtue of the modular construction of the plant and the complete independence of the gas turbine units, plant power can be reduced by two methods, (1) reducing turbine inlet temperature and (2) shutting down individual gas turbines. The heat rate obtainable as power level is reduced by the second method is illustrated in Figure 2.3.

Incremental reductions in plant power by unit shutdown cause only slight increases in heat rate down to as low as half power. While it is unlikely that such wide fluctuations in demand will occur in a base load plant, there is another advantage to the modular concept in that major components can be removed from service for scheduled or unscheduled maintenance without complete loss of plant output, and in some cases without appreciable reduction in plant efficiency as shown on Table 2.2.

The extensive experience of Dorr-Oliver with fluidized beds in varied applications has established that beds can be shut down for periods up to two days with loss of approximately 150°F per day of inside temperature. After such a brief shut down period a bed can be restarted on coal and brought to full load in about half an hour. Except for the steam turbine, therefore, the plant would be applicable to intermediate or peaking duty. If only one module were maintained on base load operation,the steam turbine would be at temperature and

MATERIAL AND ENERGY BALANCE DIAGRAM
PFB COMMERCIAL PLANT

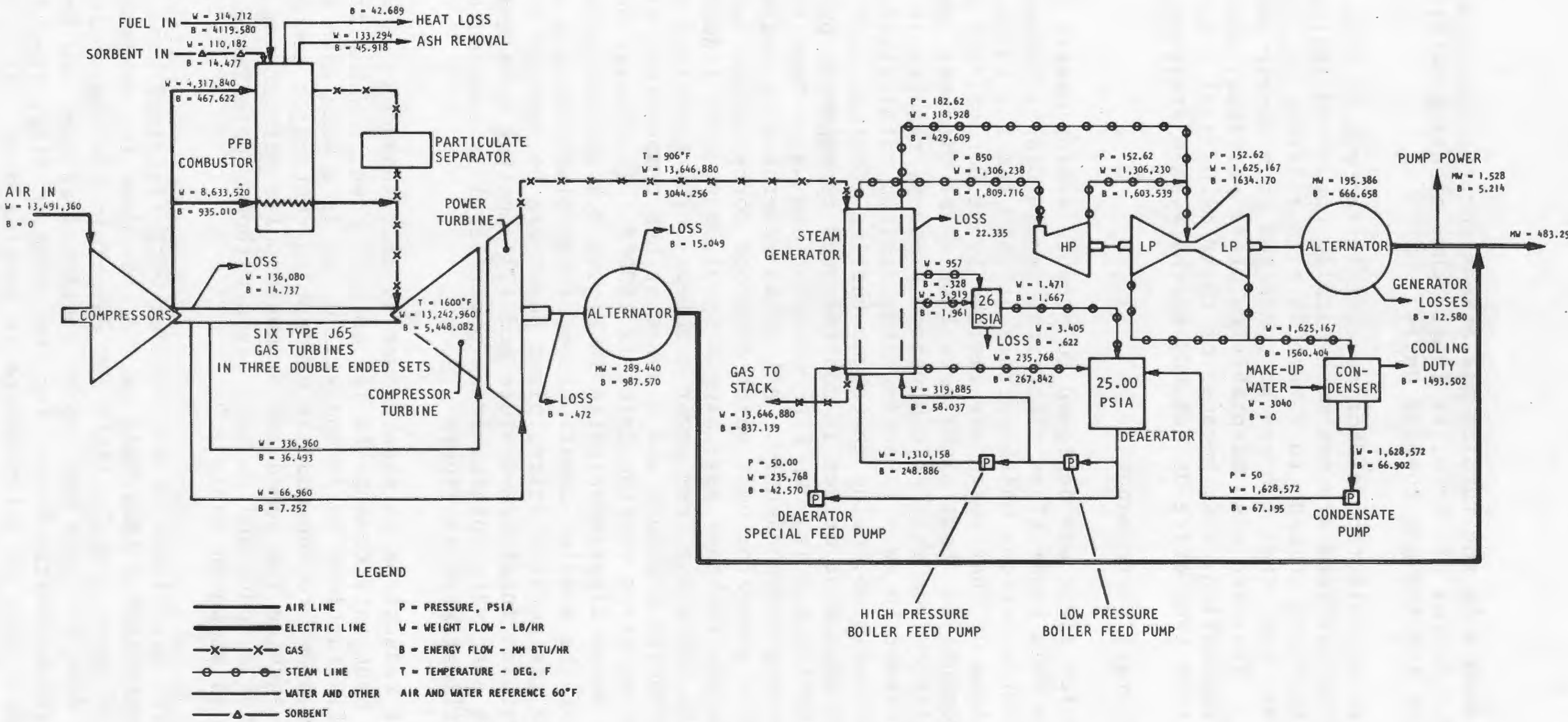


Figure 2.2

TABLE 2.1

COMMERCIAL PLANT

DESIGN HEAT AND MATERIAL BALANCE

	MATERIAL LB/HR	ENERGY MM BTU/HR	%	POWER M.W.
FEEDS				
COAL	314,712	4119.580		
AIR	13,491,360	0.0		
SORBENT	110,181.6	14.477		
MAKE-UP WATER	3,405	0.0		
SUBTOTAL	+13,919,658.6	+4,134.057	+100	
PRODUCTS				
STACK GAS	13,646,880	-837.139		
BED OFF-TAKE	133,293.6	- 45.918		
SUBTOTAL	-13,780,173.6	-883.057	-21.36	
COOLING DUTIES				
STEAM TURBINE CONDENSER		-1493.502	-36.13	
WORK				
GAS TURBINE GROSS WORK		-987.570		289.440
STEAM TURBINE GROSS WORK		-666.658		195.386
AUXILIARY POWER		+5.214		1.528
SUBTOTAL		-1649.014	-39.89	
LOSSES				
POWER TURBINE MECHANICAL LOSSES		-0.472		
GAS TURBINE ALTERNATOR		-15.049		
STEAM ALTERNATOR		-12.580		
GAS TURBINE AIR LOSS	-136,080	-14.737		
PFB HEAT LOSS (BY DIFF.)		-42.689		
STEAM GENERATOR HEAT LOSS		-22.335		
BLOW DOWN HEAT LOSS	- 3,405	-0.622		
SUBTOTAL	-139,485	-108.484	-2.62	
THERMAL EFFICIENCY 40.03%				

500 MW P.F.B. MODULAR COMMERCIAL PLANT

TURN DOWN CAPABILITY

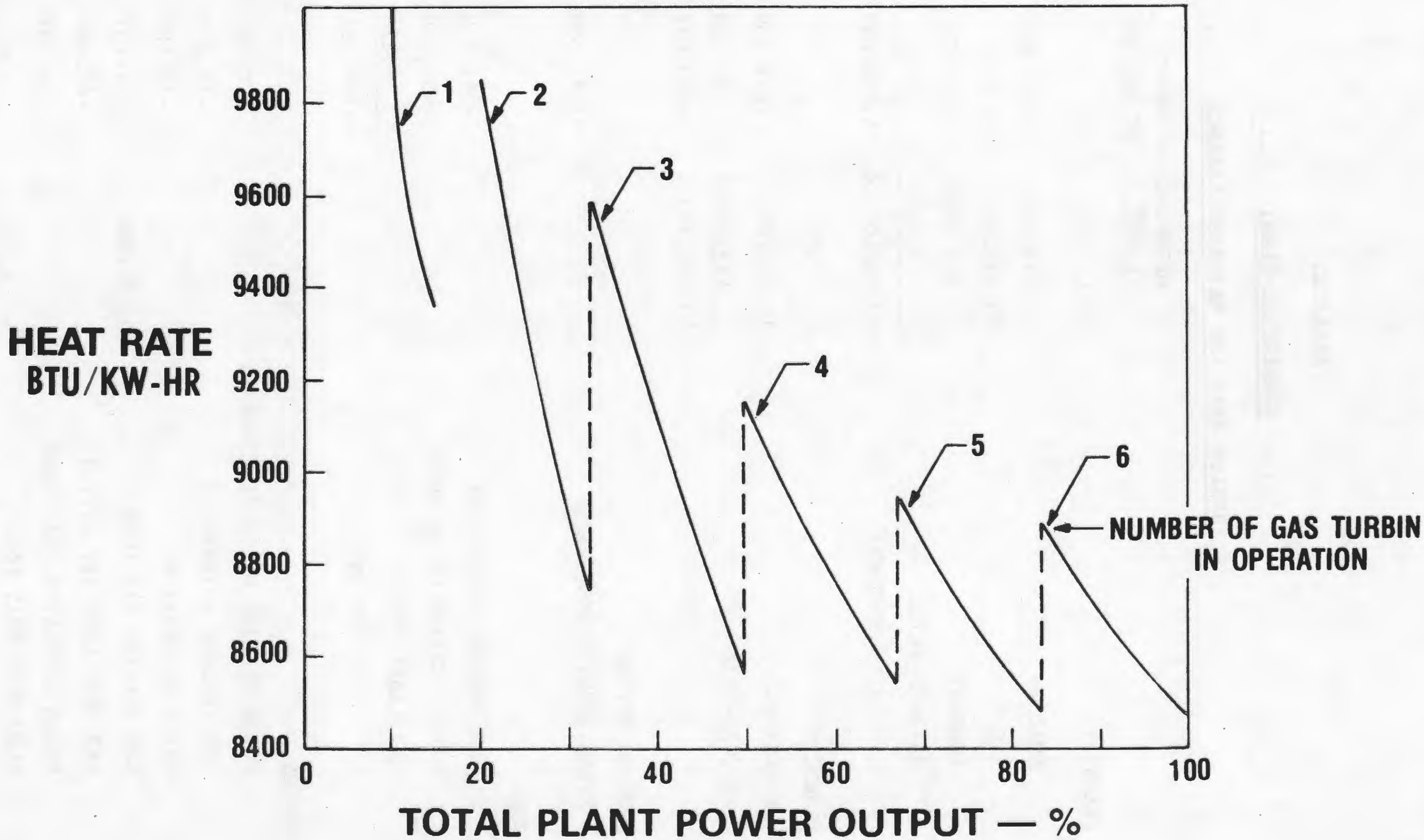


Figure 2.3

TABLE 2.2

500 MW MODULAR COMMERCIAL PLANT

POWER AVAILABILITY BASED ON MAJOR UNSCHEDULED MAINTENANCE

MAINTENANCED ITEM	POWER MV	% TOTAL PLANT POWER	HEAT RATE BTU/KW HR
GAS TURBINE	401	83	8,540
PFB/HOT GAS CLEAN-UP	401	83	8,540
WASTE HEAT BOILER	401 - 450	83 - 93	8,540 - 9,140
STEAM TURBINE	290	60	14,240
ST ALTERNATOR	290	60	14,240
GT ALTERNATOR	320	66	8,560

the remainder of the plant could be reactivated quickly to restore full operation on demand. This flexibility of operation will permit overnight or weekend reduction of load with very little penalty in efficiency and with the capability of quick resumption of load on schedule or in an emergency due to failure of other network facilities.

2.1.2 Plant Overall Arrangement

The PFB commercial base load power plant is a 500 Megawatt (net) combined cycle plant consisting of 300 megawatts generated by three double-ended generators each driven by two gas turbines, and 200 megawatts generated by a condensing steam turbine generator.

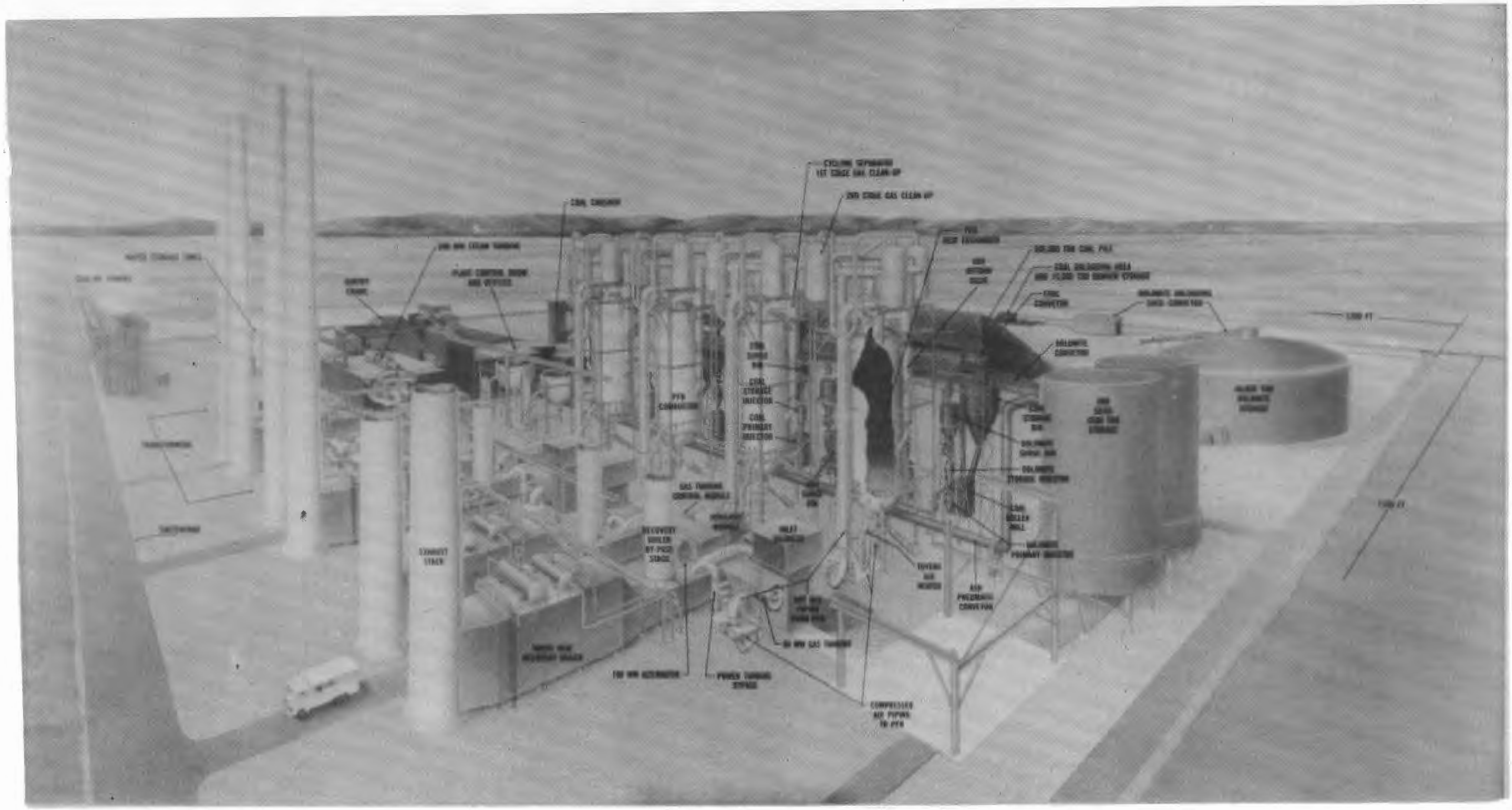
Figure 2.4 is an artist's conception of the commercial plant. Figures 2.5 and 2.6 are a plot plan of the plant and Figures 2.7 and 2.8 a plant elevation. The plant, including coal storage area, is 1,100 ft by 1300 ft. The packaging of the gas turbine and waste heat boiler system is modular. The 500 MW plant described is also representative of plants of 160 MW or multiples thereof. Furthermore, the 500 MW plant can be operated to meet a substantially reduced power demand at essentially the design point plant efficiency by shutdown of individual gas turbine units.

Complete coal and dolomite unloading and storage facilities are provided. Coal will be received from 100 car trains into below grade bunkers of 10,000 ton capacity. The station, normally fed directly from the bunkers can also be supplied from a 300,000 ton reserve pile. Dolomite will be supplied to the station from a domed storage structure of 40,000 ton capacity. Belt conveyors transport coal and dolomite from storage facilities to six PFB locations. Operating supplies of coal and dolomite are maintained at each PFB. The coal is milled to required particle size and reaccumulated for injection into the PFB. Dolomite particle size is controlled by screening prior to feeding into the bed through separate injectors.

Ash flows out of the PFB and is fluidized by 100 psig air in a vertical column. As ash is lifted up the column, surrounding water jackets cool it until it is finally drawn off through a lock hopper system and pneumatically conveyed to a 4,500 ton silo storage system where it is retained until removed from the plant.

Plant design characteristics and guidelines are shown in Table 2.3. Economic factors are given in Table 2.4 and operating and design parameters in Table 2.5. The steam turbine design characteristics are listed in Table 2.6.

Figure 2.4



CURTISS WRIGHT POWER SYSTEMS 500 MW PFB COMBINED CYCLE POWER PLANT

PFB COMMERCIAL POWER PLANT
PLOT PLAN

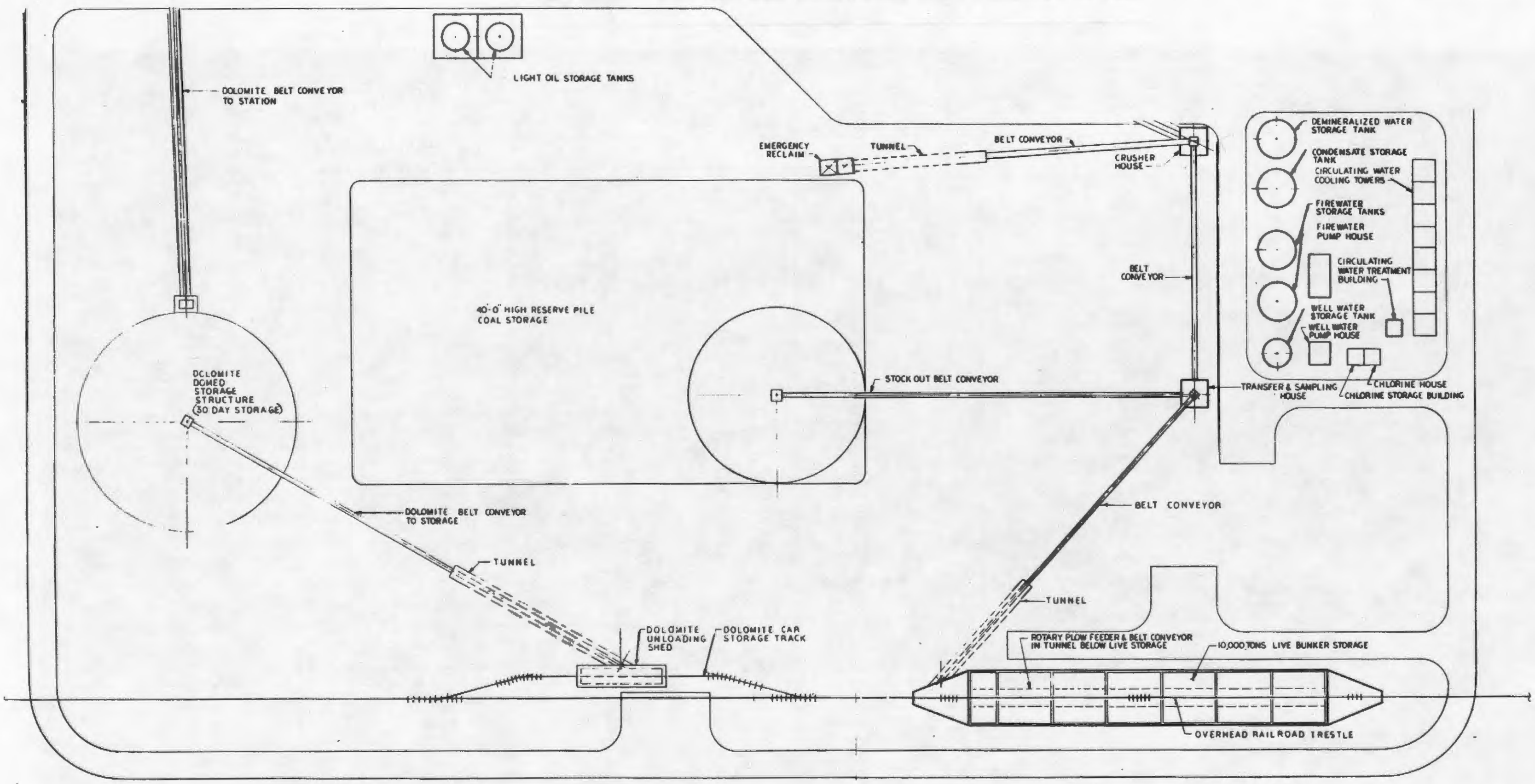


Figure 2.5

PFB-I-212C

PFB COMMERCIAL POWER PLANT
PLOT PLAN

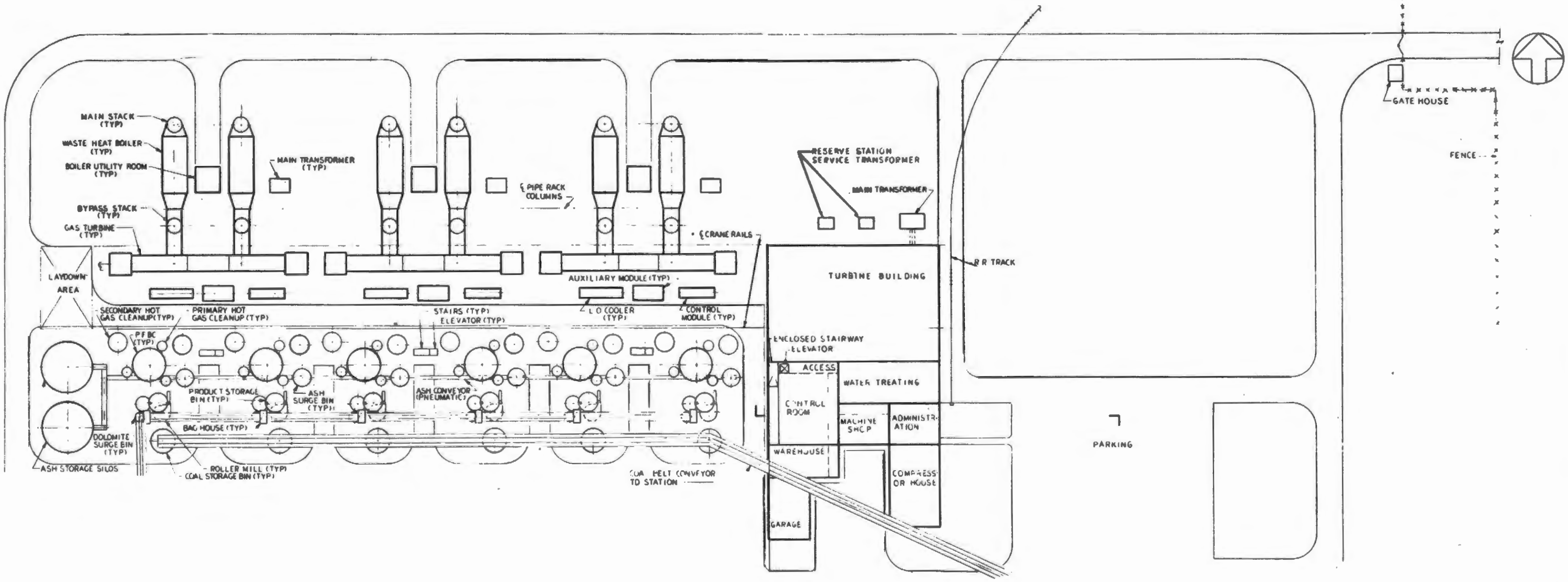
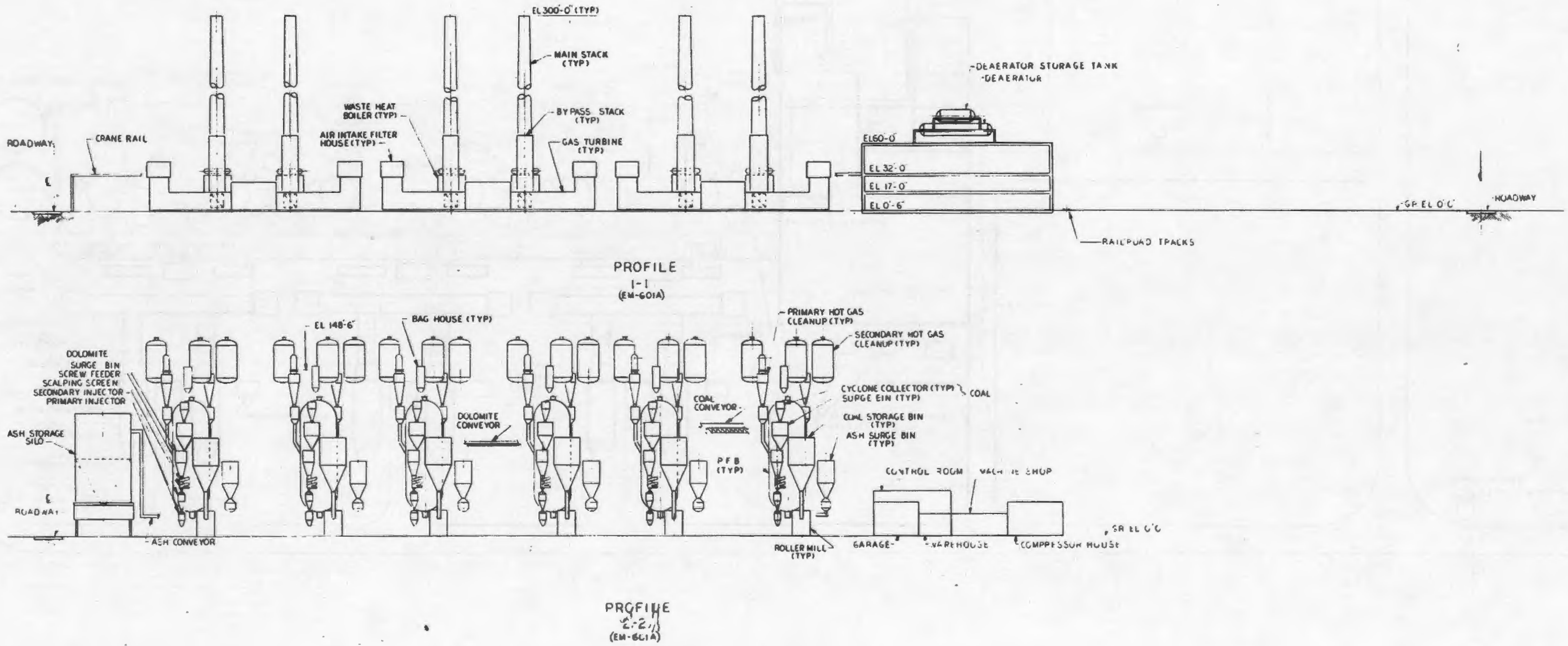


Figure 2.6

500 MW COMMERCIAL PFB POWER PLANT
SYSTEM SCHEMATIC



PFB-I-213D

Figure 2.7

500 MW COMMERCIAL PFB POWER PLANT TRANSFER SYSTEM

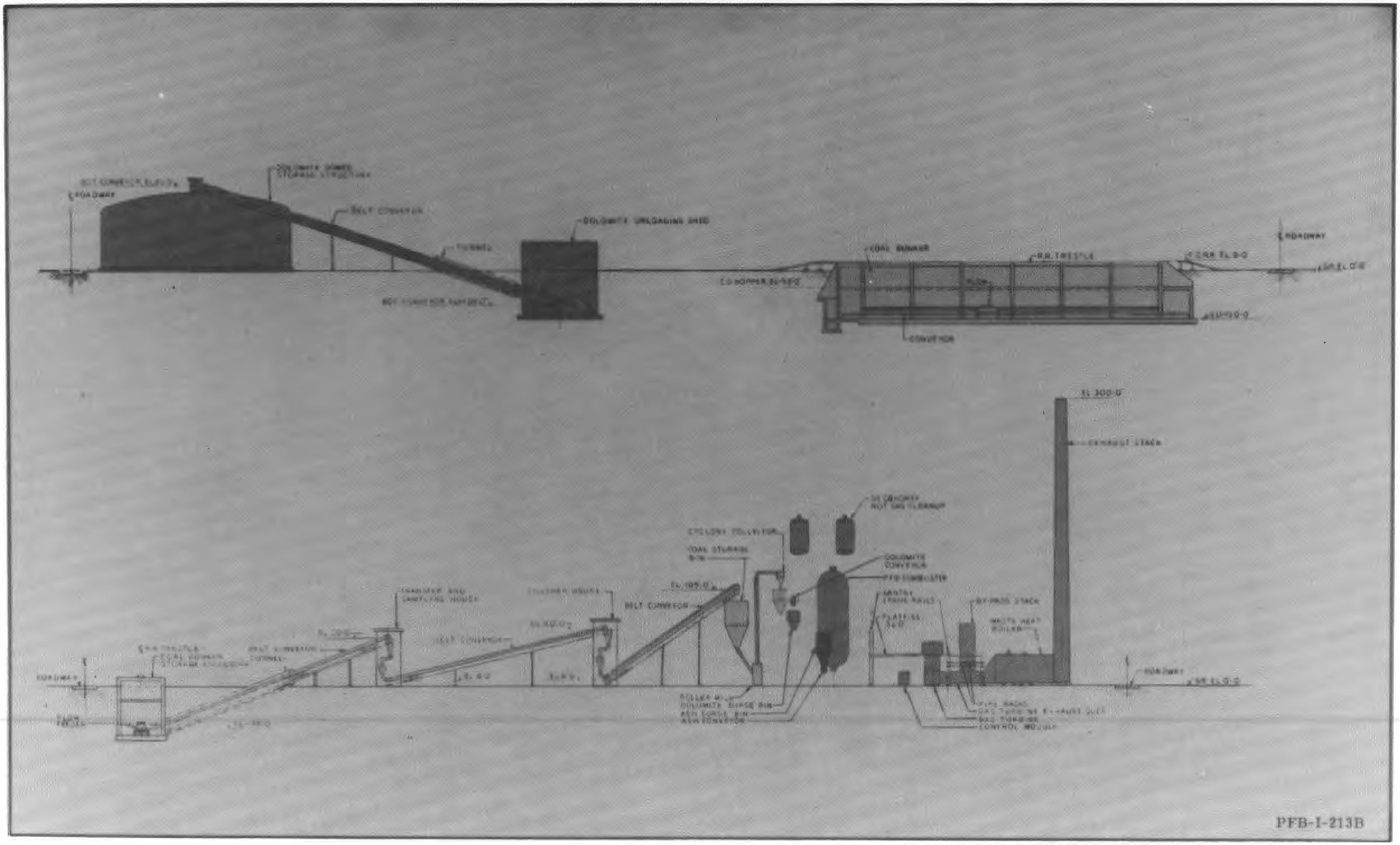


Figure 2.8

TABLE 2.3

PLANT DESIGN CHARACTERISTICS AND GUIDELINES

Plant Design Characteristics

Plant Packaging	Modular
Nominal Module Rating	160 MW
Coal Sulfur Content	> 3.0%
PFB Heat Exchanger Type	Air Cooled
Power Turbine Type	Free (Gas Coupled)
PFB Sorbent Material	Dolomite
Primary Cleanup	Cyclone
Secondary Cleanup	Rotary Flow Cyclone

General

Soil Loadings	5-6 Kips Maximum, 2-3 Kips Average
Electric Output	115 KV to Customer Switchgear
Fuel	
Bituminous	Manor No. 44 by Rail
Light Oil (startup)	Available by Rail or Truck
Sorbent	
Dolomite	U.S. No. 1337

Fuel

Coal - Manor No. 44	
Heating Value (HHV)	13,090 Btu/lb
Proximate Analysis, Wt Pct	
Moisture	0.8
Volatile Matter	23.0
Fixed Carbon	61.6
Ash	14.6
Ultimate Analysis, Wt Pct	
Hydrogen	4.3
Carbon	73.7
Nitrogen	1.4
Oxygen, by difference	1.9
Sulfur	4.1
Ash	14.6

Sorbent

Dolomite - U.S. No. 1337	
$CaCO_3$	54.2%
$MgCO_3$	44.8%
Inerts	1.0%

TABLE 2.4

PLANT ECONOMIC AND ENVIRONMENTAL FACTORS

Loading Basis	Base Load
Economic Life of Unit	30 Years
Interest Rate for Present Worth Calculations	10.5%
Annual Fixed Charge Basis	17-1/2%
Fuel Cost Over Plant Life (1983 to 2013)	\$1.63/MM Btu
Value of Incremental Capability	\$500/KW
Average Annual Capacity Factor	75%
Land Cost	\$1,000 per Acre
Noise Design Standard	NEMA D at 400 Ft
Air Pollutants Allowable	
SO_2	1.2 lb per Million Btu
NO_x	0.7 lb per Million Btu
Particulate	0.1 lb per Million Btu

TABLE 2.5

PLANT OPERATING AND DESIGN PARAMETERS

Overall Plant

Net Plant Power Output	483 MW
Plant Coal Consumption	315,000 lb/hr
Plant Heat Rate	8,524 Btu/kw/hr
Plant Overall Efficiency	40.03%

Gas Turbine Generator

Total Power Output (6 Gas Turbines and 3 Generators)	289 Net
Gas Turbine Inlet Airflow (6 Turbines)	3,748 lb/sec
GT Inlet Δ P	3"H_2O
GT Compressor Pressure Ratio	7:1
PT Exit Area (Blade Stress Limit)	35 Sq Ft
PT Exit Mach No. (Airflow Sizing)	0.35
Exhaust Pressure	10"H_2O
Exhaust Temperature	906°F
Alternator Speed	3600 rpm

Pressurized Fluidized Bed Combustor

Combustor Gas Temperature	1650°F
PFB Superficial Velocity	2.7 FPS
PFB Heat Exchanger Tube Free Space	4 In.

TABLE 2.6

STEAM TURBINE GENERATOR DESIGN CHARACTERISTICS

Throttle Conditions	800/825 psia/°F
Throttle Flow Steam	1,306,239 lb/hr
Power Output	194 MW
Exhaust Size	23" Four Flow
Exhaust Pressure	2.0 in. Hg abs
Generator Cooling	Hydrogen
Power Factor	0.90
Voltage/Frequency	22/60 kv/Hz
Excitation	Brushless

2.1.3 Component Performance

2.1.3.1 Gas Turbine Performance

The gas turbine units are based on the aerodynamic design of the CW 6515 Industrial Gas Turbine Compressor. This compressor has excellent performance at the selected pressure ratio and has an extensive development and engine service background in aircraft engines and in commercial stationary application such as, the Jet-Air Compressor and the MOD POD 8 electrical generating plant. The unit size was established by the maximum sized power turbine for 3600 rpm operation combined with acceptable power turbine leaving Mach number for good turbine efficiency. This resulted in a gas turbine having five times the airflow of the CW 6515, so the compressor design was scaled upward by that factor of flow or a linear scale of 2.236. The mechanical design was changed to an industrial type construction and provision was made to transfer compressor delivery air to the PFB and return mixed products of combustion and bed coolant to the turbine. A new two stage compressor drive turbine and a two stage power turbine both designed to industrial standards were added. New turbines were required because the turbine inlet temperature attainable in PFB operation is lower than that normally used for aircraft engines or oil fired gas turbine power plants, and the pressure losses in the PFB are considerably higher than those of conventional combustors.

2.1.3.2 PFB Performance

The pressurized fluidized bed combustor is designed to operate at a constant temperature of 1650°F with a superficial velocity of 2.7 fps. Dolomite will be used as the sulfur sorbent, with a calcium to sulfur ratio of 1.5 to assure at least 90 percent sulfur retention which, for the selected 4.1 percent sulfur coal, will result in less than 0.8 pounds/million Btu of sulfur dioxide in the plant exhaust, well below the Federal Environmental Protection limit of 1.2. The low fluidization velocity not only minimizes elutriation of bed material, ash and coal fines but also considerably reduces erosion of bed cooling tubes and permits the use of a bed heat exchanger of very high effectiveness such that turbine inlet temperature obtained by mixing bed flue gas and coolant air will be a maximum of 1600°F. One third of the compressor air to the bed is used for fluidization and combustion which results in an excess air of 33 percent. Both the high excess air and the recycling of first cyclone dust to the bed will contribute to a high combustion efficiency, expected to be in excess of 99 percent.

The bed depth was established at 16 feet to provide the required heat transfer surface area for the finned tube heat exchanger in the bed. Flue gas passes through a primary cyclone, which will return particulate matter larger than 10 micron diameter to the bed, and then through a secondary filter which is expected to separate particles larger than 2 micron size with high efficiency. The flue gas is mixed with the bed cooling air before being returned to the gas turbine expansion section.

In order to determine the range of operating conditions for the PFB design, performance of the gas turbine with PFB combustor was estimated for varying power levels and ambient temperatures. Figure 2.9 shows the compressor map with the engine operating line from synchronous idle to maximum power superimposed, indicating that the gas turbine will operate satisfactorily throughout the operating range without air bleed or variable geometry. Tabulated on Table 2.7 are significant performance data for three power levels on a standard day and for base load rating on hot and cold days. In accordance with common practice in gas turbine power systems, the heat rate is based on the lower heating value of the fuel used, i.e. on the actual heat available from the combustion process. For the selected coal, Manor No. 44, and Dolomite, Pfizer 1337, the relationship between the coal higher heating value and that used in these calculations is defined below:

<u>Fuel Heating Values Used in Analysis</u>

Coal and Sorbent Combined LHV (Btu/lb Coal)	12,737
for a. Coal HHV (Btu/Lb Coal).	13,090
b. Coal LHV (Btu/Lb Coal).	12,691
c. Change in Calorific Value for Bed Sulfation Reaction (Btu/Lb Coal).	+276
d. Change in Calorific Value for Bed Calcination Reaction (Btu/Lb Coal).	-230

Base load rating for the gas turbine is defined by turbine inlet temperature of 1600°F. Figure 2.10 shows the variation of power and fuel flow with ambient temperature at Base Load and at 90 percent and 80 percent ratings which are defined by constant temperatures of 1542°F and 1483°F respectively.

Figures 2.11 - 2.14 present the Turbine Inlet Temperature, Exhaust Temperature (to the waste heat boiler), Exhaust Gas Flow, and Coal Flow versus Gas Turbine Power for selected Ambient Temperatures. Each gas turbine and fluidized bed combustor is capable of power reduction to synchronous idle, approximately 5 MW power, without variable geometry of air bleed for surge control, although modular plant operation requires no lower than half power turndown per twin turbine module for reduction to one-sixth plant power or per individual turbine for reduction to one-twelfth of total plant power.

PFB COMMERCIAL PLANT COMPRESSOR PERFORMANCE

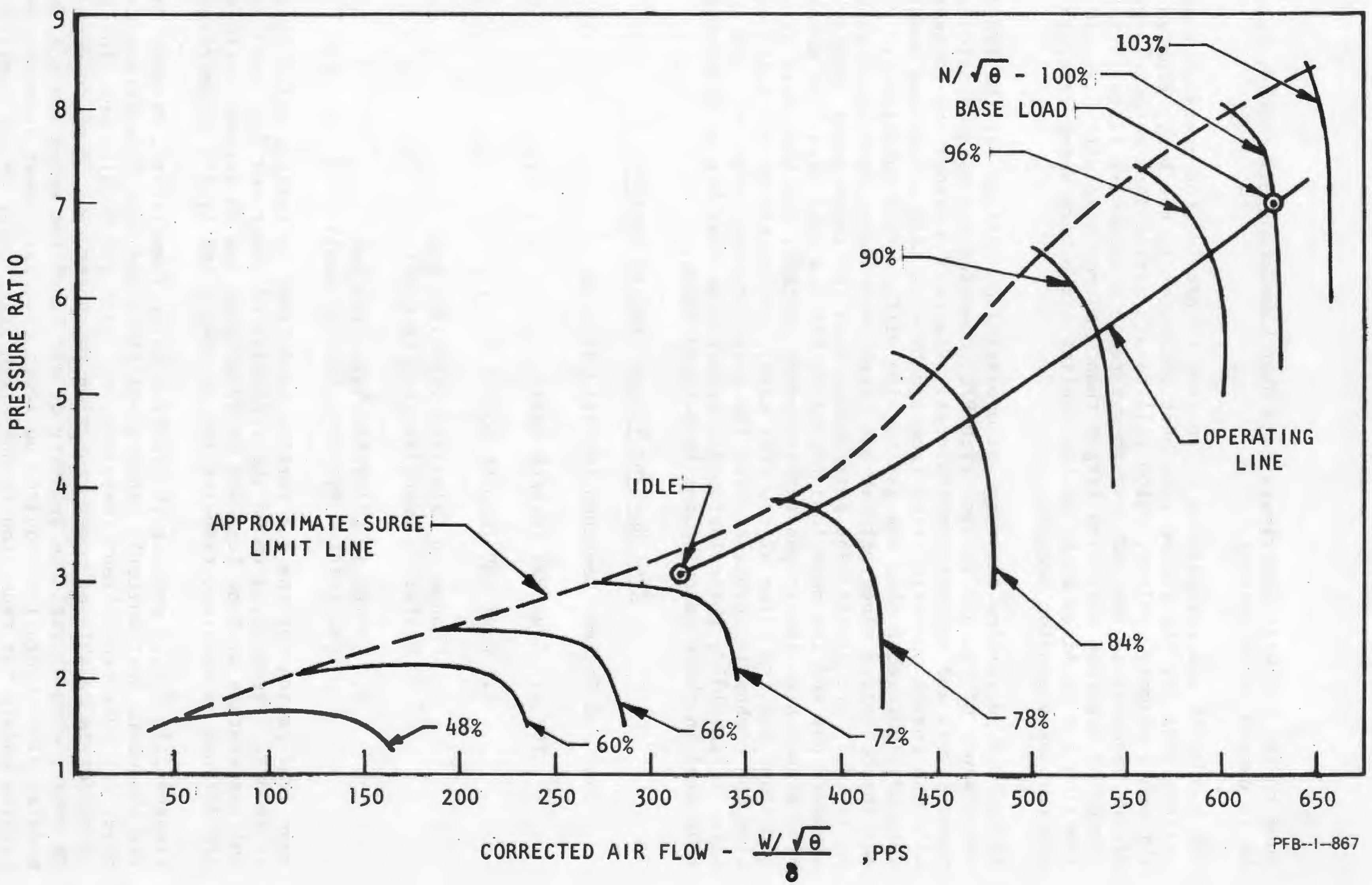


Figure 2.9

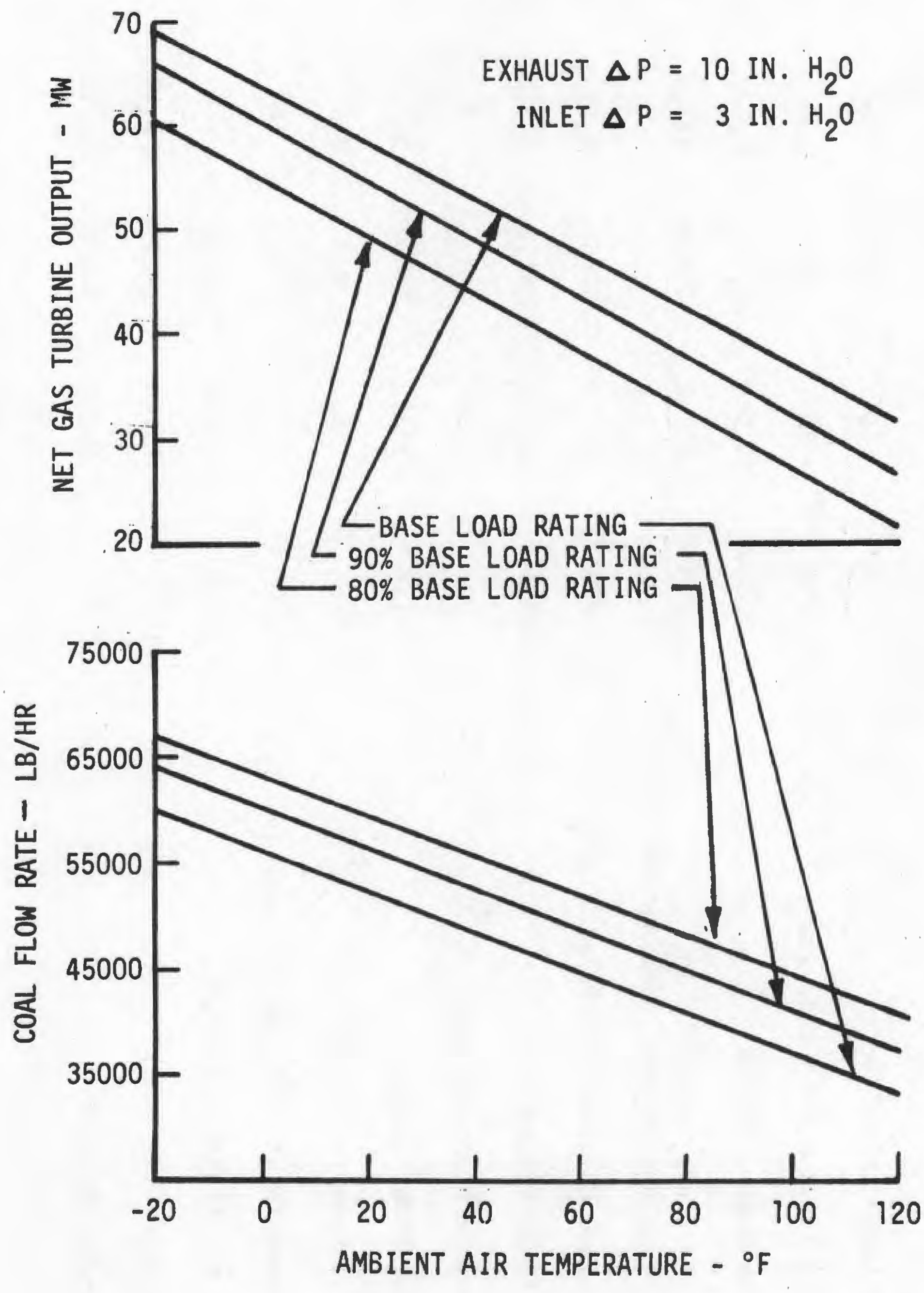
TABLE 2.7

COMMERCIAL PLANT
CYCLE PERFORMANCE DATA

For 1 Unit = 1 Gas Turbine plus 1 PFB
Overall Unit Performance at Sea Level Barometric Pressure

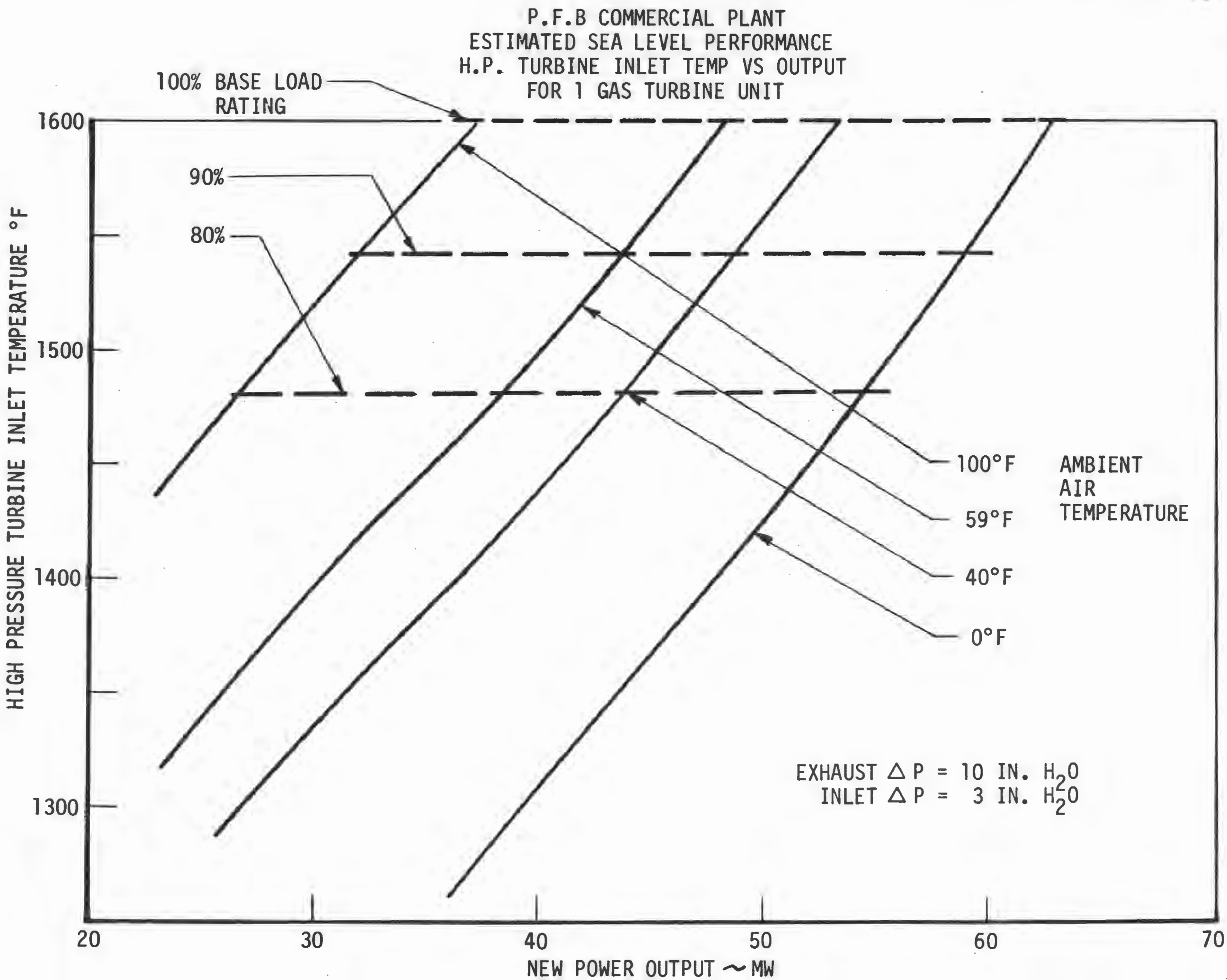
Ambient Temperature, °F	59	59	59	100	0
Percent Gas Turbine Base Load Power	100	80	60	100	100
Gas Turbine Generated, KW	48,240	38,580	28,720	36,880	63,760
Heat Release (LHV), Btu/Hr x 10^6 (Based on Coal and Sorbent Combined LHV)	668.3	571.4	476.0	568.7	806.1
Heat Loss (Bed Material Off-Take) Btu/Hr x 10^6	7.653	6.537	5.456	6.511	9.230
Inlet Airflow, Lb/sec	624.6	587.6	541.9	546.6	717.6
Inlet Pressure Drop, In. H_2O	3	3	3	3	3
Exhaust Gas Flow, lb/sec	631.8	593.2	546.0	552.6	726.6
Exhaust Gas Temeprature, °F	906	851	803	950.2	863
Exhaust Pressure Drop through Boiler, In. H_2O	10	10	10	10	10
Bed Material Off-Take, lb/sec	6.230	5.322	4.441	5.300	7.513
Coal Feed, lb/sec	14.57	12.46	10.38	12.40	17.58
Sorbent Feed, lb/sec	5.101	4.361	3.634	4.341	6.153

PFB COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
POWER OUTPUT & COAL FLOW RATE
FOR 1 GAS TURBINE UNIT



PFB-I-874

Figure 2.10



PFB-I-210

Figure 2.11

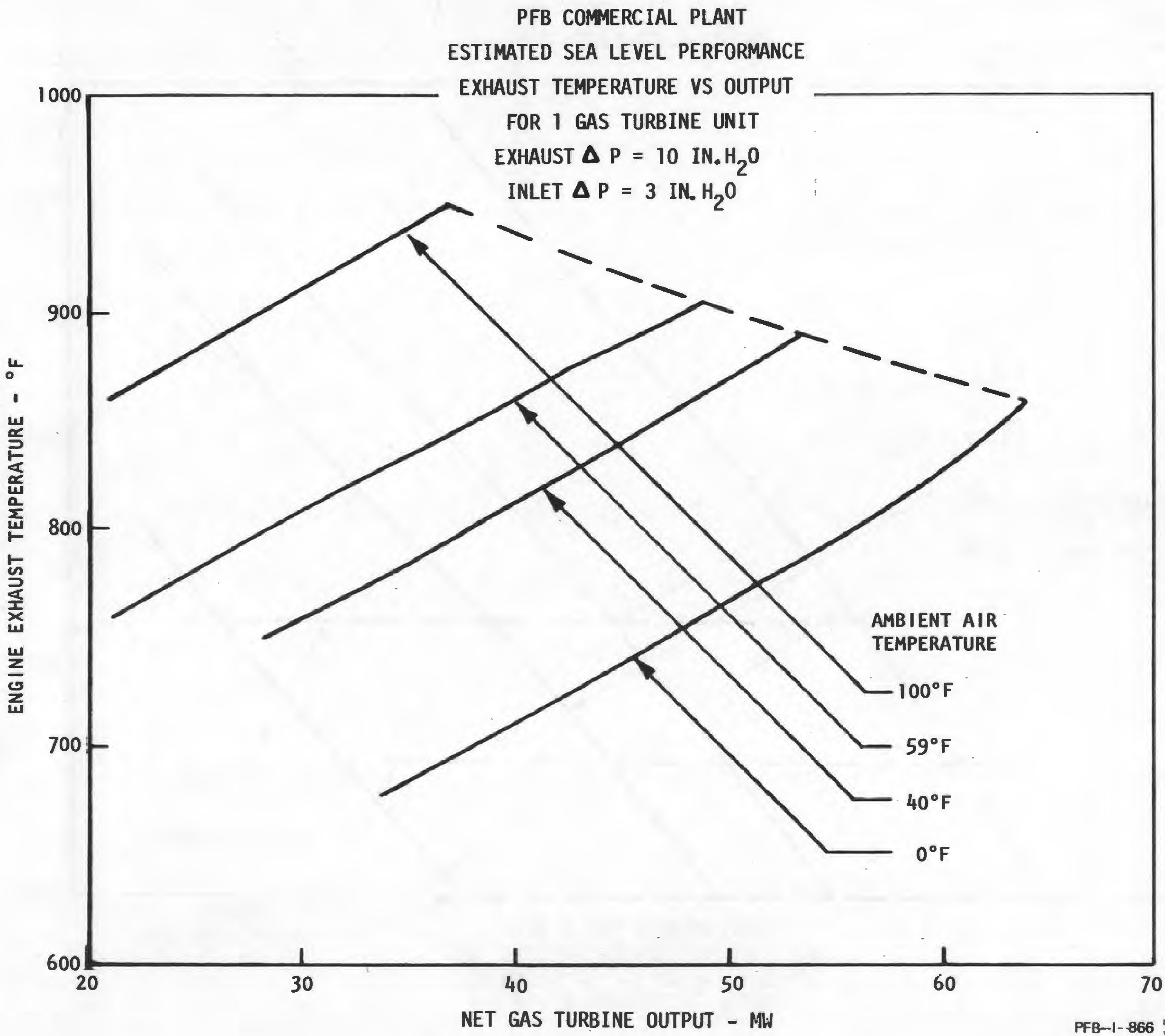

PFB COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
EXHAUST TEMPERATURE VS OUTPUT
FOR 1 GAS TURBINE UNIT
EXHAUST Δ P = 10 IN. H_2O
INLET Δ P = 3 IN. H_2O
1000
900
800
700
600
ENGINE EXHAUST TEMPERATURE - °F
20
30
40
50
60
70
NET GAS TURBINE OUTPUT - MW
AMBIENT AIR TEMPERATURE
100°F
59°F
40°F
0°F
PFB-I-866

Figure 2.12

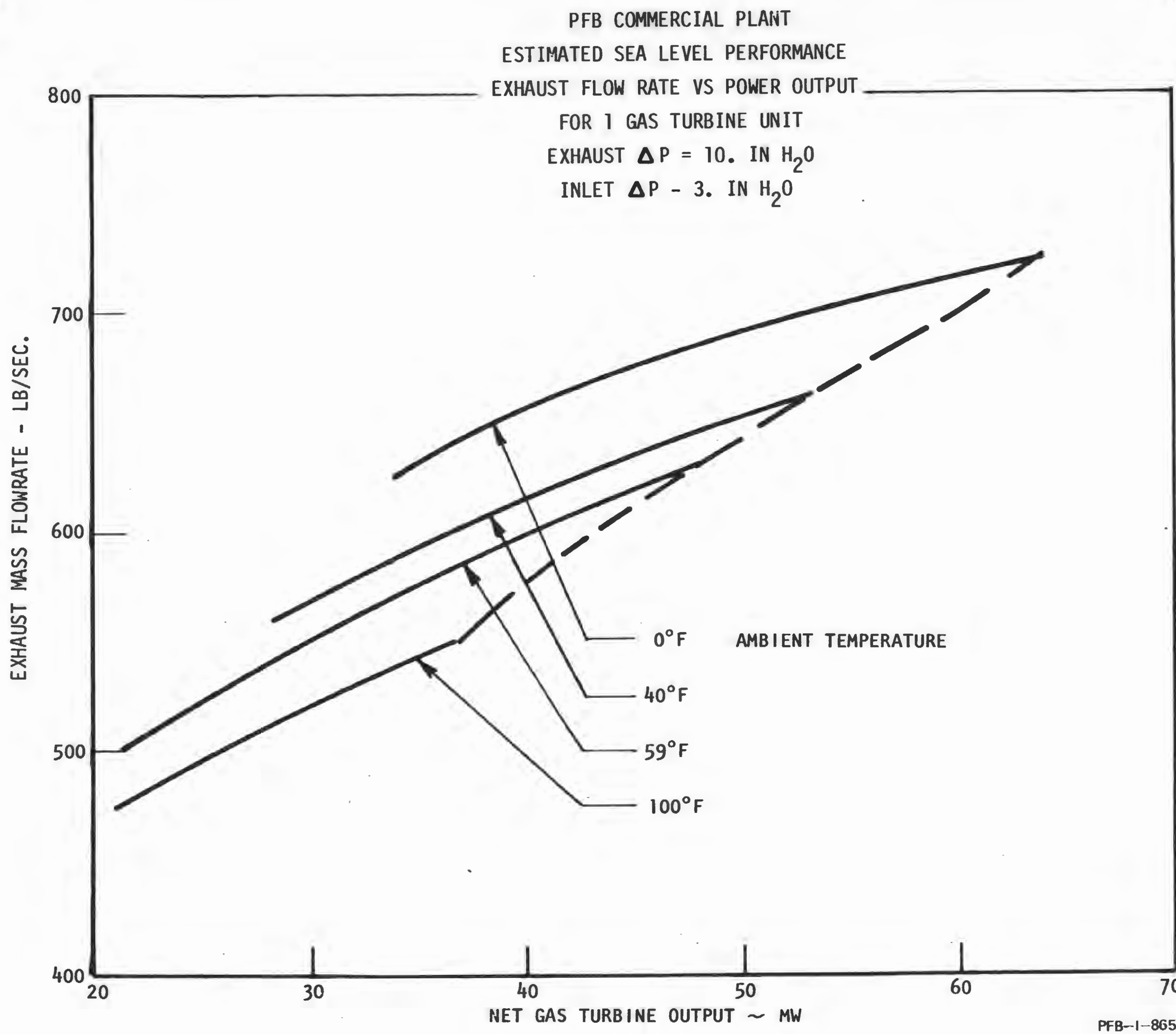

PFB COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
EXHAUST FLOW RATE VS POWER OUTPUT
FOR 1 GAS TURBINE UNIT
EXHAUST ΔP = 10. IN H_2O
INLET ΔP - 3. IN H_2O
EXHAUST MASS FLOWRATE - LB/SEC.
800
700
600
500
400
0°F
40°F
59°F
100°F
AMBIENT TEMPERATURE
20
30
40
50
60
70
NET GAS TURBINE OUTPUT ~ MW
PFB-I-865

Figure 2.13

PFB COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
COAL FLOW RATE vs POWER OUTPUT
FOR 1 GAS TURBINE UNIT

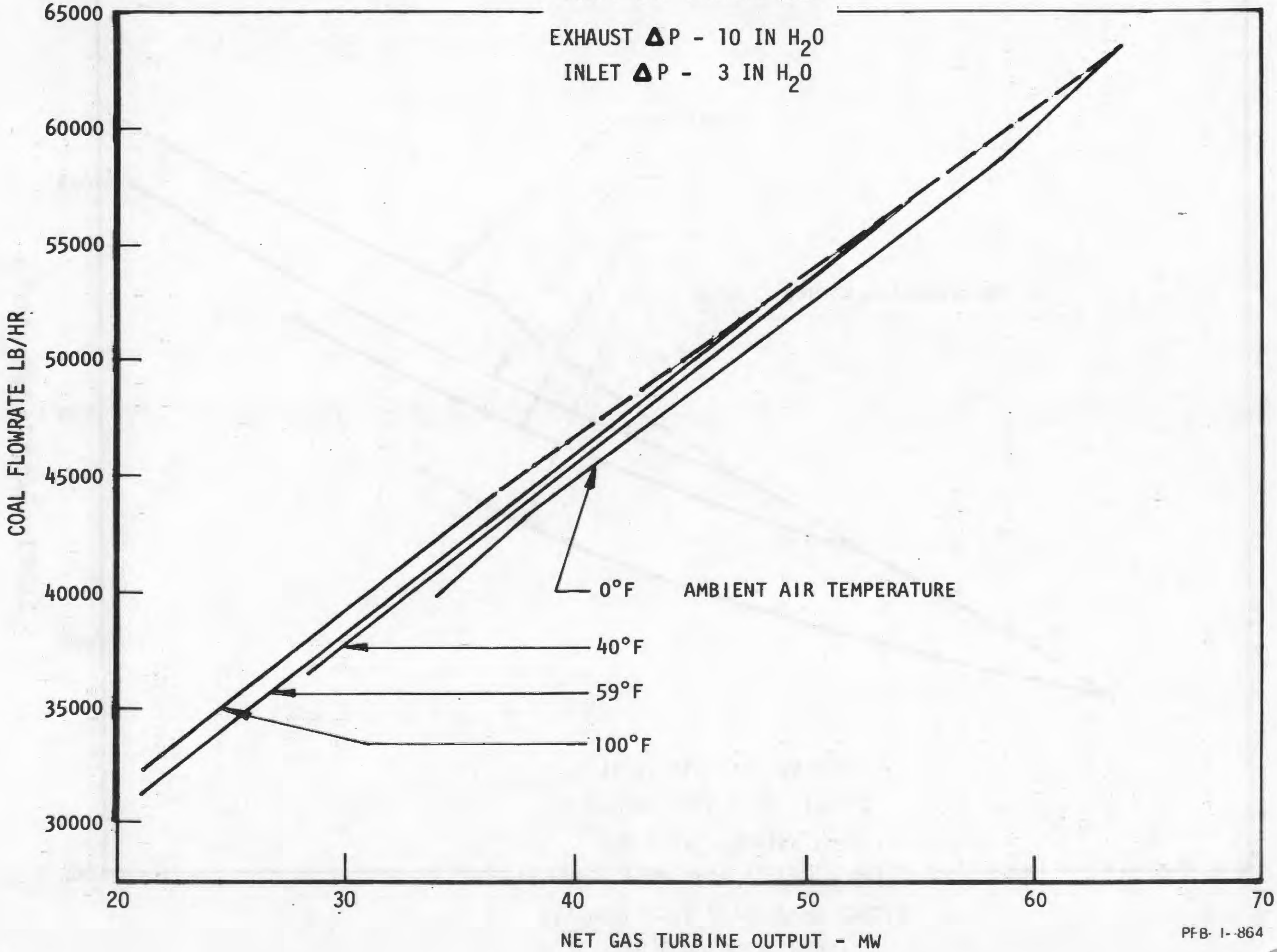


Figure 2.14

2.1.3.3 Steam System Performance

Each gas turbine exhausts into a waste heat recovery boiler which generates high pressure steam at 800 psia and 825°F and low pressure steam at 175 psia and 700°F. Steam from the six boilers is delivered to a single condensing steam turbine unit which consists of a high pressure turbine and a four flow low pressure turbine having 23 inch last blade height. A 3600 rpm alternator of about 200 MW is driven by the steam turbine. Condenser pressure for this conventional steam system was assumed to be 2 inches of mercury absolute. As part of the modular plant concept, provision is made to shut down boilers individually as the associated gas turbines are shut down. Under these conditions, with live boilers producing full rated steam pressure, temperature and flow, the steam turbine efficiency is not seriously reduced until plant power level falls below fifty percent.

2.1.3.4 Environmental Performance

Atmospheric Emissions - Six 13 ft ID, 300 ft high double-shell steel stacks will emit a total of approximately 13,500,000 lb/hr of flue gas at 274°F and an exit velocity of roughly 87 fps. The following table compares emissions of particulates, SO_2 and NO_x, to the Federal New Source Performance Standards when coal is burned.

	Total Emissions		Fed. Emission
	Lb/Hr	Lb/MM Btu	Standard, Lb/MM Btu
Particulate	199	0.048	0.10
SO_2	2,612	0.626	1.2
NO_x	876	0.21	0.70

Maximum ground level concentrations expected of particulates and SO_2 are compared to National standards below:

		Plant Concentrations	National Std.	
			Primary	Secondary
SO_2	3 hr, ppm	0.054	-	0.50
	24 hr, ppm	0.016	0.14	-
	annual, ppm	0.003	0.03	-
Part	24 hr, ug/m^3	3.21	260	150
	annual, ug/m^3	0.43	75	60

Solid Waste Disposal - It is estimated that a total of approximately 135,000 lb/hr of dry solids will be produced. The solids will be composed of fly ash, calcium sulfate and calcium and magnesium oxides. Disposal will include placing this material on land in layers 5 feet deep, and covering this area with 8 inches of topsoil and seeding. Other solid wastes requiring on-site disposal will be the solids generated in the coal pile runoff treatment system which will be disposed of in an acceptable land disposal area.

2.1.4 Component Conceptual Design

2.1.4.1 PFB Combustor and Heat Exchanger

The general arrangement of the Pressurized Fluidized Bed Combustor (PFBC) (Figure 2.15) consists of a vertically mounted 28 ft ID pressure vessel which is divided into three zones; the air compartments below the distributor plate, the 16 ft deep bed containing the air heat exchanger and the freeboard. Finned, vertically oriented heat exchanger tubes are dispersed throughout the bed section to control bed temperature.

The PFB combustor is approximately 33 ft 3 in. OD and 135 ft from ground to centerline of the gas outlet. The combustor supports three primary cyclones, each primary cyclone discharging its solids into the PFB combustor, and its gas into a secondary hot-gas cleanup cyclone.

Several arrangements for the PFB combustor and heat exchanger were studied before selecting the most suitable design, considering performance requirement, design complexity, serviceability, and cost.

The selected design concept for the PFB combustor is a single walled pressure vessel lined with refractory insulation and using concentric flow (bayonet type) heat exchanger tubes in the active bed region as shown in Figures 2.15 and 2.16. A layout of a PFB combustor unit showing typical field piping, coal and dolomite injection equipment, gas cleanup cyclones, and the gas-turbine power plant is shown in Figures 2.17, 2.18 and 2.19 for a preliminary PFB design concept.

The refractory lined combustor pressure vessel is 28 feet internal diameter and 76 feet high. Internally, a distributor plate located at approximately 1/3 of the vessel height, supports 973 finned heat exchanger tubes and 945 tuyeres. Below the distributor plate is a flat topped conical plenum which collects the hot gas from the heat exchanger tubes. Externally, the pressure vessel is supported on four columns. The outlet of the vessel at the top conducts the hot contaminated gas through one pipe to the inlet of the primary cyclones. The complete system, which is 137 feet high and includes the PFB, primary and secondary cleanup cyclones and ash removal system, is enclosed in a steel framework for support and conveninece of servicing.

The PFB is started by introducing air heated to 1100°F by a separate heater into the tuyere plenum shown in Figure 2.17 to feed the tuyeres and fluidize the bed until the bed temperature reaches 1100°F, at which point coal is fed into the combustor and sustained burning occurs. The separate heater is then switched off and normal operation proceeds. Additional gas or oil fired heaters in the freeboard ignite any flammable mixture that may occur during starting and assist in raising the bed to normal operating temperatures. These are turned off during normal operation. During the start-up, the airflow will be blocked through the heat exchanger tubes and diverted through the turbine.

COMMERCIAL PLANT PFB
WITH
CONCENTRIC FLOW HEAT EXCHANGERS

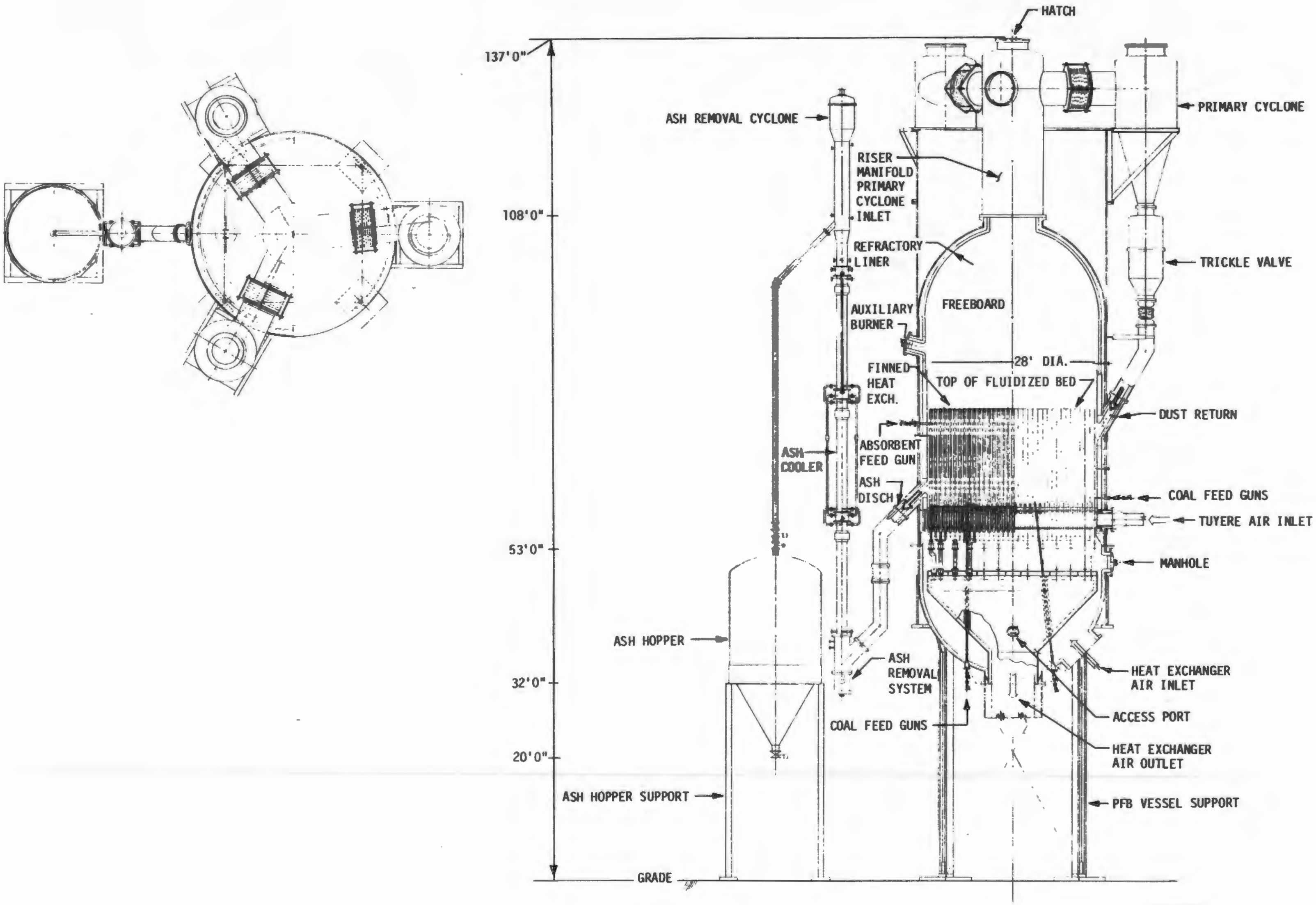
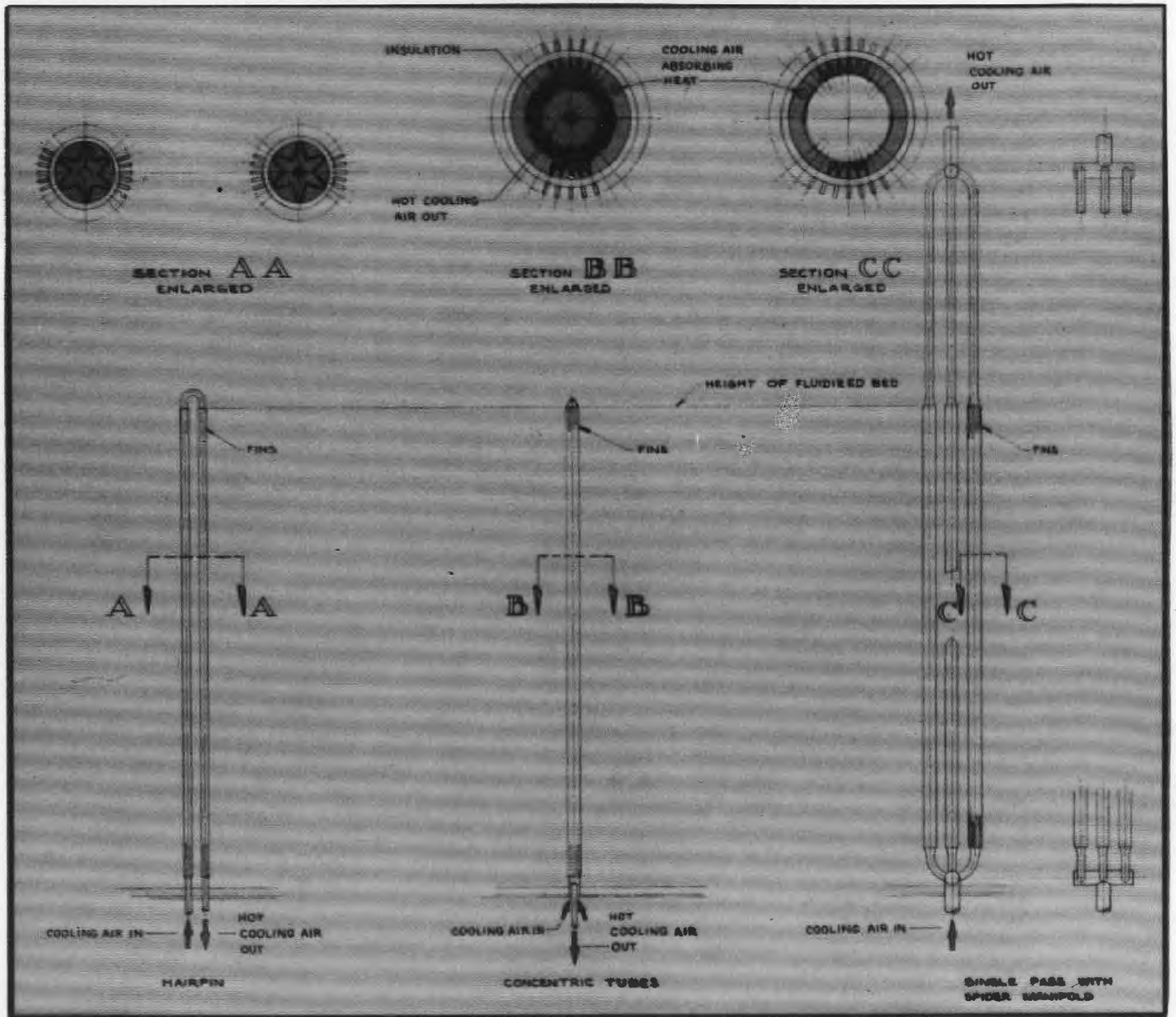


Figure 2.15

HEAT EXCHANGER TUBE DESIGN CONFIGURATIONS



PFB-I-231

Figure 2.16

GENERAL ARRANGEMENT - GAS TURBINE AND PFB COMBUSTOR

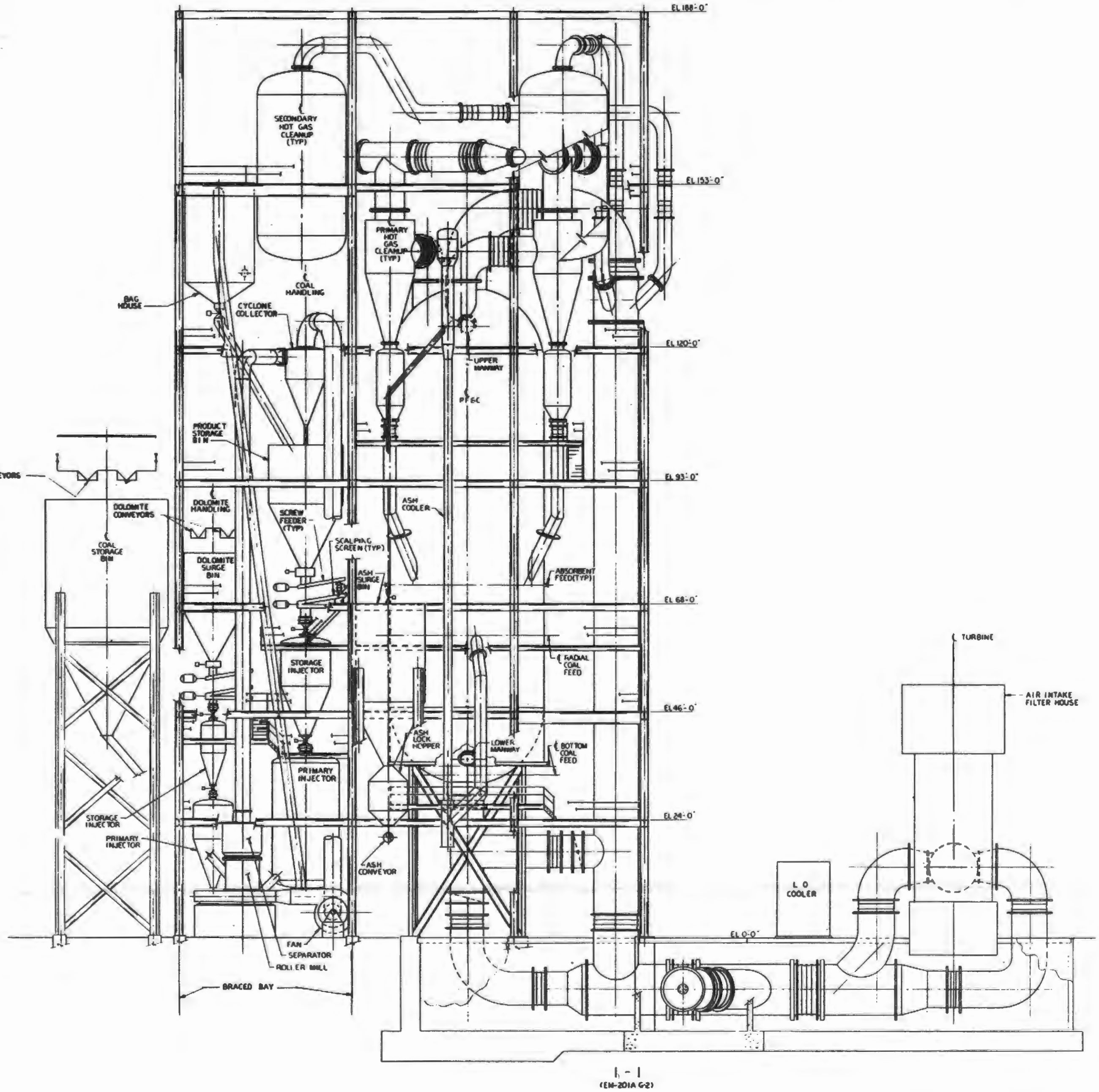


Figure 2.17

2-29

PFB-I-400

GENERAL ARRANGEMENT - GAS TURBINE AND PFB COMBUSTOR

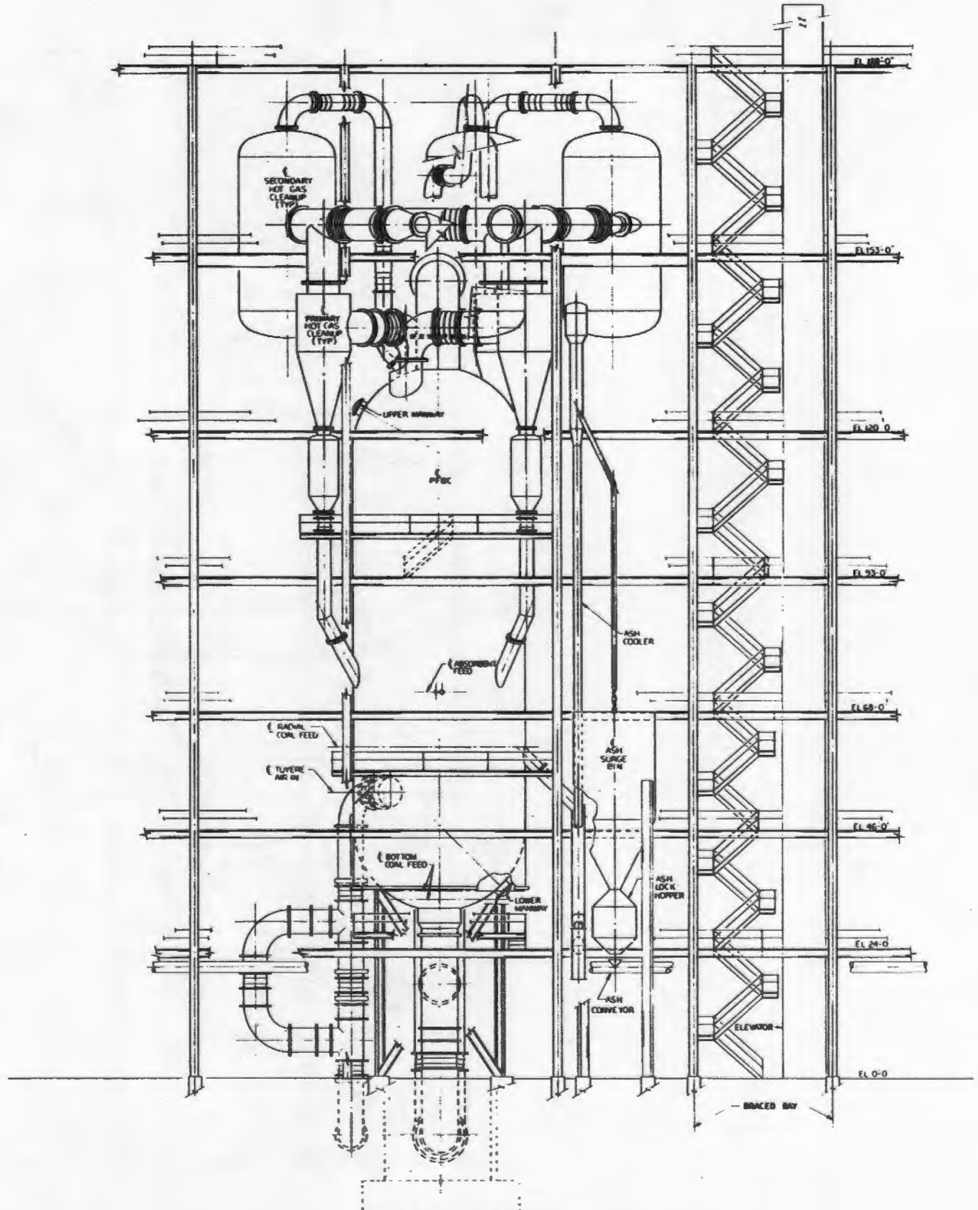
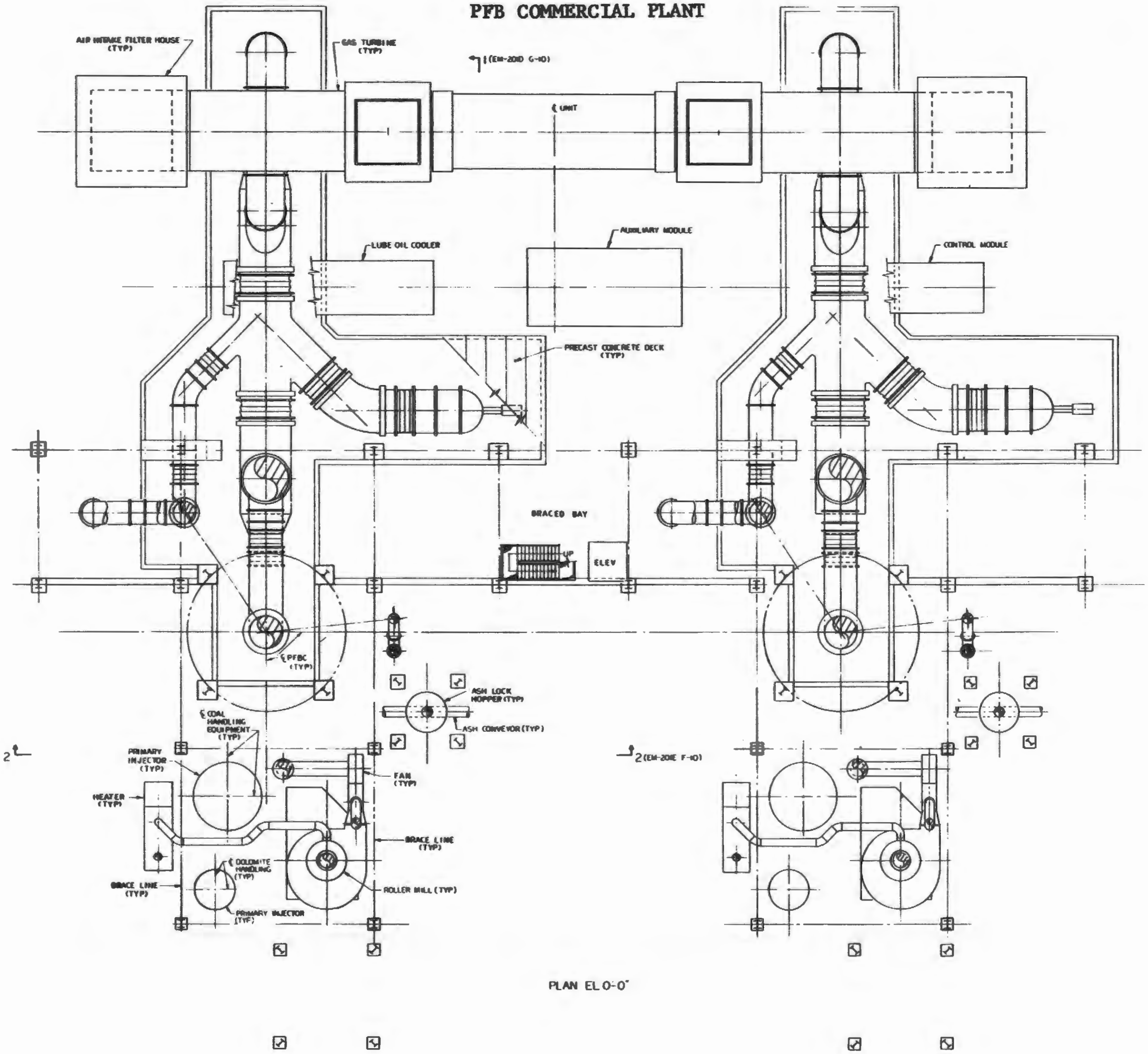


Figure 2.18

2-2

PFB COMMERCIAL PLANT



PLAN EL 0-0"

Figure 2.19

PFB-I-397

In normal operation, gas turbine compressor discharge air at 506°F and 102.2 psia (standard 59°F day) is introduced into the PFB combustor pressure vessel with 1/3 entering the plenum feeding the tuyeres and 2/3 entering the plenum feeding the heat exchanger tubes. The air feeding the tuyeres fluidizes the bed and sustains combustion. It leaves the combustor, heated to 1650°F at a pressure of 94.42 psia, containing combustion products and particulates and enters the primary cyclones to remove as much of the particulate as possible. The isolated particulate is reintroduced into the fluidized bed. The partially cleaned air is next directed to a secondary cleanup process and finally rejoins the "clean" air which was directed through the heat exchanger tubes and heated in the fluidized bed heat exchanger. It then exits the PFB combustor pressure vessel at 1600°F and 93.22 psia. It is this combined heated air that is reintroduced into the turbine.

In a normal combustor shutdown sequence the coal supply is stopped and the air to the PFB is bypassed back to the turbine, thus allowing the bed to slump and stay hot for the next start-up.

PFB Combustor Vessel - The technical specification guide for the design of the PFB pressure vessel shell is the ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2. The cylindrical section of the vessel is constructed of three inch carbon steel. The refractory lining is sized to maintain a maximum shell temperature of 260°F.

Thermal studies of refractory insulation effectiveness in the freeboard and bed regions were made for various combinations of insulating materials to select a final insulation arrangement for the PFB vessel. Refractory materials were investigated in various single and two-layer combinations of varying thicknesses. Thermal gradients were calculated through the vessel wall.

For the inner surface film coefficient in the bed region, a value of 70 Btu/hr-ft^2°F was used. A value of 5 Btu/hr-ft^2°F was used in the freeboard region. The heat loss from vertical surfaces presented in Figure 2.20 is shown for different ambient conditions of air temperature and wind velocity (i.e., 100°F still air, 70°F still air, 0°F air with 20 mph wind, etc.).

A finalized insulation arrangement for the PFB vessel bed, freeboard, top dome and bottom section was chosen, based primarily on the ability of the brick to withstand abrasion. Insulation thicknesses were sized to provide acceptable heat loss from the PFB vessel to the atmosphere and to limit outside wall temperature to 250°F on a 100°F, no wind day to minimize hazard to plant operating personnel. The configurations were then analyzed for the other ambient conditions used as criteria for the design, namely, 70°F no wind day, 0°F no wind day, and the 0°F, 20 mph wind day. Temperature gradients through the aforementioned sections were calculated for the ambient conditions being investigated, and were used for shell stress calculations.

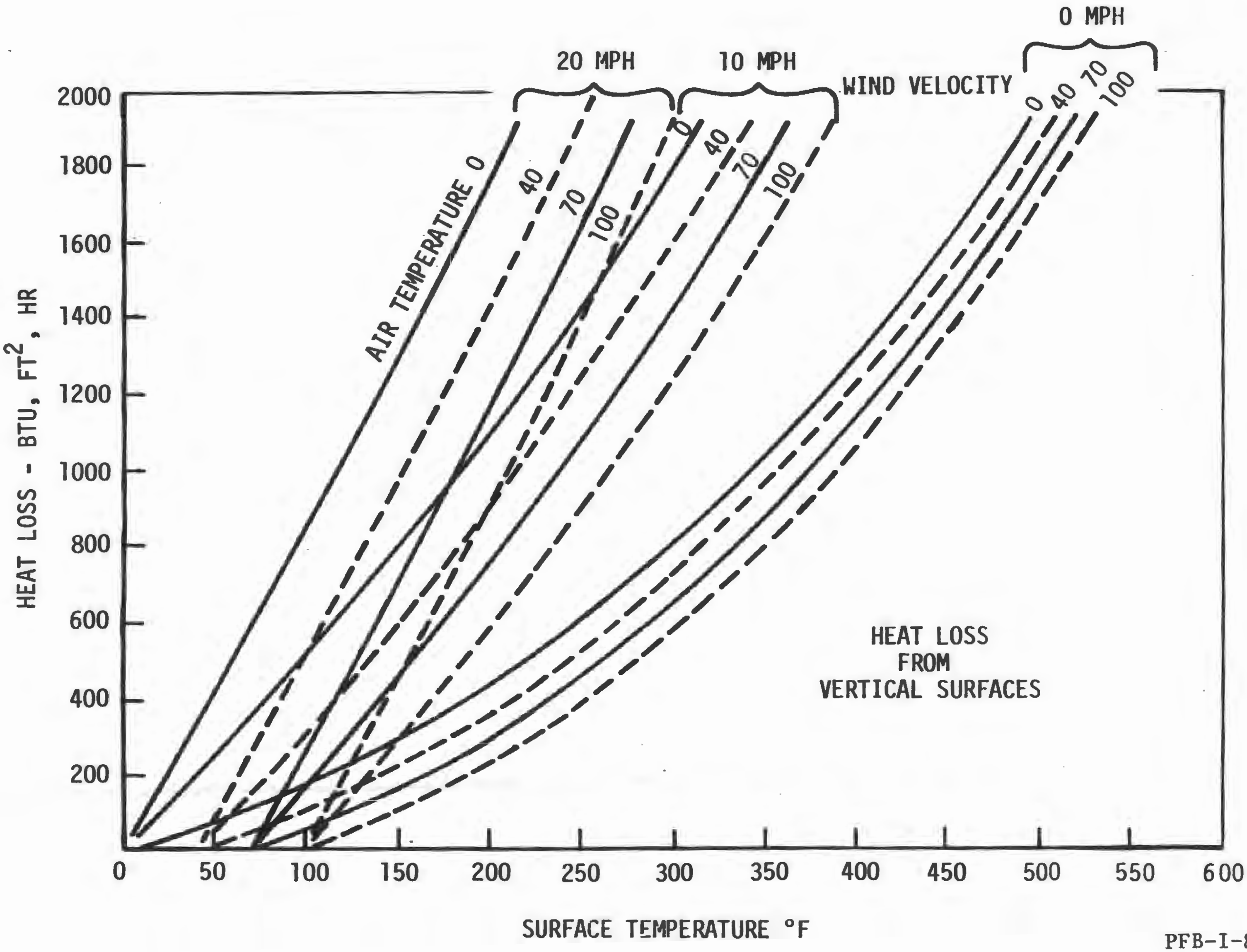


Figure 2.20

PFB-I-875

The final insulation configuration of the liner in the cylindrical section surrounding the bed and 8 feet into the freeboard is 9 inches of brick backed up by a castable refractory. The brick is a high-alumina (60%) characterized by high purity and density. The remainder of the freeboard and top hemispherical head are lined with a two-component castable, gun applied. Typically, an abrasion and erosion resistant low iron castable which should provide good protection against particulate laden gas and CO, would be used.

Since the bottom hemispherical head is subjected to a maximum of 1100°F during the starting cycle the liner requirements are less stringent. Here, a lightweight gun applied castable with good strength (1000 to 1700 psi cold crushing) and insulating value would be used.

The construction materials of the key structural components of the PFB combustor have been selected for reliable service, low-cost and ease of fabrication and assembly. The pressure vessel shell is fabricated from SA 515 Grade 70 carbon steel having a minimum tensile strength of 70,000 psi and a minimum yield strength of 38,000 psi at room temperature. Penetrations and reinforcements of the pressure vessel shell are of the same material.

The vessel shell was stress analyzed by subdividing it into three mathematical models (Top, Middle and Bottom). The most difficult design conditions occur on a 0°F day, 20 mph outside wind, with 117 psi internal gas conditions (cold day maximum power output), combined with an overturning moment due to a Zone 1 earthquake 750,000 lb side load. Amplified design pressures were used on the steel shell due to thermal expansion of the two-layer refractory. The resulting calculations indicated the 3" and 1-3/4" thickness vessel dimensions.

Heat Exchanger - Tubes in the bed transfer heat to air, which flows to the turbine of the gas generator. Coolant tube design affects, among other parameters, the performance, cost, durability, and maintainability of the bed.

The heat exchanger tubes and their spacing in the bed have been designed to achieve the desired heat transfer from the active fluidized bed. A bayonet tube concept (incoming flow through an annular gap between two concentric tubes and return flow through the center of the inner tube) was chosen because it is shortest in length and lighter in weight than other concepts which were evaluated. This tube does not have to extend into the combustor freeboard where it would be exposed to a more complex erosive/corrosive environment than exists in the bed region.

The tubes were arranged in a square matrix with four inch spacing between rows of tubes for free movement of the bed material. External and internal fins optimize heat transfer. The minimum space between external fins was established as 0.025 inch to avoid plugging of the spaces between fins. An external fin thickness of 0.125 inch and a fin height of 0.4 inch were established as practical values for manufacturing and heat transfer in a deep bed heat exchanger. A study of tube sizing (Figure 2.21) showed that the cooling tube surface on the bed side is optimal when the nominal tube size is approximately 4 inches.

PIPING AREA PARAMETERS

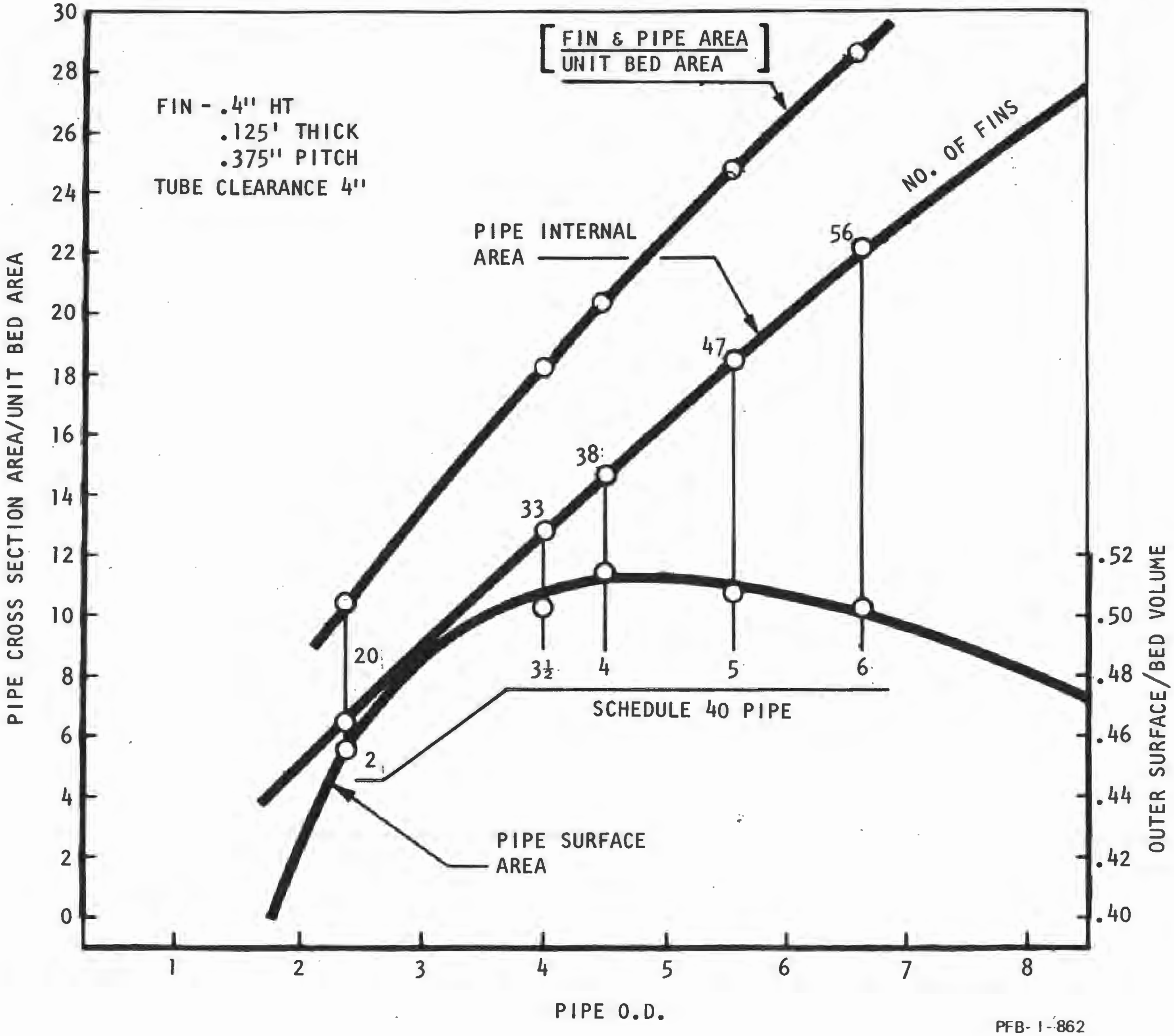


Figure 2.21

Two types of internal fin geometry are acceptable for the PFB heat exchanger. The first, a thick fin (minimum 0.1 inch) of a rectangular cross-section, is suitable for welding, brazing or extrusion of fin-tube assemblies. The second, a thin fin of "pleated" sheet stock, is suitable for brazing to the inner tube surface. Figure 2.22 illustrates the relative performance of the two types of interior fins as installed in a 4 inch schedule 40 coolant tube for various fin spacings. The exterior fin height, thickness and spacing has been held constant for these studies. The results of these analyses indicate that the PFB heat exchanger thermal load can be satisfied in a 16 foot deep bed with a number of fin geometries.

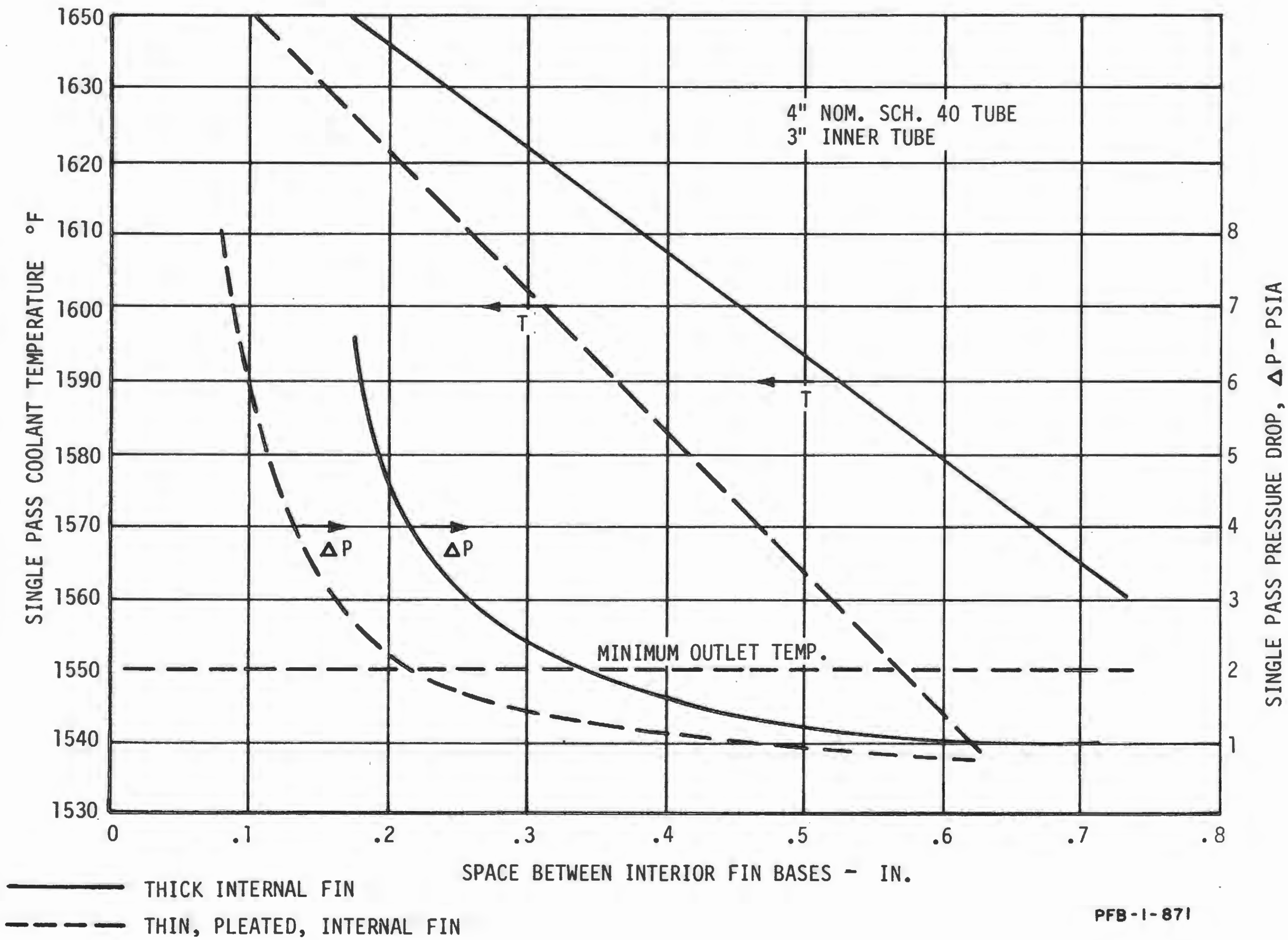
The entire tube assembly consists of an outer tube finned on the inside and outside, and an inner tube is insulated to prevent the heated air from giving up heat as it returns to the plenum collector in the lower portion of the combustor vessel. Air is conducted up past the inner fins and back down through the inner insulated tube.

The heat exchanger tube assembly is fabricated from Haynes 188, a wrought cobalt-base alloy with good resistance to oxidation and to high temperature sulfidation. The alloy is non-hardenable by heat treatment and is used in the solution treated or annealed condition.

The outer or finned tube is secured to the lower plate of the PFB distributor through a thermal sleeve which reduces soak back. The inner tubes are connected by manifolds to a lower collector. The collector is SA 515 Grade 70 carbon steel since it is completely insulated on the inside where the temperature of the air is 1650°F and is exposed on the outside to 500°F compressor discharge (PFB combustor inlet) air.

Several design concepts for the distributor plate, which supports the entire heat exchanger assembly and fluid bed material weight, were evaluated to obtain a feasible configuration utilizing low cost materials while allowing access space for maintenance. The distributor is a multi-layer structure including the upper bedplate, support tubes, lower plate and outer cylinders joining the bedplate and the bottom plate which are all designed of 2-1/4 percent chromium, 1 percent molybdenum alloy SS 387 Grade 22, Class 1. This material was chosen because of the startup condition which requires that 1100°F air be supplied to the tuyeres to fluidize and heat the bed to ensure that coal combustion can be initiated and sustained. The distributor must also meet the soak back condition which is described in the following paragraphs where temperatures of 800"F to 1000°F are experienced after an emergency shutdown and slumping of the bed. The tensile strength and the yield strength of this alloy are high enough at these temperatures to provide for a structurally sound design. The relatively short time at these temperatures should pose no problem with oxidation-corrosion. The distributor plate is covered with 5 inches of insulation, resistant to erosion. The distributor plate which is not considered a pressure vessel, is designed in accordance with Appendix D of Division 1 of the ASME Code noted earlier entitled "Suggested Good Practice Regarding Internal Structures".

SINGLE PASS OUTLET TEMPERATURE & Δ P
AS A FUNCTION OF INTERNAL FIN SPACING



PFB-1-871

Figure 2.22

In the event of a rapid shutdown of air supply to the PFB vessel, or in the case of a turbine/compressor accident, no cooling air would be available for the heat transfer tubes inside the vessel bed region. This would in effect leave a larger mass of material, the tubes, the collapsed bed, etc. weighing about 400,000 lbs - at 1650°F, with no cooling provision, since the large amounts of insulation on the inside of the vessel would allow only a fraction of the heat to escape over long periods of time. With a driving potential of over 1000°F between the bed and lower chamber, heat would begin to flow down into the distributor plate section and lower inside support structure, raising its temperature to some unknown level. This "soak back" of heat into the normally 500°F section of the PFB vessel might raise the metal temperature to such a point that the plate and support structure would weaken and sag under the load of the bed and tubes. To predict the highest "soak back" temperature of the bed support plate, a thermal model of the PFB vessel was made, for use with a computerized thermal analyzer program. The thermal analyzer program is a first forward difference program which is capable of calculation of both steady-state and transient temperature distributions for virtually any geometric configuration and set of boundary conditions. By setting the appropriate initial and boundary conditions and then allowing the thermal model to run the equilibrium, a history of a "soak back" condition was approximated. Temperatures of the important vessel sections were identified as a function of time. From the curve shown on Figure 2.23 it is apparent that the bed support plate reaches a peak temperature of about 800°F in approximately 70 hours, and then very slowly, cools down as the vessel continues to lose heat to the atmosphere.

Based on the structural design and materials used for the PFB support plate, the maximum allowable plate temperature is about 1200°F, thus with this design, there is no problem due to the "soak back" condition.

The distributor plate also contains penetrations for tuyeres and bottom feed coal guns. The tuyeres which contain patterns of holes from which the small jets of combustion air emerge, will be constructed of a 300 series heat resistant stainless steel since the temperature during startup will be about 1100°F and for the emergency shutdown condition, when the bed slumps, it is estimated that temperatures of 1300°F to 1400°F will occur.

Twenty three coal feed guns from the lock-hopper injection system penetrate the distributor plate, in the space otherwise allotted to tuyeres, to provide the fuel in the center region of the bed and an additional 24 coal feed guns penetrate the shell radially in the lower region of the fluidized bed.

The guns are sized to limit fuel input to an equivalent heat release of about 15 million Btu/hr for each gun. To help prevent plugging of the guns they are air cooled. The guns are designed to be removable during operation for servicing by incorporating a packing gland and blocking valve system.

COMMERCIAL PLANT BAYONET
HEAT EXCHANGER TUBE DESIGN,
"SOAKBACK" RESPONSE

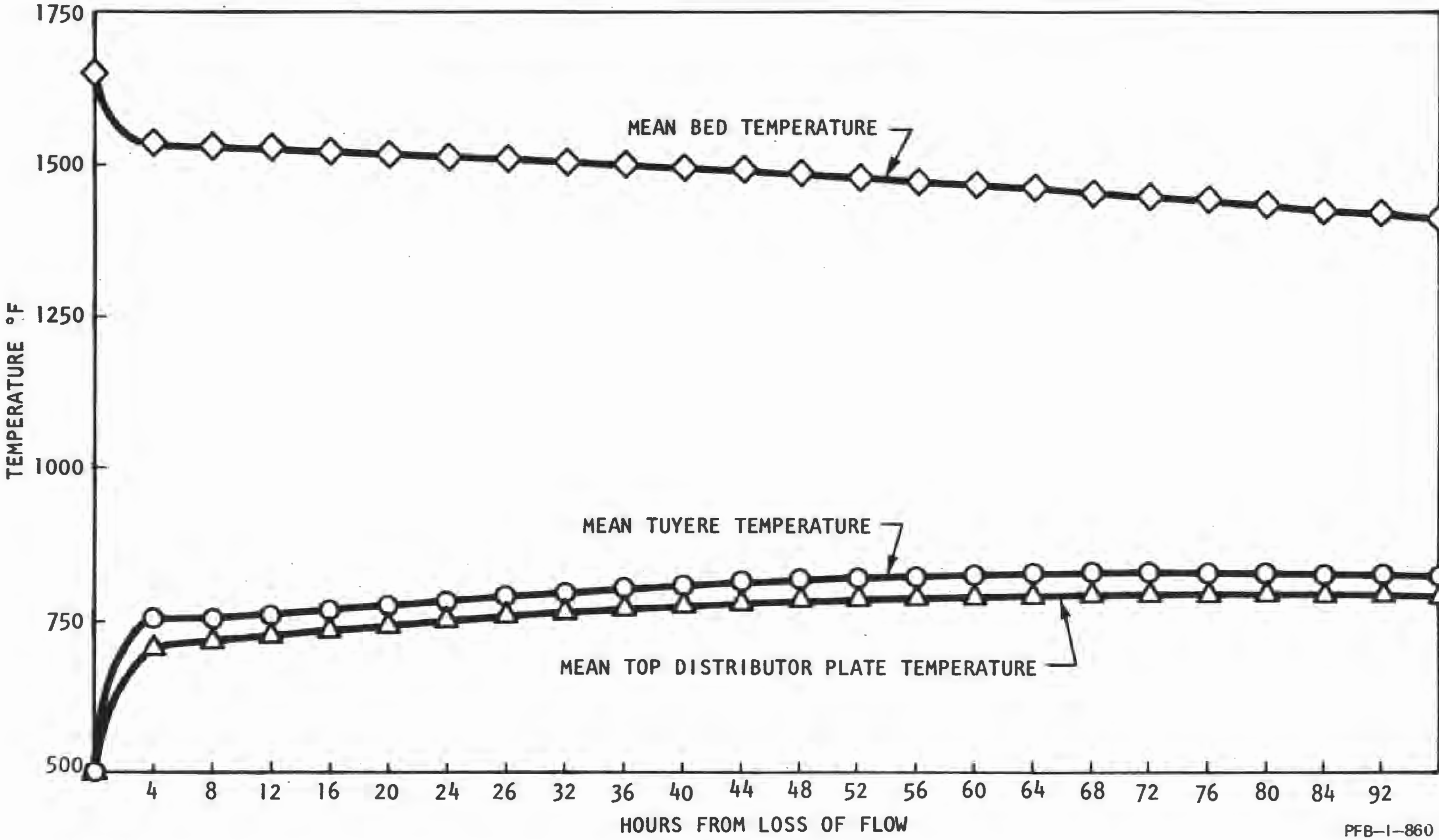


Figure 2.23

The horizontal sorbent feed guns are not expected to have plugging problems. They are not removable during operation, but can be removed when the combustor is out of service. Each gun is designed to feed up to 13,000 pph of sorbent.

2.1.4.2 Gas Turbine Power Train

There are three 100 MW gas turbine power trains in the commercial PFB plant, in addition to a 175 MW steam turbine. Each gas turbine power train consists of a 100 MW alternator driven at each end by an industrial gas turbine. The conceptual design of the industrial gas turbine is shown in Figure 2.24. Not included are the alternator and second turbine set. Figure 2.25 depicts the total 100 MW power train.

The following design criteria for the industrial gas turbine were observed to reduce system design complexity and cost. The gas turbine is oriented in-line with the alternator, has a single spool axial flow compressor driven by a 2-stage primary turbine and is gas coupled to a 2-stage free power turbine which drives the alternator. No power take-off drives are required. Journal bearings are used on both rotor mainshafts. Provision is made for bleed to unload the power turbine (a protection required to prevent overspeed during load trip, etc.), and the turbine is completely mounted for preassembled shipment to the site.

The gas turbine train comprises integral gas generator and power turbine sections mounted on a common structural base that is anchored to a monolithic concrete slab after the drive line is aligned with the alternator. The gas generator section consists of a 13-stage single spool axial flow compressor connected by shafting to a two-stage turbine. Pressurized air from the compressor is ducted to the PFB combustor. The clean hot gaseous products from the PFB combustor and heat exchanger are ducted back to drive the turbines.

Compressor air exits into a 2.20:1 area ratio annular diffuser to reduce airflow velocity and minimize downstream duct pressure losses. The air passage spills into an annular chamber and then divides and turns to leave through the two annular side outlet ports in the casing. Part of the compessor air is diverted around the hot gas inlet ducts to cool the turbine stator housing. The two coaxial hot gas inlet ducts follow a transition from circular flow sections at the casing to a 360 degree flow annulus at the turbine inlet.

Coaxial air outlet and gas inlet ports are located on each side of the engine casing between the compressor and turbine, on the horizontal centerline (see also Figures 2.17, 2.18 and 2.19). The hot gas duct is centered inside the compressor air duct to form an annular airflow passage for the compressor discharge air.

The compressor-turbine rotorshaft assembly is supported by three pivoted shoe journal bearings and a front thrust bearing. Each bearing group is mounted in a spoked bearing housing. The housings have horizontal mount pads which rest on mounting frames that tie in to the structural base.

The power turbine is located behind the compressor turbine on the same centerline and shares the inter-turbine bearing housing at the front. A six port toroidal hot gas bleed manifold is located between the turbines. The bleed passage area was sized to bypass fifty (50) percent of the gas flow around the

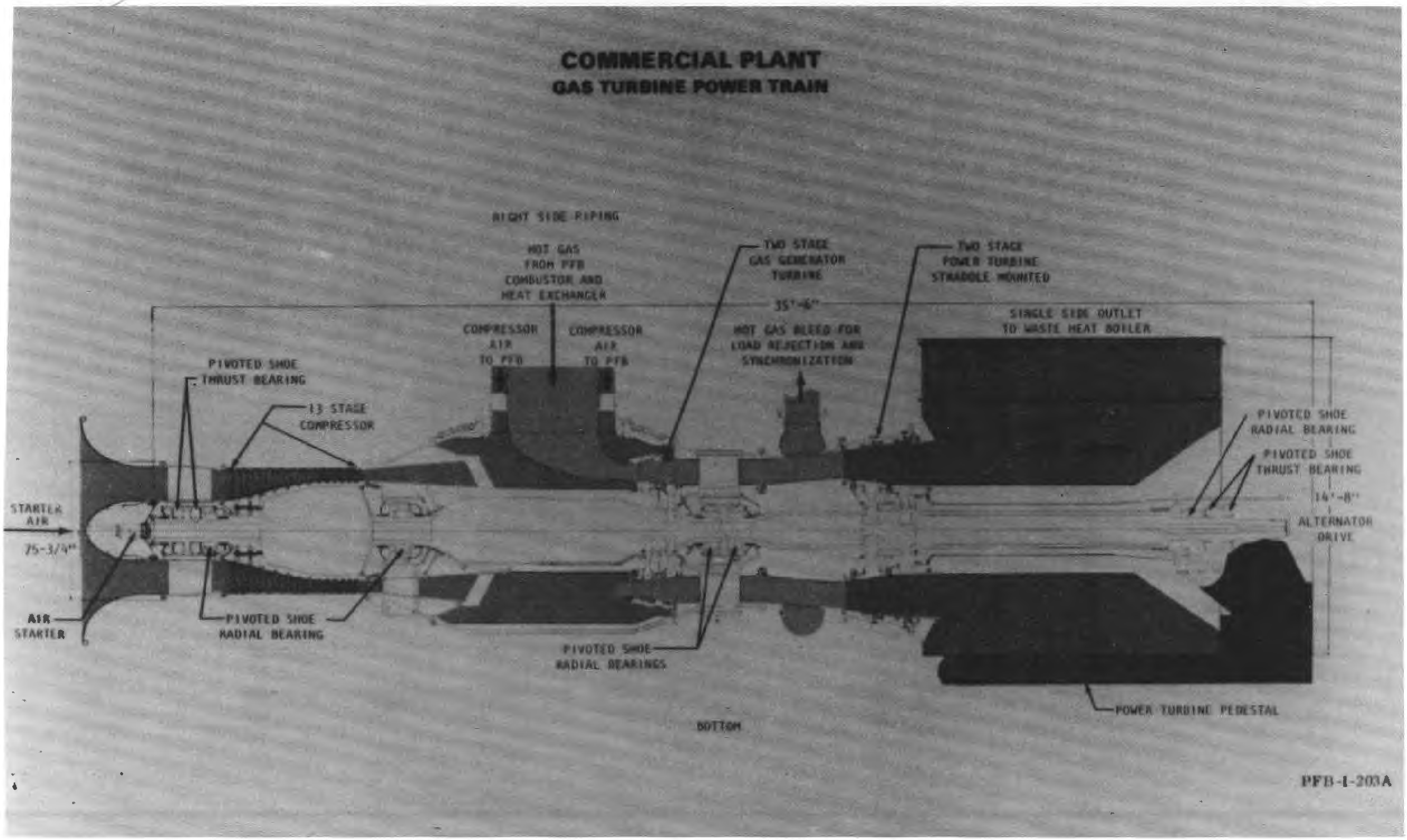

COMMERCIAL PLANT
GAS TURBINE POWER TRAIN
RIGHT SIDE PIPING
HOT GAS FROM PFB COMBUSTOR AND HEAT EXCHANGER
TWO STAGE GAS GENERATOR TURBINE
TWO STAGE POWER TURBINE STRADDLE MOUNTED
35'-6"
COMPRESSOR AIR TO PFB
COMPRESSOR AIR TO PFB
HOT GAS BLEED FOR LOAD REJECTION AND SYNCHRONIZATION
SINGLE SIDE OUTLET TO WASTE HEAT BOILER
PIVOTED SHOE THRUST BEARING
13 STAGE COMPRESSOR
PIVOTED SHOE RADIAL BEARING
PIVOTED SHOE THRUST BEARING
14'-8"
STARTER AIR
75-3/4"
ALTERNATOR DRIVE
AIR STARTER
PIVOTED SHOE RADIAL BEARING
PIVOTED SHOE RADIAL BEARINGS
POWER TURBINE PEDESTAL
BOTTOM
PFB-I-203A

Figure 2.24

PFB COMMERCIAL PLANT

TYPICAL 100MW G.T. POWER TRAIN

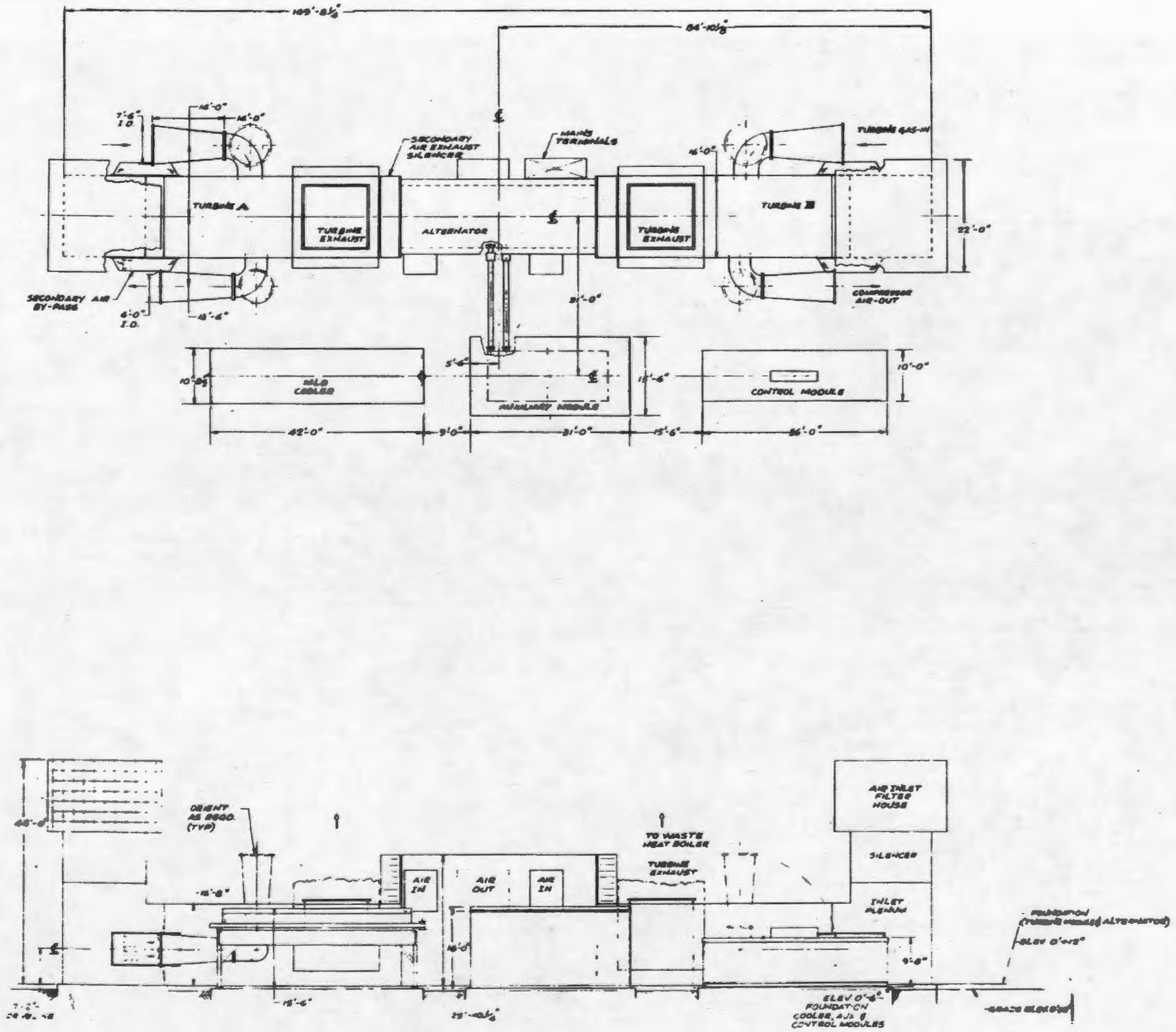


Figure 2.25

PFB-I-18A

power turbine and into the duct to the waste heat boiler to prevent an overspeed during emergency shutdown of the alternator, such as a circuit break. Bleed will also be used for phase synchronization before closing the circuit breaker, and during gas generator startup.

The bleed flow is regulated by six hot gas valves located in the piping outside the acoustic enclosure. All of the valves will have an instant open-close capability. One valve will also have modulating features for synchronization.

The power turbine is supported by two pivoted-shoe journal bearings and a thrust bearing. The rear journal and thrust bearings are pedestal mounted to the structural base.

The exhaust gas volute is an asymmetric duct in which the power turbine exhaust gases are diffused and discharged horizontally into the duct to the waste heat boiler. All casings and housings from the inlet to the pedestal have horizontal bolting flanges for convenient assembly and service operations. The material selections for the various gas turbine components are shown in Table 2.8.

Bearing Housings - Each of the four bearing housings comprises an outer casing and inner centerbody connected by radial struts. The upper halves of the outer casings are removable to gain access to the upper bearing cap. The lower cap is an integral part of the centerbody and contains the oil drain cavities. Each bearing housing is supported on A-frames which are secured to the common base. The front main bearing housing is also the gas generator thrust mount. Axial movement is restrained by thrust blocks, but transverse sliding motion is provided for. Axial alignment is maintained by a longitudinal key between the bottom centerline of the engine and the structural base. All other housings permit both axial and transverse sliding. The thrust mount for the power turbine is in the pedestal.

Compressor - The compressor aerodynamic design is scaled upward directly from a CW 6515 gas turbine engine. The airflow scale factor is 5.0 and the new compressor speed is 3712 rpm. The basic aerodynamic and centrifugal loadings will be essentially the same. No changes to the blade airfoils are needed except for size and the materials used. Blade attachments will be redesigned for installation into the compressor rotor drum and disks. The stator vanes will insert into circumferential "T" slots in the compressor casing. The first seven stator vanes will retain their present inner shrouded configurations.

Air/Gas Volute Section - The air/gas volute casing houses the compressor air outlet duct and turbine gas inlet duct as well as the compressor turbine housing assembly. Heat shields are provided on the inside of the outer casing to protect it from radiation and on the inner housing to protect the rotor shaft from radiation. The inner housing is a cantilevered cylindrical structure over the rotor shaft assembly and is mounted to the rear flange of the outer diffuser housing through radial struts and a supporting cone. The forward end of the inner housing provides the extension of the diffuser passage. The aft end holds the inner fishmouth seal for the turbine inlet gas duct and first stage turbine stator vane support.

TABLE 2.8

MATERIALS SUMMARY

ENGINE BASIC PFB COMMERCIAL PLANT

	COMPONENT	MATERIAL
1.	INLET HOUSING	TYPE 410 CAST ANNEALED
2.	COMPRESSOR BLADES & VANES	GREEK ASCOLOY AMS 5616 RC32-36
3.	COMPRESSOR CASING	TYPE 410 ANNEALED FORGED
4.	COMPRESSOR DISKS	AMS 5616 RC32-36
5.	COMPRESSOR DRUM & SHAFTING	TYPE 410 RC32-36
6.	DIFFUSER HOUSING	TYPE 409 WELDED
7.	PFB AIR/GAS PORT HOUSING	NI-RESIST D5B CAST IRON
8.	GAS MANIFOLD TO TURBINE	TYPE 310
9.	COMPRESSOR TURBINE HOUSING	NI-RESIST D5B
10.	COMPRESSOR TURBINE VANES & BLADES COMPRESSOR TURBINE DISKS & STUB SHAFTING	MAR M 246 OR IN 792 A-286
11.	INTER TURBINE HOUSING	PEARLITIC NODULAR CAST IRON
12.	INTER TURBINE HOUSING LINER	AISI 321
13.	GAS BLEED MANIFOLD	NI-RESIST D2C & AISI 321
14.	POWER TURBINE HOUSING	NI-RESIST D2C
15.	POWER TURBINE VANES & BLADES	UDIMET 500
16.	POWER TURBINE SHAFTING	ASTM A-470 CL7
17.	POWER TURBINE DISKS	TYPE 422
18.	EXHAUST VOLUTE	TYPE 409
19.	PEDESTAL	PEARLITIC NODULAR CAST IRON

Turbine - The compressor and alternator are each driven by two-stage axial flow turbines. The compressor turbine support housing is located inside the air/gas casing. Axial retention is provided by a combination radial flange and spline that is positioned between the flanges of the air/gas casing and the rear main bearing support. The radial centering spline permits free differential thermal expansion.

The power turbine housing is an external structure that attaches to the gas bleed manifold on its forward end and attaches to the exhaust volute on its aft end. This housing and the upstream gas bleed manifold are both supported from the rear main bearing housing. The power turbine housing attachment with the exhaust gas volute uses a sliding joint with a piston ring seal on both inner and outer diameters.

Design of both the compressor turbine and power turbine housings is similar to the Curtiss-Wright CT-2 power turbine configuration which is in commercial service. It features stationary shrouding which in conjunction with the stator vanes isolates the basic structure from direct contact with the hot gases. The compressor turbine housing is cooled by allowing a portion of the compressor discharge air to bleed into the cavities behind the vanes and stationary shrouding. Both turbine housings are split and flanged on the horizontal centerline for servicing.

The turbine rotor blades are tip shrouded and fir tree attached to the disks. Both disks are bolted into their respective rotor shaft assemblies.

Preliminary turbine analyses for both the compressor turbine and power turbine established gas passages dimensions and mean-line aerodynamic conditions. Blade quantities were estimated and a preliminary check of the direct stress in the rotor blade airfoil root sections was made to determine material selection. The compressor-turbine first rotor blade may need convective cooling to reduce the root section metal temperature. Internal cooling passages can be precision cast into the rotor blade and the cooling air would also be used to cool the firtree attachment with the disk.

Exhaust Volute - The exhaust gas volute is sized for a 2:1 area ratio annular diffuser and a 4:1 area ratio exit opening, referenced to the power turbine exit area of 5015 sq in.

The volute is independently mounted to the structural base through ball-jointed struts and a thrust pin. Piston rings seal the annular entrance to the volute at the power turbine exit. Static gas pressure at this station is slightly less than ambient, assuring that no hot gas will leak into the turbine enclosure.

The volute is constructed in four flanged sections which are joined at assembly. One section is installed over the rotor shaft at the time the turbine is assembled. Three of the sections are shipped separately and can be assembled to either a right or left hand orientation. Tie-bars reinforce the rectangular exit opening. All flat surfaces will be reinforced as required with stiffeners.

Starter - A pneumatic type starting system has been selected for the simplicity of air start operation and the availability of developed, reliable units in the power range required. The starter is an axial drive unit that mounts to the centerbody of the front main bearing housing inside the bullet nose inlet fairings. The starter is a complete package containing an air turbine, reduction gearbox, clutch and splined output shaft. The shaft couples directly to the front end of the rotor mainshaft for cranking.

An air supply pipe connects to the front of the starter. This pipe enters the bullet nose from the inlet plenum of the acoustic enclosure. Starter exhaust air discharges into the bullet nose and through peripheral slots into the engine air inlet annulus. Because this exhaust air is ingested by the engine, precautions will be taken to prevent contamination originating in the supply piping system.

Starting torque requirements of the gas turbine were estimated and starter selection was based on a rotor shaft mass moment-of-inertia of 2745.6 slug-ft^2 and a time to 500 rpm of approximately 50 seconds. Light-off occurs at 313 rpm and the starter cuts out at 894 rpm.

Main Shaft Bearings - The power train consists of two rotor mainshaft and balancing assemblies. The gas generator mainshaft comprises a compressor rotor drum and 2-stage turbine wheel assembly connected by shafting having 3-spaced bearing journals and a forward thrust collar. The power turbine mainshaft consists of a shaft mounted 2-stage turbine rotor assembly with bearing journals at each end and the aft thrust collar.

A summary of the preliminary static bearing loads, and thrust bearing loads for the full power design condition is shown below.

ROTOR SHAFT ASSEMBLY BEARING LOAD

Bearing Location	Gas Generator Forward	Gas Generator Center	Gas Generator Aft	Power Turbine Forward	Power Turbine Aft
Size, in.	10	14	13	13	12
Radial Static Load, lb	7,400	12,700	8,500	13,500	12,500
Axial Thrust Load, lb	72,991	-	-	-	49,120

The axial thrust bearing loads were based on analysis of the aerodynamic and static pressure loads, selective placement of rotating labyrinth seals for thrust area variation, venting and sixth stage compressor bleed for pressurization. The radial static bearing load values were used in the critical speed analyses. Preliminary critical speed analyses were made for both the gas generator and power turbine rotor shaft assemblies which were found satisfactory.

Tilting pad journal bearings are used at all five mainshaft support locations (i.e. compressor-turbine and power turbine). This type of bearing is very effective in preventing oil whip, thus eliminating a possible operating problem in the future. Split bearing shells are used for assembly and maintenance. The bearings have length-to-diameter ratios of about 0.40.

Double split equalizing thrust bearings with integral shaft collars are used on both rotor mainshafts. Kingsbury special bearings (SPB) were chosen due to their larger shoe bore. The compressor-turbine shaft utilizes a 22-1/2 inch bearing and the power turbine a 22 inch bearing.

Turbine, Auxiliary and Alternator Modules - The turbine module consists of a fully assembled power train on a continuous heavy flanged steel base and the acoustic enclosure (Figure 2.25). The train includes a compressor, turbine, power turbine, partial exhaust volute, bearing pedestal and mounting frames.

This assembly is transported and installed as a unit. The envelope dimensions of the skid and mounted equipment are 10 ft 6 in. width and 12 ft 2 in. height, a size which can be transported by rail or truck to the site. Because of its size the exhaust volute has sections which are shipped separately and assembled at the site.

The turbine train is housed in an acoustic enclosure which includes an inlet air filtration and silencing system, and a cooling air and exhaust silencing system. The enclosure provides for the containment of both the compressor and turbine generated noise.

Each auxiliary module provides the lubrication requirements for one 100 MW power train. The module consists of an oil reservoir with a redundant tank mounted pumping and filtering system inside an acoustically insulated and weatherproof structure (Figure 2.26).

Oil is pumped through an outdoor heat exchanger and a filter to the power train to lubricate the alternator and gas turbine journal bearings and couplings. The main oil supply is rated at 1054 GPM at 100 psig with approximately 9 percent being bypassed by the oil pressure control valve regulator.

The design features of the main lube oil system include:

a. Oil reservoir with 5 minute retention time to reduce foaming.

b. Three 25 KW low intensity heaters in the reservoir to maintain the oil at 80°F or above at low ambient conditions.

c. Duplex full flow filters with a 3-way valve to allow changes while running.

d. Three outdoor oil coolers with 3-way valve interconnecting loops. One cooler is a spare.

e. Duplex A.C. pumps.

f. Three emergency D.C. pumps.

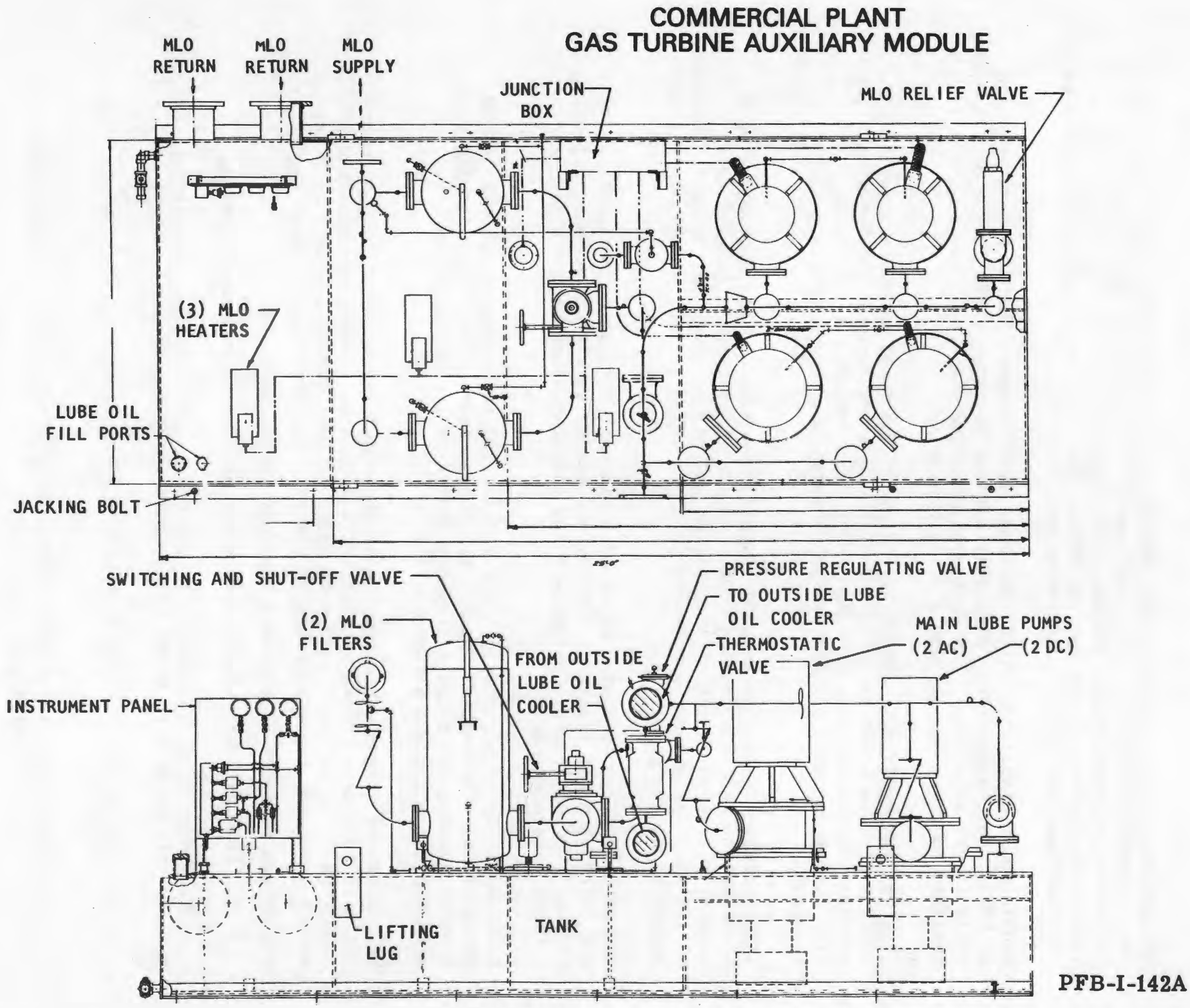

COMMERCIAL PLANT
GAS TURBINE AUXILIARY MODULE
MLO RETURN
MLO RETURN
MLO SUPPLY
JUNCTION BOX
MLO RELIEF VALVE
(3) MLO HEATERS
LUBE OIL FILL PORTS
JACKING BOLT
SWITCHING AND SHUT-OFF VALVE
PRESSURE REGULATING VALVE
TO OUTSIDE LUBE OIL COOLER
THERMOSTATIC VALVE
MAIN LUBE PUMPS
(2 AC)
(2 DC)
(2) MLO FILTERS
FROM OUTSIDE LUBE OIL COOLER
INSTRUMENT PANEL
LIFTING LUG
TANK
PFB-I-142A

Figure 2.26

The alternator is a turbine-driven 2-pole synchronous machine operating at 3600 rpm, 60 Hz frequency, and 13,800 volts with a rated output of 100 MW at 15°C and 0.85 power factor. The unit is housed in an acoustical enclosure with a canopy on top that contains the ventilating system. The alternator is axially lined between the two turbine modules connected to their output shafts by flexible couplings.

The rotor is carried on pressure lubricated sleeve bearings mounted in pedestals at each end of the rotor body.

The following site conditions represent the criteria for design of the various power train enclosures and modules:

Temperature.	-30°F to 100°F
Relative Humidity.	0 to 100%
Wind	100 mph
Snow	40 psf
Seismic.	Zone 1, Factor 1
Noise.	Nema D at 400 ft
Life	30 years

All module enclosures are acoustically insulated to reduce the high sound intensity emitted by the internal machinery. The acoustical treatment of each module is sized to reduce the intensity outside the module to meet "OSHA" requirements of 90 dbA at 3 feet from the periphery for 8 hours exposure. Also, the modules including the intake and exhaust systems of the turbines must not contribute sound intensities to the overall plant noise level greater than allowed to meet Nema D at 400 feet from the periphery of the plant.

2.1.4.3 PFB Combustor and Gas Turbine Interconnecting Piping

The main compressed air and hot gas field piping connects each PFB combustor vessel to its respective gas turbine. One PFB combustor services each gas turbine and there are two gas turbines and therefore two PFB combustors per power train. The piping arrangement includes an air/gas ducting system having a low pressure drop and low heat loss, and also interconnects the start-up and heat-up combustors, cyclone separators and power turbine gas bleed. A schematic of a typical duct routing system is shown in Figures 2.17 thru 2.19.

Atmospheric air is compressed leaving the compressor in two 90 in. OD ducts which combine into a 126 in. OD compressed air supply duct to the combustor. The 126 in. duct divides into two lines: an 80 in. OD line carrying air to the PFB combustor-heat exchanger and a 55 in. OD duct carrying air to the PFB combustor for combustion with the coal and dolomite. This 55 in. OD duct contains a bypass with a heat-up combustor for use during startup.

The air leaving the PFB combustor-heat exchanger combines with the gas leaving the primary and secondary hot gas cleanup systems into a common 110 in. OD refractory-lined duct, which connects to the gas turbine.

Modulating valves are located in line (tuyere and heat exchanger inlet ducts) to permit control of the bed temperature. A modulating jumper valve can divert the heat exchanger air back to the turbine if there is over-cooling of the bed.

The link from gas turbine to PFB combustor is coaxial ducting. This arrangement provides space saving and heat retention advantages over separate parallel ducting. The coaxial duct is a continuation of the coaxial air/gas porting from the sides of the casing in the turbine. The hot gases flow through the inner duct and compressor air flows through the annular passage. Coaxial ducting is also used for the start-up combustor bypass loop. Other branch ducts have unidirectional flow and circular cross-sections.

All cool air ducting from the compressor to the PFB is externally covered with a 2 inch insulation blanket to minimize any heat loss to the atmosphere. The duct wall will operate normally at the compressed air temperature of about 500°F. A section of the cool air ducting will also operate at 1100°F for short periods of time when the PFB heater is used.

All hot heat exchanger outlet air and combustion gas ducting will be refractory lined on the inside to reduce heat loss and limit the maximum temperature of the duct shell to 250°F for structural purposes and less costly material selections. The inside surface on all refractory insulated ducting will also have a metal liner to assure that pieces of the refractory will not break loose or wear away and be carried into the turbine. The inner gas duct in the coaxial segment of the line is also insulated and a metal inner liner will similarly be used. A 1.5 inch insulation blanket is used to limit the temperature drop in the hot gas coaxial return to the turbines.

Some of the piping is located in underground trenches to minimize system cost. These will have removable concrete covers for ease of serviceability.

The ducting system incorporates suitable supports and guides which carry the deadweight loads and pressure developed thrust loads. The elevated piping support structure is incorporated into the skeletal structure supporting the PFB.

Thermal expansion and tolerance variations are accommodated with flexible bellows at critical locations. Untied bellows are used in axial compression applications. Tied bellows are used where a lateral hinge movement can compensate for expansion and no thrust load is carried.

The duct sections are constructed from rolled and fabricated sheetmetal. Circumferential flanges are added where connections are made with in-line component installation. Centerline flanges are provided to facilitate assembly at some branch junctions especially where inner ducts or liners are used.

Low flow velocities are maintained throughout the ducting arrangement to minimize the effect of line pressure drops on the operating performance and to reduce erosion. An overall pressure drop of 1.2 psi occurs in the ducting between the compressor exit and tuyere inlets. On the return segment the overall pressure drop between the bed outlet and compressor turbine inlet is 1.7 psi. Clean air duct velocity is limited to 45 fps between the compressor discharge and combustor inlet. Hot gas velocity is limited to 38 fps in lines to the primary and secondary clean-up cyclones, minimizing the effect of erosion caused by particulate impingement on the lined surfaces. Finally a 140 fps velocity is used after the secondary cleanup and in the coaxial return duct to the turbine because particulate erosion is no longer a problem, there are no valve losses, and the higher velocity permits a smaller sized duct.

Most of the valves required in the ducting system have been located to operate in the 500°F air temperature environment (see table below). all are set automatically for either modulated or open/shut operation at all power settings. Butterfly valves are used in the duct lines to the heat exchanger, tuyeres and tuyere bypass loops. The high temperature valves for the gas bleed lines operate at up to 1187°F and gate type valves will probably be used.

COMMERCIAL PLANT VALVE APPLICATION SUMMARY

LOCATION	FUNCTION	TYPE	MAX. PRESS.
Auxiliary Combustor	Air To Combustor	Butterfly	105 Psia
Tuyere Heater	Open/Close To Heater	Butterfly	105 Psia
Tuyere Heater Bypass	Open/Close to PFB	Butterfly	105 Psia
Bed Cooling Air Bed Bypass Air	Modulate To Control Bed Temperature	Butterfly	105 Psia
Free Turbine Bypass	Gen. Synchronizing and Load Rejection	Butterfly	60 Psia

2.1.4.4 Combustion Gas Particulate Removal

Primary Cyclone - The primary cyclone, Figure 2.17, is designed to handle hot effluent gas from the PFB combustor for primary separation of entrained particles before the secondary cleanup. As the dust laden gas is introduced tangentially to the cyclone, the relatively coarser particles are separated from the gas stream by centrifugal force and discharged through the bottom of the cone section.

Each cyclone is internally lined with both an abrasion resistance layer and a thermal insulation layer of castable to form a composite lining. The cyclone shell is designed, fabricated, and tested according to ASME Code, Section VIII, Boiler and Pressure Vessels, at the design pressure of 150 psig and the design vessel temperature of 500°F. The vortex finder is readily removable, if necessary, through a flanged connection and is constructed of SS-316L.

Particles collected in the cyclone are recirculated back to the combustor bed through a dipleg connection. Due to the pressure differential between the reactor bed and the cyclone, particles collected may be re-entrained into the cyclone unless a means is provided to prevent gas backflow. A discharge valve is provided for this purpose, attached to the bottom of the cyclone dipleg, and normally closed. It remains closed until the static head of accumulated particles in the dipleg exceeds the pressure differential between the cyclone and the bed. The valve then swings open, discharging the particles, until the static head of the particles is less than the pressure differential. The discharge valve is contained in a pressure vessel to permit high pressure operation.

The primary cyclone collected particles are returned so most of the unburned coal and entrained sorbent can be fully reacted. Another objective of the cyclone return is to maintain fines in the bed, thereby improving bed fluidization, heat transfer characteristics, combustion and sulfur capture efficiency.

Secondary Hot-Gas Cleanup - Three cyclones will be furnished for each PFB combustor, following each primary cyclone, to remove particulate matter to 0.0368 grains per actual cubic foot prior to the combustion gas stream combining with the PFB combustor cooling air stream. The gas volume to each unit will be approximately 35,000 acfm at 1,650°F and 94.2 psia. The design pressure drop through the secondary hot-gas cleanup cyclone will be 1 psi.

Each secondary cyclone will be 18 ft OD, 40 ft 6 in. high, will weigh approximately 347,000 lbs, and will be refractory brick-lined.

The cyclone will operate as follows: 21,000 acfm of flue gas will be conveyed to the lower gas chamber past an orifice plate and a stationary turning vane which will impart a rotary motion to the gas. Centrifugal force will direct the particulate toward the outer wall of the vessel where it will be engaged by a scondary gas stream of 14,000 acfm and will be directed spirally downward. Particulate will be collected in the base of the vessel and conveyed to silos. The flue gas which is cleaned to 0.0368 gr/acf will be combined with cooling air from the PFB combustor to result in an overall grain loading of 0.0123 gr/acf entering the gas turbine.

2.1.4.5 Material Handling

Coal Handling System - The coal handling equipment is shown on the Conceptual Flow Diagram - Coal Handling, Figure 2.27 and on the plant arrangement drawing, Figures 2.7, and 2.8. On-site trackwork will handle 100 car unit trains for coal as shown in the plant arrangement. An overhead railroad trestle is provided for coal unloading and a "V" shaped bunker is provided below the trestle for coal live storage of 10,000 tons. A rotary plow feeder provided below the bunker controls the rate of flow at 300 or 600 tph and feeds coal to the reclaim conveyor in the tunnel.

The reclaim and inclined belt conveyors (330 ft long and 300 ft long respectively) collect coal in the tunnel below the bunker and deliver it above ground to the transfer and sampling house.

A cantilevered belt conveyor (125 ft long) or a belt conveyor (230 ft long) will discharge coal to the stockpile to develop reserve storage, up to 300,000 tons, or will deliver coal from the transfer and sampling house to the crusher house.

Belt conveyors deliver coal from the crusher house to the station above the silos and distribute coal to the silos.

An as-received sampling system complete with samplers, feeders, crusher, reject equipment, and all chutes, is located in the transfer and sampling house. A surge bin having a 2 hour storage capacity of approximately 54 tons, fabricated of A-36 steel and lined with abrasion resistant steel, is also located in the crusher house.

The cascading belt conveyors and subsequent coal handling equipment are modular in that a set of equipment is provided for each PFB combustor with a total of six sets for the entire plant. Figure 2.27 shows the arrangement for each module. Six 25 ft diameter x 26 ft straight side height coal silos, each having 12 hour storage capacity of approximately 330 tons, are provided. The silos will be made of A-36 steel with stainless cladding at the outlet of each bottom cone.

Six impact mill systems will be furnished. Each system will have a capacity of 35-40 tph and will be furnished with a centrifugal fan, classification separator, cyclone separator, bag filter with exhaust blower, heater, surge bin, all necessary coal and air ducts and with a rotary valve inlet feeder.

Six pressurized coal injection systems will be furnished, each feeding approximately 885 ppm of coal (53,100 pph). Each coal injection system is supplied through a feeder and scalping screen from a system surge bin and each system will include a primary injector mounted on load cells, a storage injector, motor operated valves, injection rate control, air pressure control, and transport piping to the PFB combustor. For each coal feed, approximately 1,159 scfm of air will be required at 100 psig. The maximum intermittent flow of air for pressurizing the storage injectors will be approximately 1,000 scfm at approximately 175 psig.

CONCEPTUAL FLOW DIAGRAM
COAL HANDLING SYSTEM

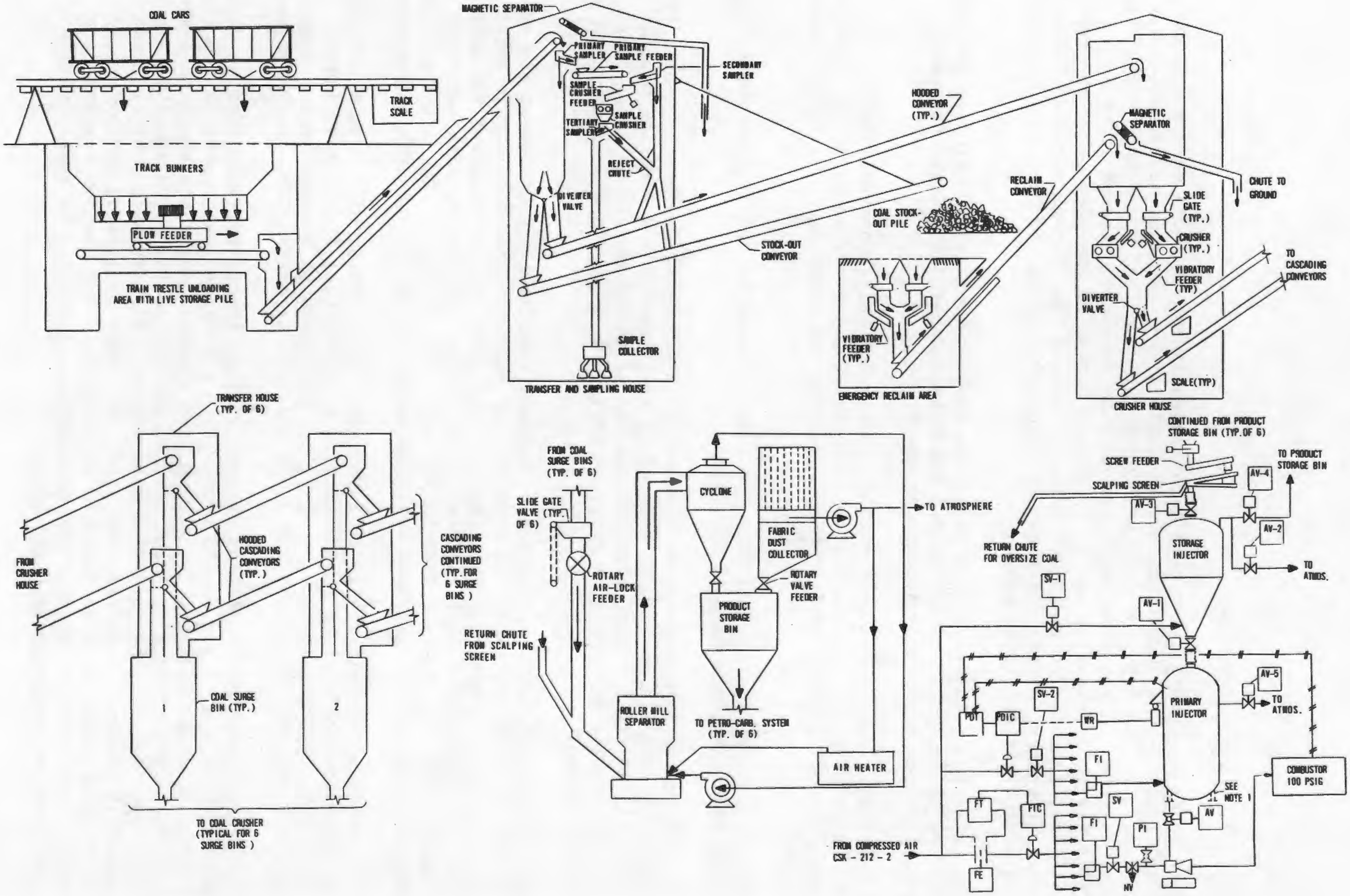


Figure 2.27

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Controls for both the impact mill systems and the injection systems will be located locally and at the main station control room.

Dolomite Handling System - The dolomite handling equipment is shown on the Conceptual Flow Diagram - Dolomite Handling, Figure 2.28 and in the plant arrangement drawings, Figures 2.7 and 2.8. Spur tracks will handle dolomite cars and a track hopper with grating will be provided. A track hopper shed is also provided to protect the unloaded dolomite from weather. Four vibratory feeders at track hopper outlets will control rate of flow at 400 tph to the gathering conveyers which will collect dolomite from the feeders and deliver it to a conveyor going above ground.

The 450 ft long belt conveyor will receive dolomite from gathering conveyors and deliver it to the dolomite storage structure. The storage structure is a 200 ft diameter x 80 ft high domed structure, storing approximately 42,000 tons of dolomite.

Vibrating bin activators and feeders will be used for inducing flow of dolomite for reclaim from the storage structure. Belt conveyors, 335 ft long, each having a capacity of 100 tph, will deliver dolomite from storage to the station above the silos. Cascading belt conveyors will distribute dolomite to plant silos.

Six dolomite injection systems will be furnished, each feeding approximately 310 ppm (18,600 pph). Each injection system is supplied through a feeder and scalping screen from a system surge bin and each system will include a primary injector mounted on load cells, a storage injector, motor operated valves, injection rate control, air pressure control, and transport piping to the PFB combustor. For each dolomite feed, approximately 273 scfm of air will be required at 100 psig. The maximum intermittent flow of air for pressurizing the storage injectors will be approximately 250 scfm at approximately 175 psig.

Controls for the injection systems will be located locally and at the main station control room.

Ash Handling System - The ash handling equipment is shown on the Conceptual Flow Diagram - Ash Handling, Figure 2.29.

The design of the ash system is based on a 15 percent ash coal and 100 percent collection of spent dolomite. The system is designed to remove ash from all six PFB combustors on a continuous basis. Two 1,800 cfm blowers (one spare) will provide the conveying air for the entire system. Two storage silos, including bag filters and dustless unloaders for ash discharge, are provided.

The largest proportion of the ash is obtained from the PFB combustors each of which has an associated ash cooler system which transports, cools and discharges the ash generated in the combustor. It comprises a cooling section, disengaging section, cyclone, pressure seal leg and ash bin.

CONCEPTUAL FLOW DIAGRAM
DOLOMITE HANDLING SYSTEM

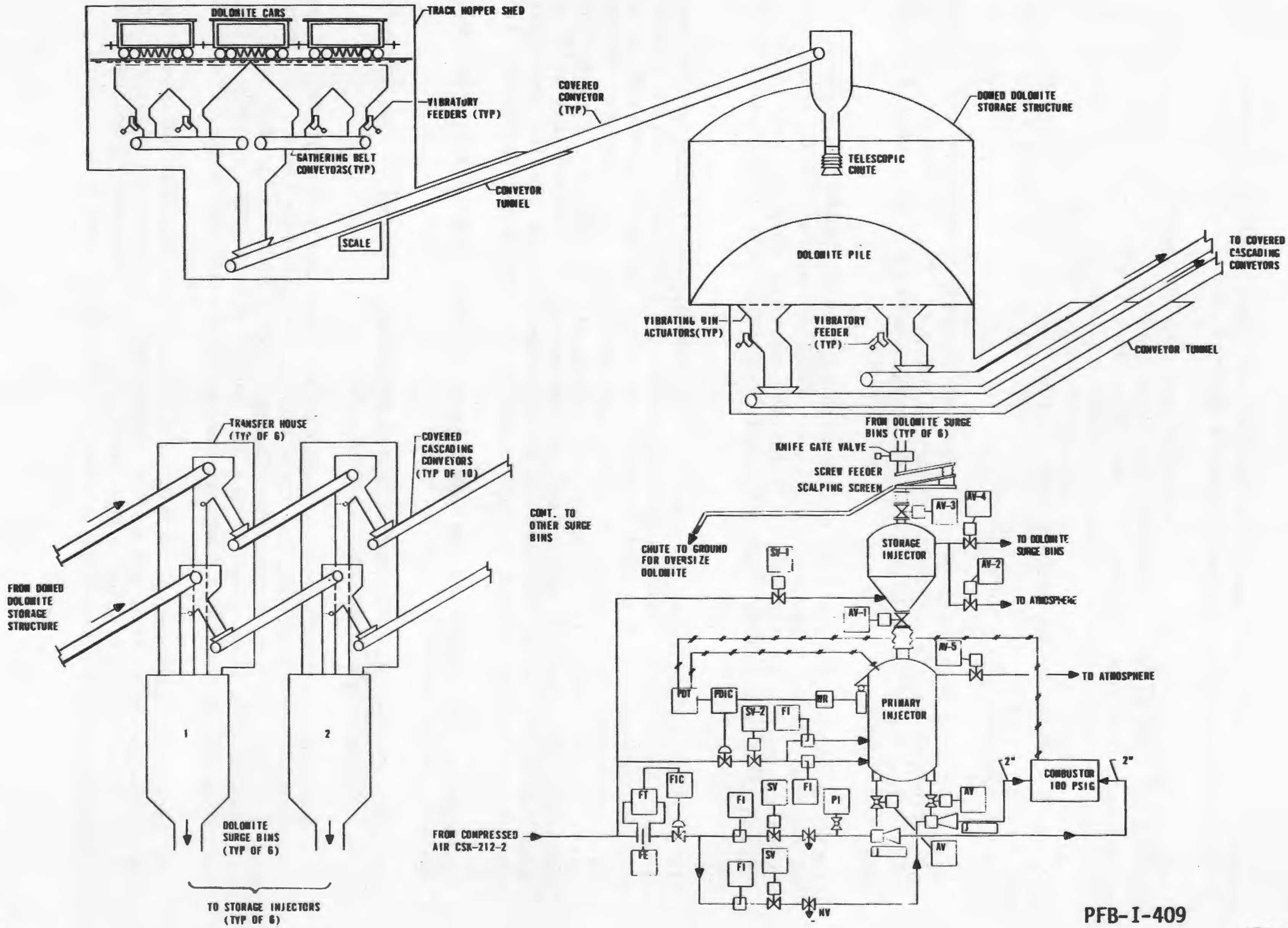

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Figure 2.28

CONCEPTUAL FLOW DIAGRAM ASH HANDLING SYSTEM

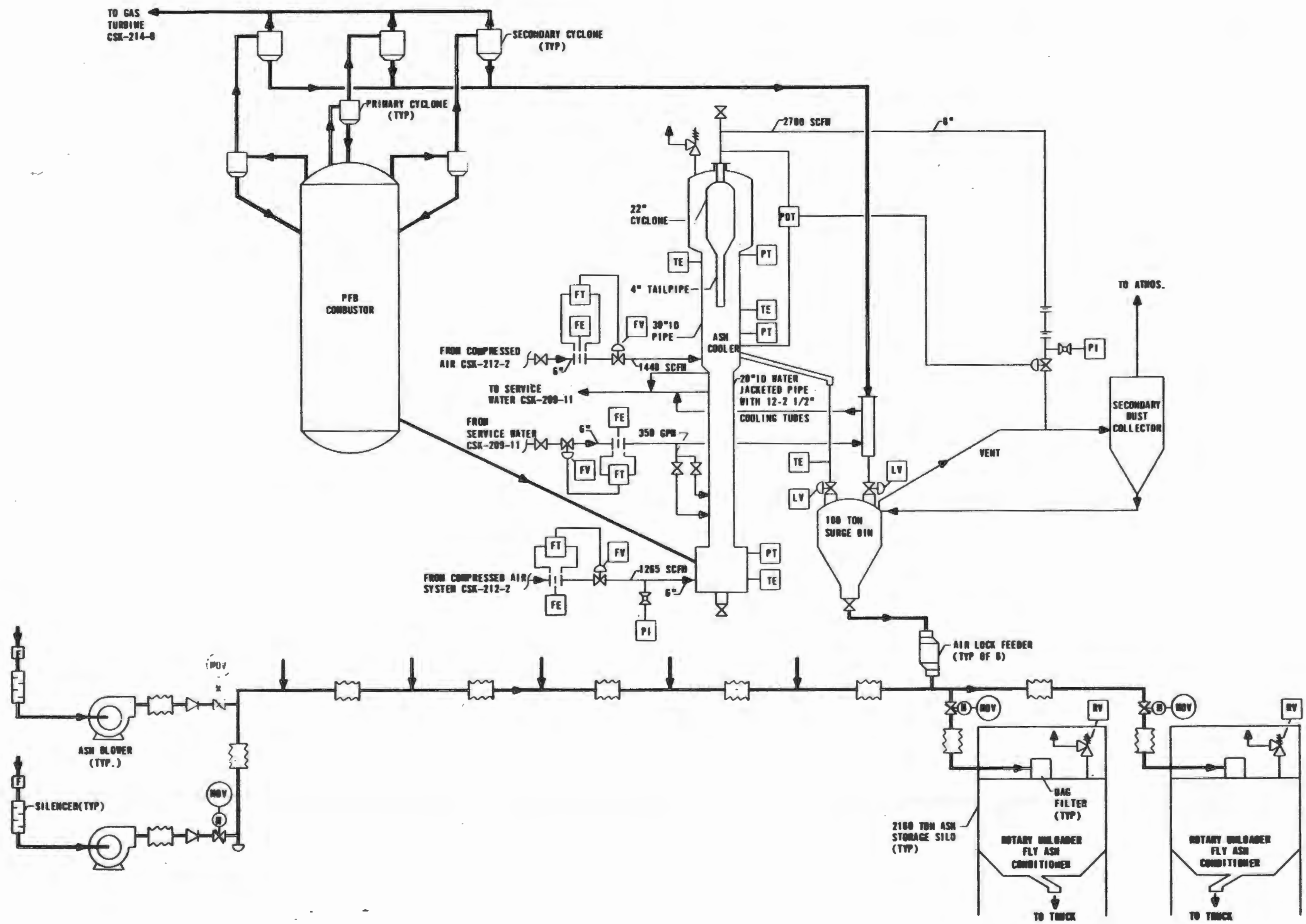

Figure 2.29

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In operation, the solids from the PFB reactor are discharged to an 80' standpipe by means of a refractory lined inclined pipe. The solids are elevated in the standpipe by fluidizing air entering at the bottom. A water jacketed column containing 12 water cooled tubes is designed to cool the solids to below 600°F.

Cooled solids are lifted further to an expanded section in the next 20 ft of the standpipe. This section contains a 30 inch ID fluidized bed which has an 8 inch ID solid discharge line. Additional fluidizing air enters at the bottom of this expanded column. Solids are withdrawn through the discharge line in plug flow to a surge bin. The discharge line has a vertical 40 ft section to provide sufficient pressure drop to the hopper to operate it as an atmospheric bin. The bin is placed on weigh cells monitoring the discharge rates. The ash bin can be emptied any time during operation without interrupting the solids flow to the bin.

Dirty gases are passed through a 22 inch ID internal cyclone located at the top of the standpipe. The standpipe has a 4 ft high by 48 inch diameter section at the top to accommodate the cyclone. Gases from the cyclone pass through restricting orifices and a pressure control valve before exhausting to a bag filter.

Approximately 22,000 pph of ash from each PFB combustor will enter each cooler. Approximately 350 gpm of cooling water will be supplied to each ash cooler from the component cooling water system. Two streams of compressed air at 100 psig will be supplied to each cooler. The lower stream, which will consist of approximately 1,265 scfm and the upper stream of approximately 1,440 scfm, will keep the ash flowing through the cooler. Ash from each cooler will discharge into a 15 ft diameter by 20 ft straight-side height, 100 ton capacity, surge bin.

The solid waste from the PFB combustor and the secondary hot gas cleanup system will be conveyed to two 50 ft diameter by 78 ft high storage silos having a capacity of approximately 2,160 tons each and equipped with unloaders. The material will then be loaded into trucks and disposed of on site.

It is estimated that a total of approximately 135,000 lb/hr of dry solids will be produced. The solids will be composed of fly ash, calcium sulfate and calcium and magnesium oxides. Based on a bulk density of 65 ppcf and a 60 percent plant capacity factor, approximately 250 acre-ft of this material will require disposal annually. Over the life of the plant, approximately 500 acres of land will be needed for disposal. The annual disposal operation will include placing this material over 50 acres, 5 ft deep, and covering this area with 8 inch of topsoil and seeding. Over the 30 year proposed plant life, it is estimated that this disposal site will be developed to a total height of between 15 and 20 ft.

2.1.4.6 Steam System

Boiler Equipment - Six drum-type, self-supporting, package-type boilers will be provided, each generating approximately 217,700 pph of steam at 850 psia, 825°F from the high pressure superheater and approximately 53,150 pph at 180 psia saturated from the low pressure drum (Figure 2.2). Each package will include high and low pressure drums and headers, superheater, economizer, bypass duct and exhaust stack, inlet duct, ladders, platforms, insulation, lagging, 10 gage reinforced steel casing, and standard boiler trim including safety valves.

Steam from each low pressure boiler drum will be discharged to a common header at a rate of approximately 53,150 pph at 180 psia. A stop-check valve, required by Code, will be followed by a motor operated shutoff valve to permit isolation of each unit. Approximately 236,000 pph of 25 psia steam will be used in the deaerator for heating and deaerating condensate.

Steam from each high pressure boiler drum will be discharged to a common header at the rate of approximately 217,700 pph at 850 psia, 825°F. A stop-check valve, required by Code, will be followed by a motor operated shutoff valve to permit isolation of each unit. Approximately 1,306,239 pph of steam at 800 psia, 825°F will be supplied to the steam turbine. A connection on the main steam header will be used to supply auxiliary steam for building heating, as well as for turbine gland steam sealing, through a pressure reducing station.

Steam Turbine - The steam turbine will be a tandem-compound four-flow readmission turbine with 23 inch last-stage blades operating at 3,600 rpm. Output will be 195,293 KW at the rated design steam conditions of 800 psia and 825°F at the throttle, exhausting at 2 inch Hg abs, and 0.5 percent makeup. The turbine generator will be supplied with an electro-hydraulic control system and lube oil system.

The generator will be rated 200 MW and will operate at 3,600 rpm, 22 KV, 3 phase, 60 Hz, and 0.9 PF. The unit will have a 0.58 short-circuit ratio. A solid-state excitation system will be furnished.

Also included with the steam turbine generator equipment will be a supervisory instrumentation system, hydrogen coolers, and other accessories necessary for a complete installation.

Hydrogen, at 30 psig, will be circulated through generator coolers to cool the generator rotor. Hydrogen seal oil coolers will be included with the turbine generator. The generator hydrogen coolers, seal oil coolers, and lubricating oil cooling water requirements will be satisfied by utilizing a component cooling water heat exchanger.

A control system will be provided to maintain the temperature of the hydrogen leaving the coolers at a preselected value recommended by the steam turbine generator manufacturer.

The cooling water system will control the hydrogen temperature leaving the coolers by modulating a pneumatically actuated control valve in the common cooling water discharge line from the coolers. The temperature control will be based on the temperature of the hydrogen in the common cold hydrogen stream leaving the coolers. All controls will be mounted locally and will be pneumatically operated.

The turbine lube oil system will consist primarily of a main oil reservoir on which will be mounted two AC auxiliary oil pumps and a DC emergency oil pump. Also on the main oil reservoir there will be two full-capacity tube type oil coolers. A shaft-driven main oil pump will be furnished as part of the front standard. Interconnecting piping, fittings, and valves will also be included with the turbine.

An initial oil charge will be furnished with the turbine. A control system will be provided to maintain the temperature of the lube oil leaving the lube oil coolers at a pre-selected value recommended by the turbine manufacturer. The cooling water system will control the lube oil temperature leaving the coolers, by modulating a pneumatically operated control valve in the common cooling water discharge line from the coolers. The temperature control will be based on the temperature of the lube oil in the common header downstream of the coolers.

2.1.5 Plant Operation and Control

The entire combined cycle plant will be controlled by the unit Coordinated Control System. The Coordinated Control System will be an integrated unit system wherein the megawatt demand automatically establishes gas turbine loading and PFB combustor firing rate in parallel. The response of the PFB combustor and gas turbines will be coordinated and maximized, consistent with reasonable rate limits.

The waste heat boilers and steam turbine will be provided with an automatic following mode of operation. With this mode of operation, megawatt demand will automatically establish waste heat boiler steam generation rate with the turbine control valves modulated to maintain a constant turbine throttle pressure.

2.1.5.1 PFB Combustor and Gas Turbine Control System

Control systems utilizing solid-state electronic components will be provided for PFB combustor-turbine control. The control system will place firing rate demands on the PFB from a coordinated control system. The coordinated PFB combustor-turbine controls will be designed to maintain turbine inlet temperature required for the load. Coal flow rate, with the resulting turbine inlet temperature, will establish generator electrical output. The firing rate demand will vary fuel flow to the PFB combustor, and PFB combustor heat exchanger flow, resulting in the required temperature to carry the load. A simplified control schematic is shown in Figure 2.30 and the air and combustion gas Conceptual Flow Diagram is shown in Figure 2.31.

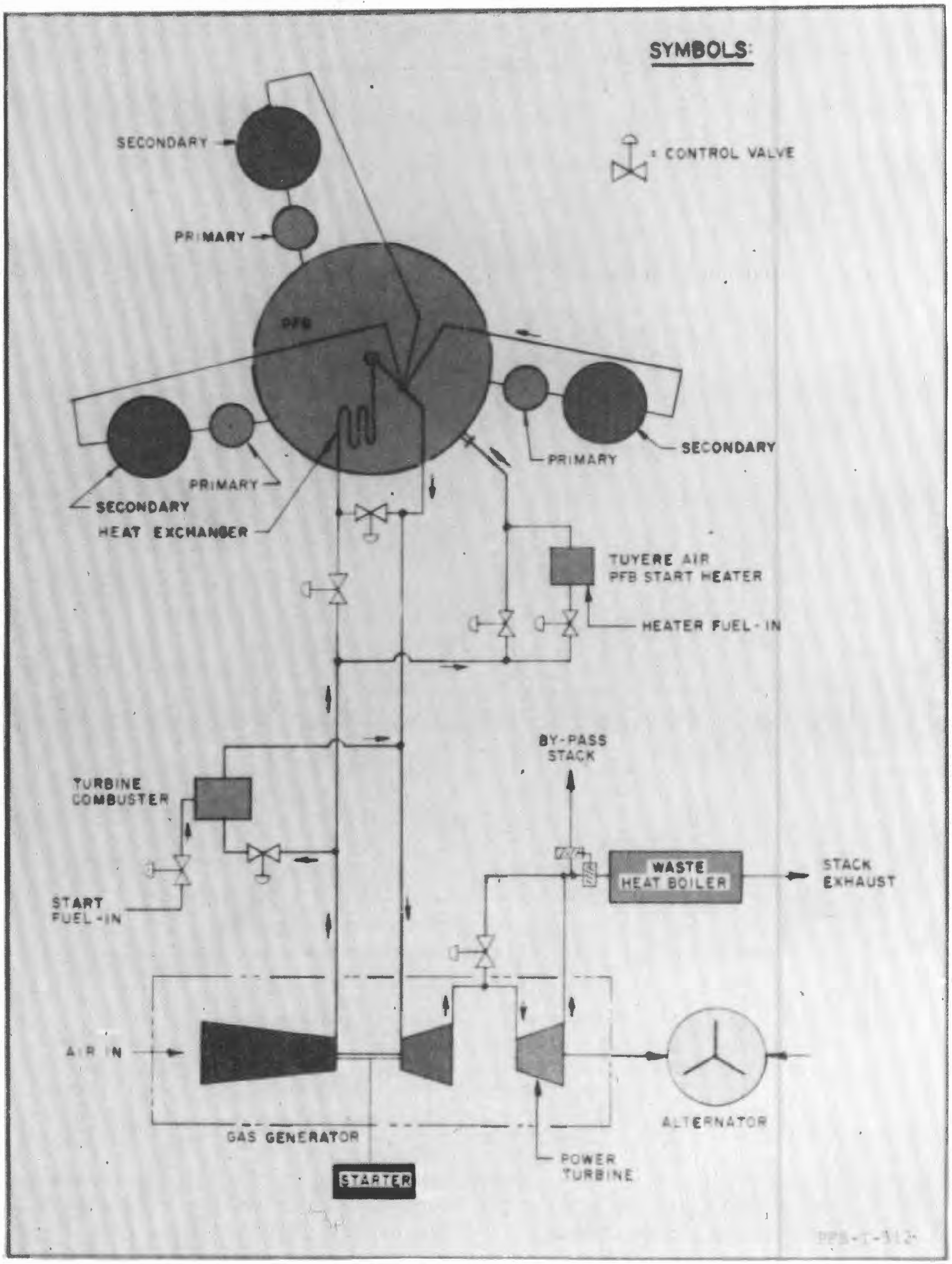

SYMBOLS:
= CONTROL VALVE
SECONDARY
PRIMARY
PFB
SECONDARY
PRIMARY
SECONDARY
PRIMARY
SECONDARY
HEAT EXCHANGER
TUYERE AIR
PFB START HEATER
HEATER FUEL-IN
TURBINE
COMBUSTER
START
FUEL-IN
BY-PASS
STACK
WASTE
HEAT BOILER
STACK
EXHAUST
AIR IN
GAS GENERATOR
STARTER
POWER
TURBINE
ALTERNATOR

Figure 2.30

CONCEPTUAL FLOW DIAGRAM
AIR AND COMBUSTION GAS

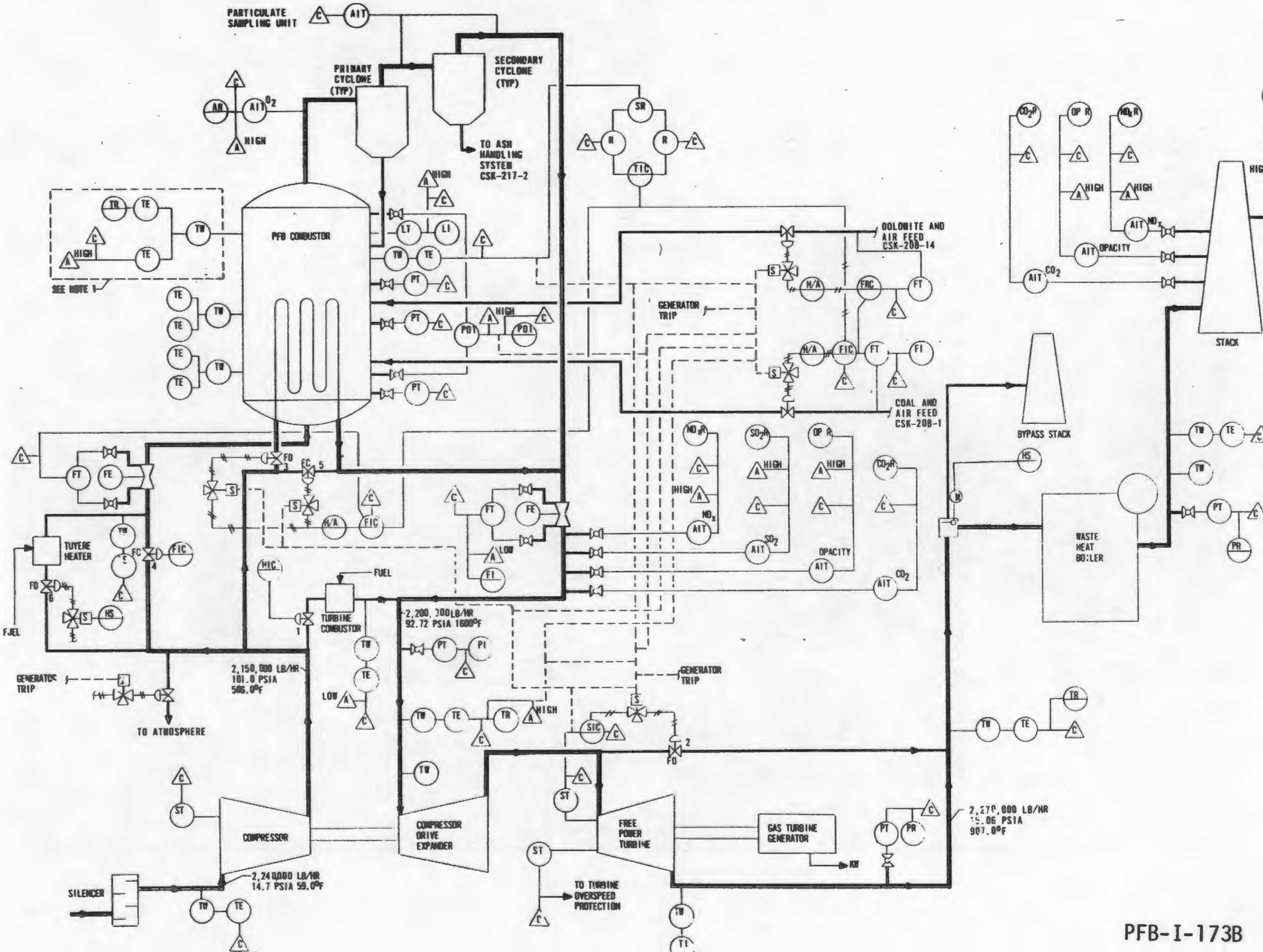


Figure 2.31

2-62

PFB-I-173B

Coal and dolomite will be transported pneumatically from the primary injector to the PFB combustor, with dolomite feed rate being automatically ratioed to the coal feed rate. The PFB combustor firing rate control system will respond to signals from the following sources:

Gas turbine inlet temperature, to maintain temperature required for load and to avoid over-temperature.

PFB combustor bed temperature, to maintain temperature required for load and to avoid over and under-temperature.

Blowoff valve system, to shut off fuel when gas turbine is tripped.

Fuel-air ratio control system, to avoid overfeeding coal.

A tubular air heat exchanger which is installed in the PFB bed will cool the bed and contribute to the temperature control of the bed. Cooling airflow will be varied by a control system containing automatic modulating valves, which will provide control of bed temperature.

A bed level control system will be provided to automatically regulate the discharge rate of calcines from the PFB combustor.

An automatic trip feature will protect the turbine from overspeed and other abnormal conditions. Upon loss of generator load, an automatic 100 percent capacity system will release turbine inlet gas to atmosphere or the locker boiler.

Gas turbine/PFB combustor start-up and operating description is as follows: (Refer to Figure 2.30).

a. At initiation of start-up, valves No. 1 and 2 are open and valves No. 3, 4, 5 and 6 are closed.

b. The air starter is energized and the gas turbine unit is brought up to turbine combustor light-off speed.

c. Turbine combustor is ignited and the gas generator is accelerated to synchronized idle speed.

d. When the gas generator stabilizes, valve No. 6 is opened and the tuyere heater is ignited allowing warm fluidizing air into the PFB combustor. At 1100°F, coal and dolomite is fed to the reactor while opening valves No. 3 and 5 for introduction of air into cooling coils and to maintain system airflow. Air proportion is 40 percent fluidizing/60 percent cooling.

e. At 1650°F, valves No. 3 and 5 stabilize the temperature in the reactor. The valves are adjusted by a selector control delay with input signals from either generator or temperature indicating transmitter. Valve No. 3 closes and No. 5 opens to maintain constant (set point) bed temperature and control the air bypass ratio simultaneously.

f. At controlling temperature of 1650°F and turbine synchronized, valve No. 4 is gradually opened. Fuel feed to the tuyere heater is restricted by shut-off valves.

NOTE: Valve No. 2 has various functions as a regulating valve, to prevent overspeed, synchronize turbine RPM and provide dump action on load reduction.

2.1.5.2 Steam Turbine Control System

The turbine controls will be designed to maintain throttle pressure by opening or closing turbine control valves, which will respond to steam system supply and protect the turbine from overpressure. The controls will also govern the admission of low pressure induction steam, which will represent a portion of the total load carried.

The turbine-generator will be equipped with an electro-hydraulic control system to provide speed and acceleration control, and emergency functions which will trip the unit on overspeed, low vacuum, thrust-bearing wear, low bearing oil pressure and other abnormal conditions. Operator's subpanels will be mounted on the main control board, and will be included as part of the system and will contain the operating and testing controls.

A turbine supervisory system will be located in the main control room which will provide the following monitoring and alarming functions: vibration, eccentricity, spindle position, control valve position, speed, and rotor position. A turbine metal temperature recorder will be provided to guide turbine metal and main steam temperature matching.

In an emergency trip-out of the steam turbine generator, the bypass dampers on all operating waste heat boilers will simultaneously open and permit the exhaust gases from each gas turbine to be discharged to atmosphere through its bypass stack.

Each bypass damper will remain open, i.e., will discharge turbine exhaust to atmosphere, permitting the gas turbine to be operative until the steam turbine is ready to go into service, at which time, the bypass damper will be closed permitting the hot gases to traverse the waste heat boiler, generating the steam required for operation of the steam turbine.

2.1.5.3 Waste Heat Boiler Control System

The waste heat boiler controls will be designed to maintain waste heat boiler low and high pressure steam header pressures required for various loads.

The load demand signal will position admission dampers to direct the exhaust gases over the high and low pressure steam generating tubes to produce the required steam header pressure to carry the steam generator load.

The high pressure steam drum will generate superheated steam. A spray attemperator system, utilizing feedwater, will be used to maintain superheat temperature within desired limits.

Each boiler will have a balancing system to automatically maintain coordination between feedwater entering the two drums and condensate entering the economizer, ensuring each economizer will contribute its required share to the overall heat input.

A feedwater flow signal will be used as a set point to the condensate control valve at the economizer inlet. A signal from a condensate flowmeter at the economizer inlet will, if necessary, make final adjustments to the control valve position.

Remote manual operation of the condensate control valve from the main control room will be provided.

2.1.5.4 Computer System

A computer system will be provided to obtain digital computer supervisory (set point) control of the analog control systems and to monitor and log the various plant parameters. The system will contain the following monitoring devices: an operator's console, a logging typewriter, an alarm typewriter, and a utility typewriter.

Two computers will be provided, one for control, and one for data logging and calculations.

The system will be capable of performing the following functions:

a. Coordinate and direct the analog controllers as required to start, stop,operate at steady-state, optimize, protect and communicate for the complete plant.

b. Scan-alarm of analog inputs, periodic log, demand log, group review, postmortem review, analog trend recording, and digital trend.

The system will be used for analog and digital inputs and those contact closures used for initiating the postmortem review.

2.1.5.5 Instruments

Sufficient instrumentation will be provided to permit safe operation of the unit if the computer system is out of service. The monitoring devices for these instruments will be located on the main control board or at local stations, depending upon their degree of importance.

A minimum of local instrumentation will be provided for local monitoring and equipment calibration. These devices will be primarily thermometers and pressure gages.

2.1.5.6 Safety and Plant Protection

The plant will be provided with a reliable system of protection to maintain plant safety in the event something unforeseen occurs. This system will override all other plant controls to return the plant to a safe condition, either operational or shutdown. The protection system consists of three basic modes of operation: (1) Emergency Shutdown, (2) Emergency Trips and (3) Runbacks, Run-ups and Limits. In emergency shutdown, the plant will be shut down normally using the master supervisory control system. Emergency conditions can occur, however, which will require emergency shutdown procedures. The emergency shutdown for the proposed systems can result from several different types of failures. The major categories are as follows:

a. Loss of coal or flow control.

b. Failure of particulate removal equipment causing particulate overload.

c. Loss of airflow to the bed.

d. Electric generator load loss.

To maintain safe operation of a complex power plant, system trips have to be included in the control scheme to interlock the various plant components. A trip results in an immediate termination of fuel flow, hot air dump, possible steam dump and open generator breaker. A list of the conditions that could cause a trip and alarm are:

Loss of Turbine Generator Load
High Bed Temperature
High Particulate Carryover
Loss of Coolant Flow
Generator Overspeed
Turbine or Compressor Vibration
Combustor High Outlet Temperature
Gas Turbine High Inlet Temperature

2.2 PILOT PLANT CONCEPTUAL DESIGN

The pilot plant is being designed and will be constructed by converting an existing MOD POD Total Energy Power Generating Station located at Curtiss-Wright's Wood-Ridge, N. J. facility (Figure 2.32). The station consists of a gas turbine driven alternator and a waste heat recovery boiler. This station currently provides the facility's requirement for electric power and steam for process and heating. The gas turbine's liquid/gas fueled combustor will be replaced with a pressurized fluidized bed combustor capable of operating on crushed coal.

A simplified flow diagram of the pilot plant is shown in Figure 2.33. Note that the steam produced in the pilot plant waste heat recovery boiler will continue to be used for facility process purposes at Wood-Ridge as compared to powering a steam turbine driving an electric generator in the commercial PFB utility power plant configuration. An artist concept of the PFB pilot plant is shown in Figure 2.34.

2.2.1 Pilot Plant Performance

The computerized performance model of the CW 6515 gas turbine driven Total Energy System has been modified to simulate the Pilot Plant Coal-fired PFB system. The performance of the gas turbine section of this PFB system was analyzed and is summarized in Table 2.9. Pressure drop of 4 in. H_2O at the inlet and 10 inches H_2O at the exhaust was used in the analysis. Part power operation from base to 10 percent power is shown.

The calcification, sulfation and combustion reactions, the solids input and removal, the change in engine match for the relatively low LHV and high pressure drop of the PFB system, and the resultant changes in thermodynamic properties of the exhaust gases were all accounted for in the computer model.

The current MOD POD 8 power system which will be adapted for the Pilot Plant was installed in 1970 primarily as a demonstration and development unit. It employs an aircraft derivative gas turbine, the J65 turbojet, and a single stage power turbine coupled through a gearbox to an 1800 RPM alternator. Several components of this system, are of older types, designed to special restrictions not applicable to a present day utility electric power plant. The gas generator turbine was limited in diameter to minimize the frontal area of the turbojet and therefore is approximately five points lower in efficiency than a modern industrial turbine of the same capacity would be. The power turbine was designed for peaking duty where low first cost dominates over high cycle efficiency. For economic reasons, therefore, it is a single stage design running at 7500 RPM to minimize its diameter. Base load design would dictate both a multistage design and direct drive at 3600 RPM for a 60 Hz generator. Change to a two stage turbine of larger diameter would improve turbine efficiency by four points while elimination of the gear box and incorporation of a modern standard 3600 RPM alternator would gain four percent in power. The overall impact of these changes to improved design standards plus a four percent increase in turbine flow capacity and airflow to achieve better compressor matching would be a 34 percent increase in gas turbine output power (optimized plant performance). A comparison of the pilot and commercial plant performance at the design condition is shown in Table 2.10.

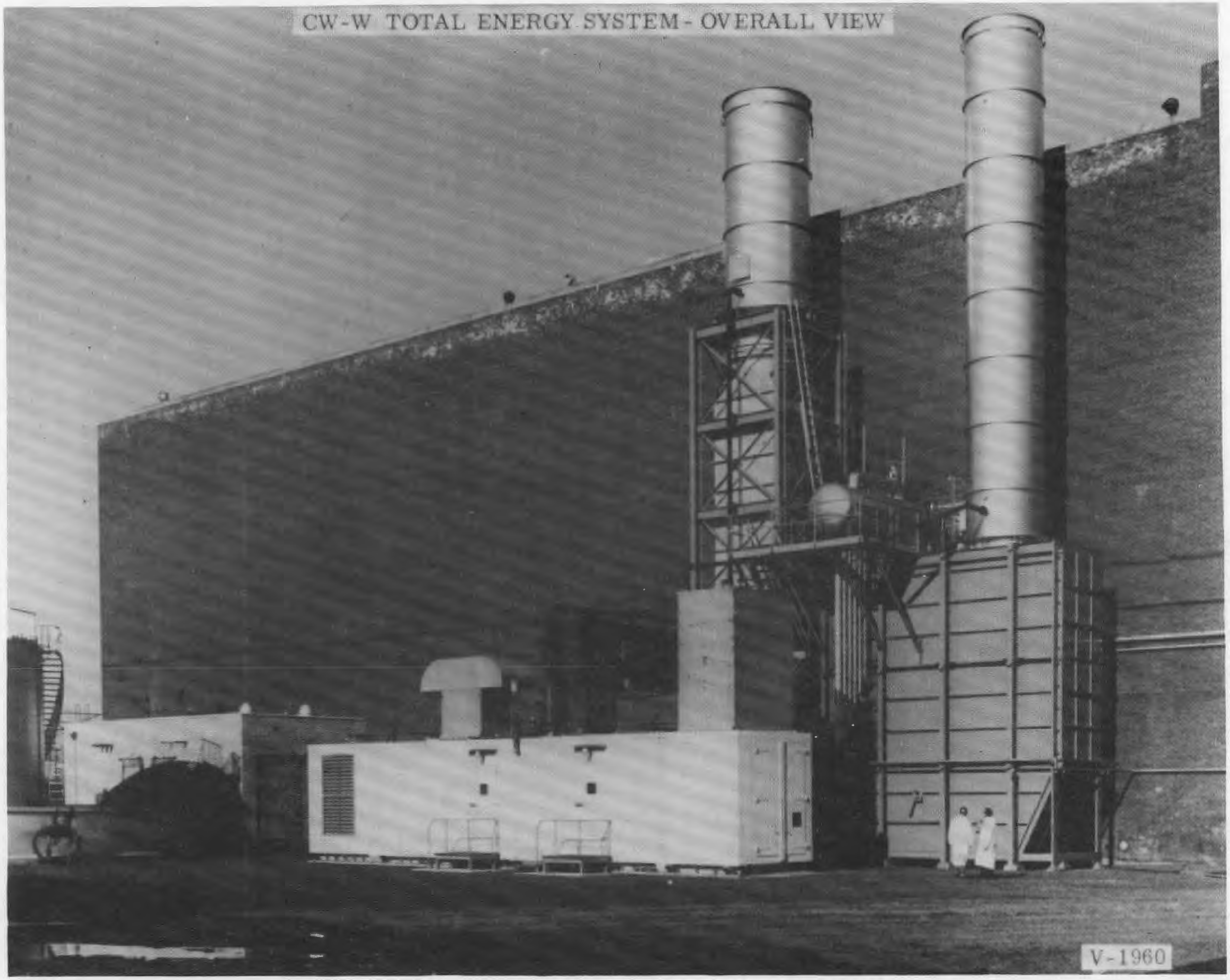


Figure 2.32

COMBINED CYCLE PILOT PLANT SIMPLIFIED FLOW DIAGRAM

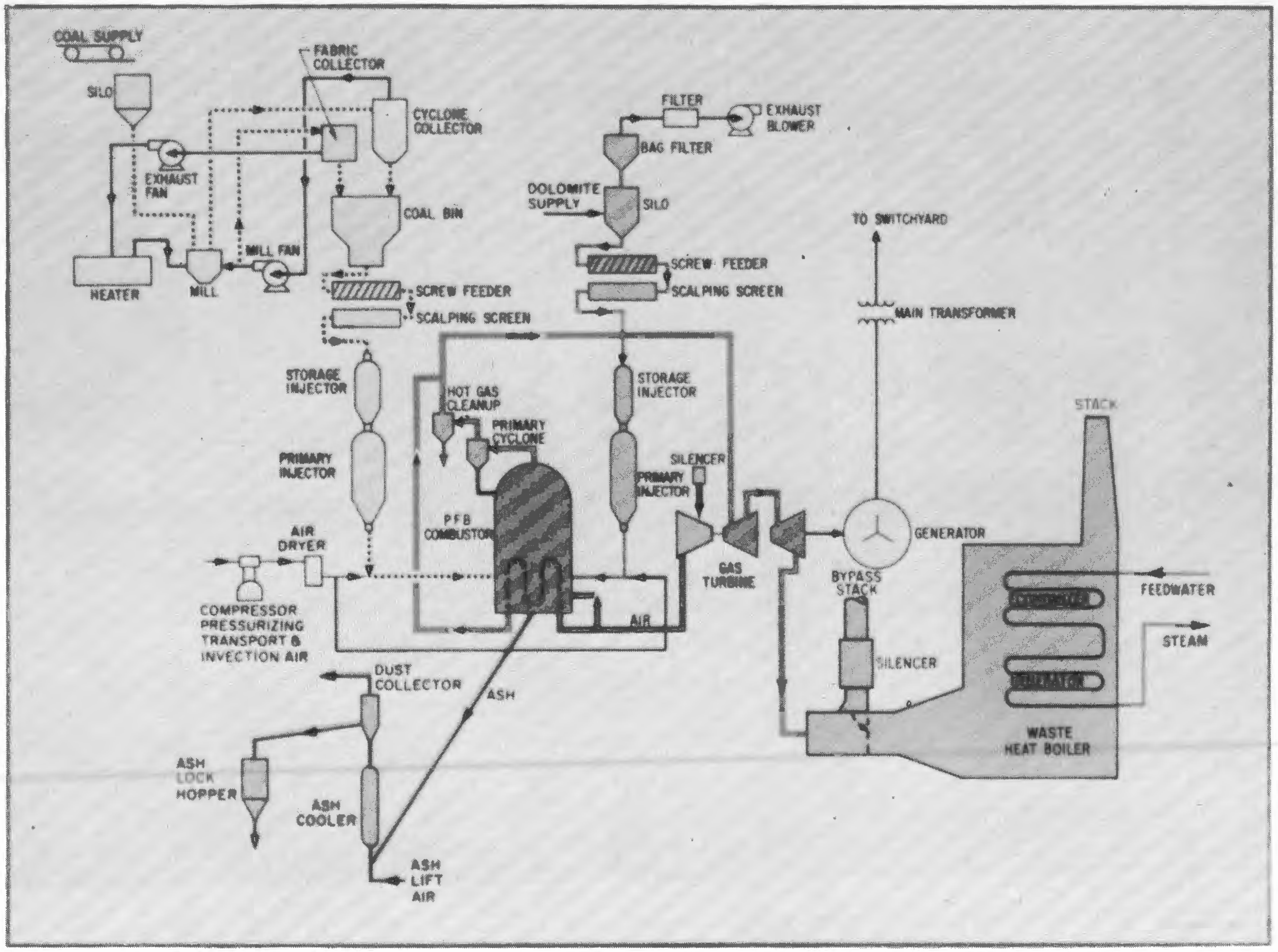


Figure 2.33

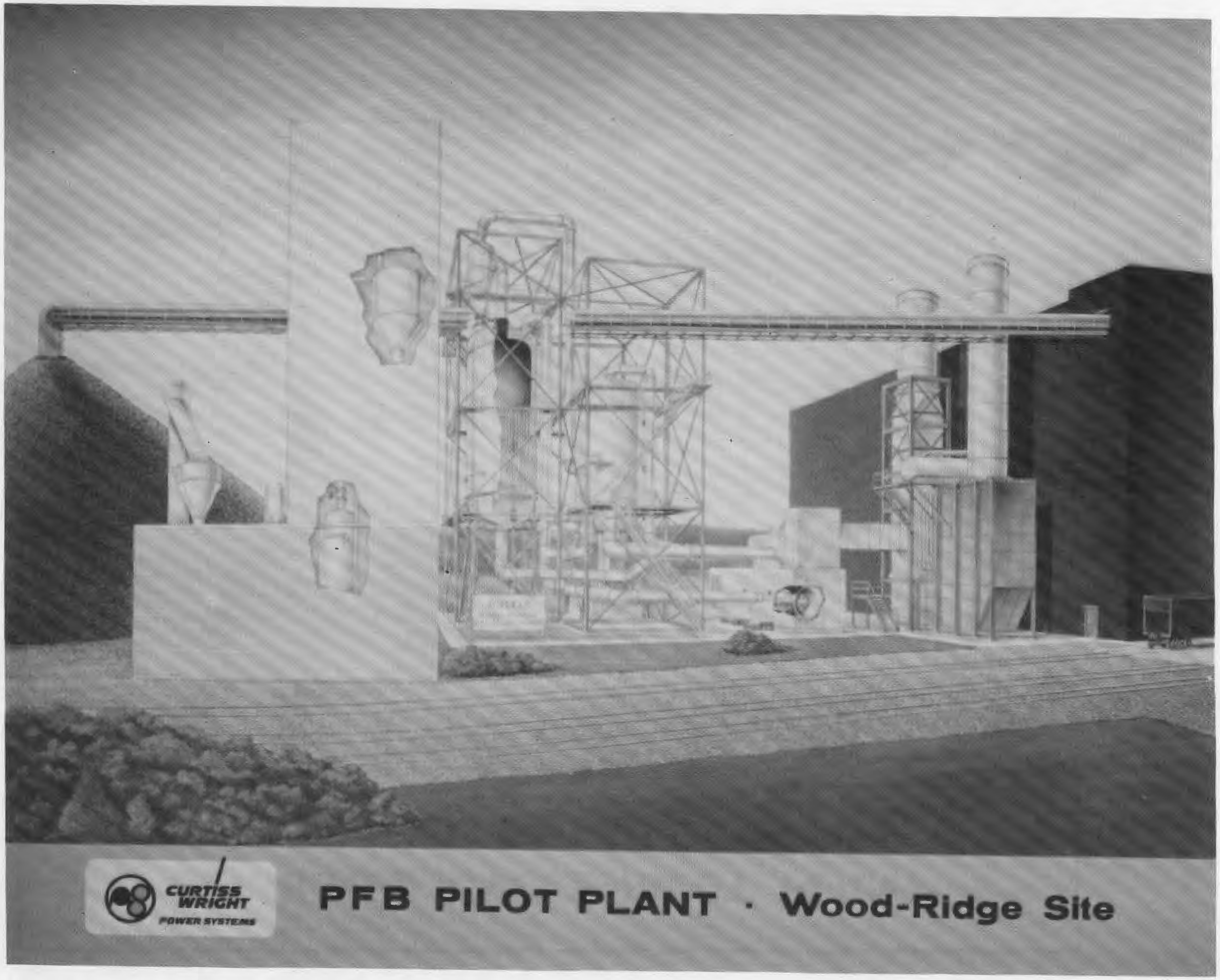

CURTISS WRIGHT
POWER SYSTEMS
PFB PILOT PLANT · Wood-Ridge Site

Figure 2.34

TABLE 2.9

PFB PILOT PLANT CYCLE PERFORMANCE DATA

OVERALL UNIT PERFORMANCE - (SEA LEVEL STANDARD)

Percent Gas Turbine Power	100	80	60	Sync Idle
KW (Gas Turbine)	7150	5720	4920	500
Heat Release (LHV) . . . Btu/Hr x 10^6 (Based on Coal and Sorbent Combined LHV)	129.2	110.0	92.0	5.16
Heat Loss (Bed Material Off-Take) . . Btu/Hr x 10^6	2.075	1.489	1.475	.827
Compressor Inlet Airflow . . . Lb/Sec	119.9	112.6	103.4	92.4
ΔP Inlet . . . In. H_2O	4.0	4.0	4.0	4.0
Exhaust Airflow . . . Lb/Sec	121.5	113.8	104.3	92.6
PT Exhaust Temperature . . . °F	961.1	895.8	844.2	633.2
ΔP Exhaust . . . In. H_2O	10	10	10	10
Bed Solid Off-Take . . . Lb/Sec	1.393	1.187	.991	.555
Coal Flow . . . Lb/Sec	2.845	2.422	2.024	1.136
Sorbent Flow . . . Lb/Sec	1.328	1.130	.945	.53
Compressor Rotor Speed . . . rpm	8155	7845	7460	7000

	Fuel Heating Values
Coal and Sorbent Combined LHV . . . . Btu/Lb Coal	12,623
for a. Coal HHV . . . Btu/Lb Coal	13,090
b. Coal LHV . . . Btu/Lb Coal	12,691
c. Calorific Value for Bed Sulfidation Reaction. . Btu/Lb Coal	+265
d. Calorific Value for Bed Calcination Reaction. . Btu/Lb Coal	-333
Combustion Efficiency . . . %	99

TABLE 2.10

COMPARISON OF PILOT AND COMMERCIAL PLANT PERFORMANCE
SELECTED DESIGN POINT DATA

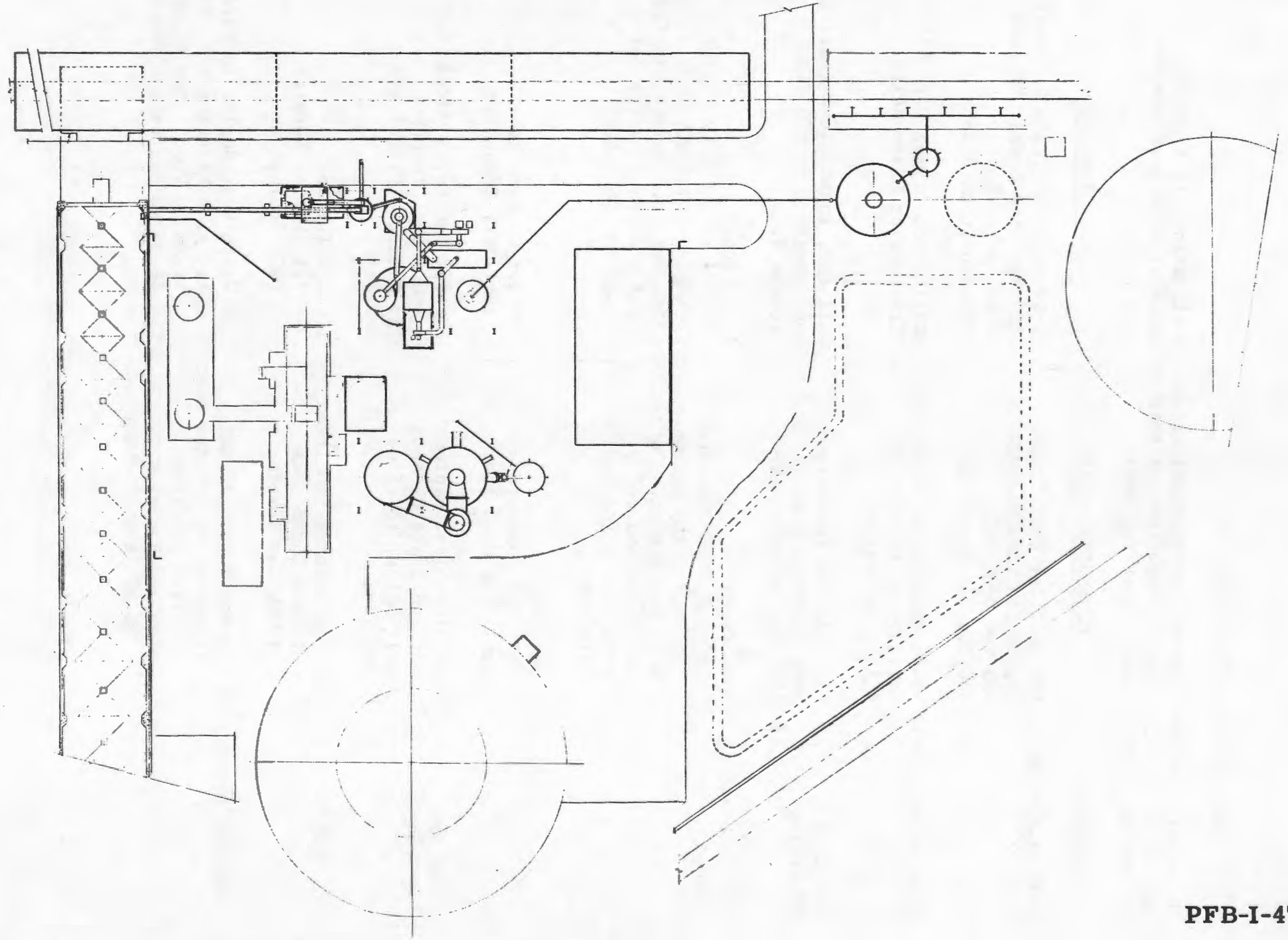
		Current Equipment	Optimized Pilot Plant	Commercial Plant Per Unit	Commercial Plant Total
Electric Power from Gas Turbine	KW	7,150	9,580	48,240	289,000
Electric Power from Steam	KW	–	6,470	32,300	194,000
Heat Rate	Btu/KW/Hr	–	8,725	8,530	Same
Coal Flow	pph	10,240	10,660	52,450	314,700
Airflow	pps	120	125	624.6	3,748
PFB Air Inlet	°F	505	506	506	Same
PFB Gas Exit	°F	1,650	1,650	1,650	Same
PFB Cooling Air Exit	°F	1,573	1,573	1,573	Same
Turbine Inlet	°F	1,600	1,600	1,600	Same
Power Turbine Exit	°F	961	906	906	Same
Process Steam at 175 psig	pph	58,000	–	–	–

2.2.2 Pilot Plant Arrangement

The pilot plant preliminary arrangement (plan and elevation) is shown in Figures 2.35 and 2.36. A comparison of this arrangement with that for the commercial plant concept is as follows:

PROCESS	COMMERCIAL PLANT	PILOT PLANT
Coal Receiving	100 Rail Car Unit Trains 10,000 Ton Live Storage 330 Ton Coal Silo System 300,000 Ton Stock Pile	10-12 Rail Car Train Per Week 1700 Ton Live Bunker Storage 10 Ton Surge Hopper 1200 Ton Stock Pile
Coal Preparation	35-40 Tons/Hr (6) Crusher, Milling and Drying With Oil-Fired Heater	Milling and Drying With Oil-Fired and/or Steam Heater
Dolomite Receiving	Rail Car, Bottom Unload Belt Conveyor System 4500 Ton Storage Silo	Rail Car, Pneumatic Unloading and Conveying to 600 Ton Storage Silo
PFB Combustor System	6 of Each: 28' I.D. PFB Combustor Triple Primary Cyclones With Ash Return. Pneumatic In-Feed and Transport System for Coal & Dolomite	1 of Each: 12' - I.D. PFB Combustor Single Primary Cyclone With Ash Return.Pneumatic In-Feed and Transport System for Coal and Dolomite
	1 per set Start-up Combustor Auxiliary Combustor	Start-up Combustor Auxiliary Combustor
Final Gas Clean-Up	Initial Choice, Cyclone for 2nd Stage Cleanup Final Choice, to be determined	Initial Choice, Cyclone For 2nd Stage Cleanup 2nd Choice - Gravel Bed Filter
Gas Turbine	6 - Gas Turbines in Three Double Ended Sets 50 MW/Gas Turbine	1 - Gas Turbine 7.1 MW/Gas Turbine (42% Scale)
Combined Cycle	1 - Steam Turbine Plant Complete With Waste Heat Boiler, Condenser, Cooling Tower, etc. 200 MW Steam Turbine	1 - Waste Heat Boiler in Parallel with Existing Boilers Steam to Wood-Ridge Plant (6.0 MW Equivalent Power)

GENERAL ARRANGEMENT
PFB PILOT PLANT - PLOT PLAN



PFB-I-470

Figure 2.35

GENERAL ARRANGEMENT
PFB PILOT PLANT - ELEVATION

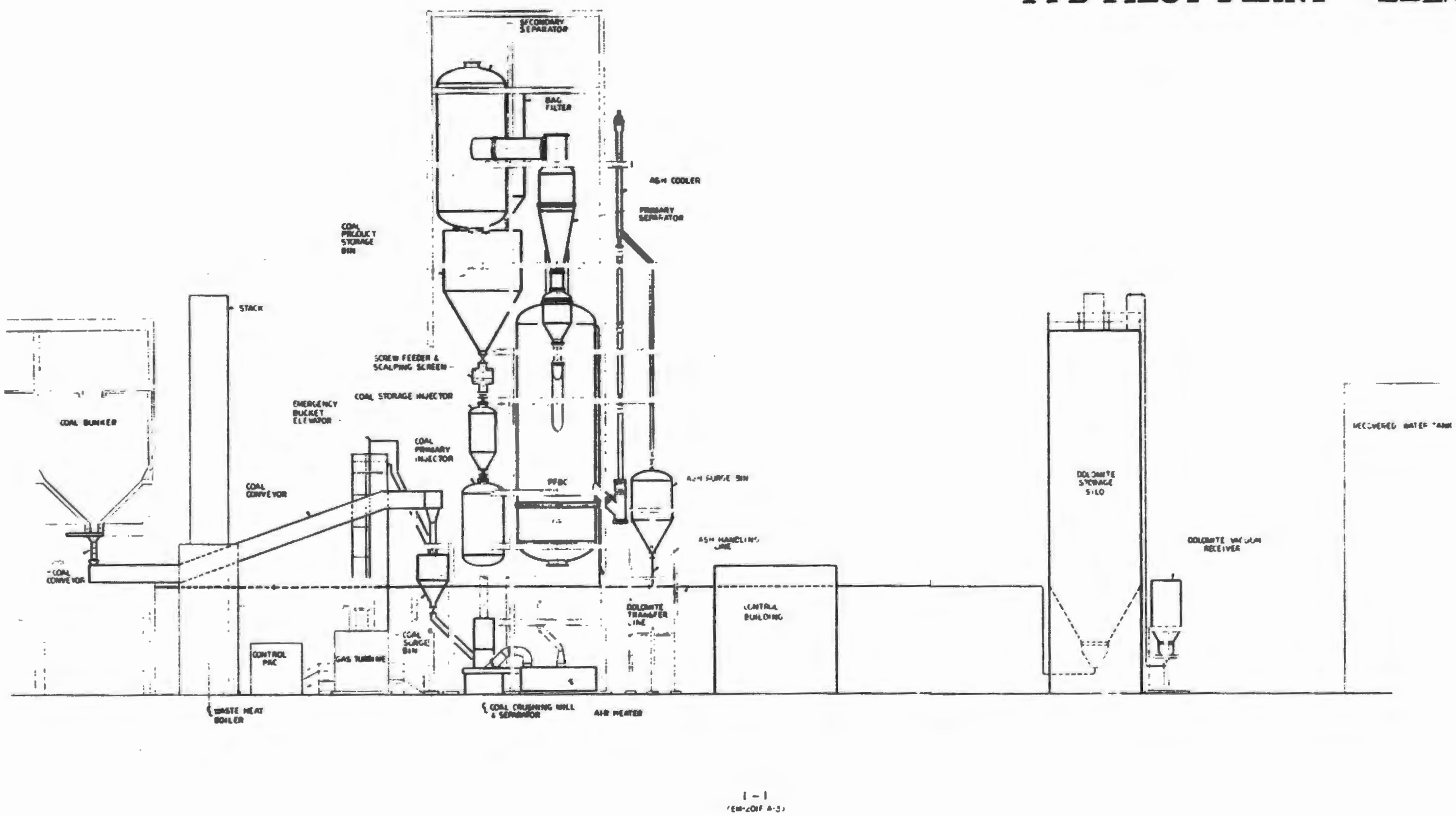


Figure 2.36

PFB-I-471

PROCESS	COMMERCIAL PLANT	PILOT PLANT
Ash Flow	1 - For Each PFB Combustor Water Cooled Fluidized Cooler With Lock Hoppers	1 - Water Cooled Fluidized Ash Cooler With Lock Hoppers
	1 - Pneumatic Conveying System	1 - Pneumatic Conveying System
	2 - 2160 Ton Ash Storage Silo	1 - 100 Ton Ash Hopper Storage Silo
Control System	Analog & Digital Process Control With Auto Data Log Backup Manual Control Boiler and Steam Turbine Controls Backup Computer Multiple PFB Controls	Analog & Digital Process Control With Auto Data Log Backup Manual Control
Environmental	Opacity Monitoring SO_2 Monitoring CO Monitoring NO_x Monitoring Particulate Monitoring	Opacity Monitoring SO_2 Monitoring CO Monitoring NO_x Monitoring Provision for Grab Sampling, Optical Particulate Monitoring

Design studies of the generator turbine module determined the extent of rework required to the structure to accommodate the necessary compressor discharge piping, turbine inlet piping, and bypass piping.

The conceptual design of the pilot plant PFB combustor is shown in Figure 2.37. The basic bed diameter is 12 ft. in diameter and fluidized bed height is 16 ft. The heat exchanger configuration is the bayonet tube configuration as in the commercial plant.

A comparison of recommended materials of construction for the key components in the pilot and commercial plants is shown in Table 2.11.

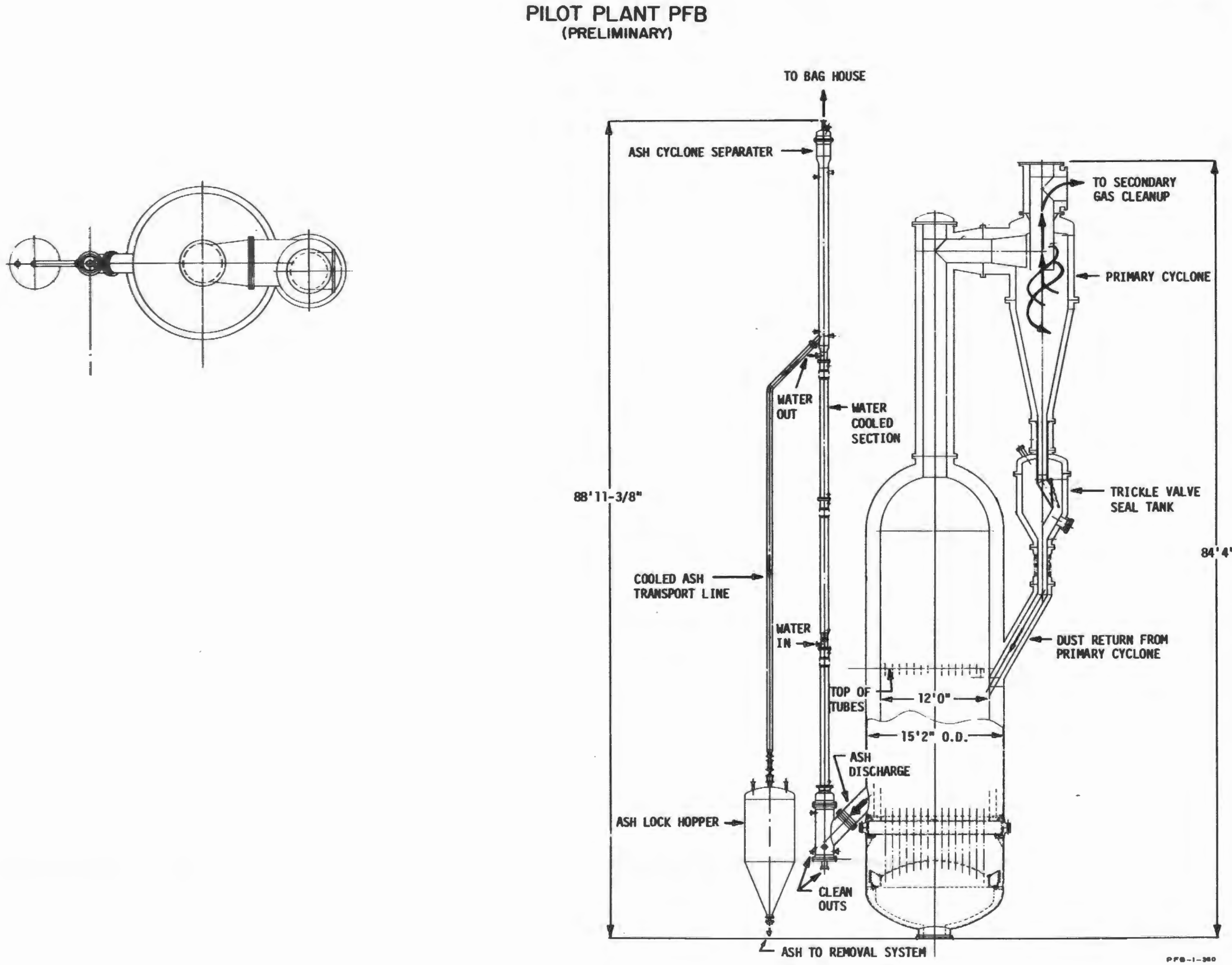

PILOT PLANT PFB
(PRELIMINARY)
TO BAG HOUSE
ASH CYCLONE SEPARATER
TO SECONDARY GAS CLEANUP
PRIMARY CYCLONE
WATER OUT
WATER COOLED SECTION
88'11-3/8"
TRICKLE VALVE SEAL TANK
84'4"
COOLED ASH TRANSPORT LINE
WATER IN
DUST RETURN FROM PRIMARY CYCLONE
TOP OF TUBES
12'0"
15'2" O.D.
ASH DISCHARGE
ASH LOCK HOPPER
CLEAN OUTS
ASH TO REMOVAL SYSTEM
PFB-1-360

Figure 2.37

TABLE 2.11

MATERIALS SELECTION

PFB COMBUSTOR/HEAT EXCHANGER	COMMERCIAL PLANT	PILOT PLANT
PRESSURE VESSEL	SA-515 GR 70	SAME
BEDPLATE AND SUPPORT GRID	SA-387 GR 22 CL-1	SAME
HEAT EXCHANGER TUBES	HAYNES 188	SAME
BED REFRACTORY LINING - HOT SIDE	BRICK (HW) UFALA	SAME
- WALL	HW40-64	
CYCLONE SEPARATORS		
PRESSURE VESSEL	SA-515 GR 70	SAME
REFRACTORY LINING - HOT SIDE	KS4	SAME
- WALL	VSL-50	SAME
AIR/GAS PIPING		
AIR	SA-515 GR 70	409 STAINLESS
GAS	SA-515 GR 70	SAME
INSULATION	INSBLANKET	SAME
LINER	INCONEL 600	SAME

GAS TURBINE			STAGE 1	STAGE 2
GAS GENERATOR TURBINE - VANES	IN-792	ALL	*INCO 738/CW-3	INCO 738
- BLADES	IN-792	ALL	*UDIMET 710	U-500
- DISC	A-286	BOTH	D 979	SAME
POWER TURBINE - VANES	U-500	ALL	HS-31	SAME
- BLADES	U-500	ALL	U-500	NONE
- DISC	AISI-422	BOTH	H-46	NONE

*ALT. TRANSPIRATION COOLED 1ST BLD. & VANE HAVE Ni-V-Cb AIRFOIL, U-500 STRUT

Section 4.0

TASK 3 - PILOT PLANT SITE EVALUATION

A Site Evaluation for the Pilot Plant was performed and included an accumulation and evaluation of data for the following areas:

- Real Estate
- Site Master Plan
- Climatological and Meteorological Data
- Foundation Investigation and Soil Analysis
- Site Survey and Local Resources Survey
- Site Transportation Study

4.1 REAL ESTATE REPORT

A real estate report prepared for the site contains a description of property, arrangements made for services, entry permits to perform site investigations, outstanding encombrances, (i.e. liens of easements) and ownership.

The pilot plant site is in northern New Jersey, at the Curtiss-Wright Corporation, Wood-Ridge Facility, located in the Borough of Wood-Ridge, Bergen County, New Jersey. The facility bounded by the Boroughs of Lodi, Hasbrouck Heights, and Wallington includes 160.74 acres and 37 buildings. This facility manufactures and overhauls turbo-machinery (including gas turbine and reciprocating engines for aircraft and industrial applications) and pressure vessels, steam generators and pressurizers for nuclear power generator applications. The site is owned by the Curtiss-Wright Corporation and there are no liens or other encumbrances.

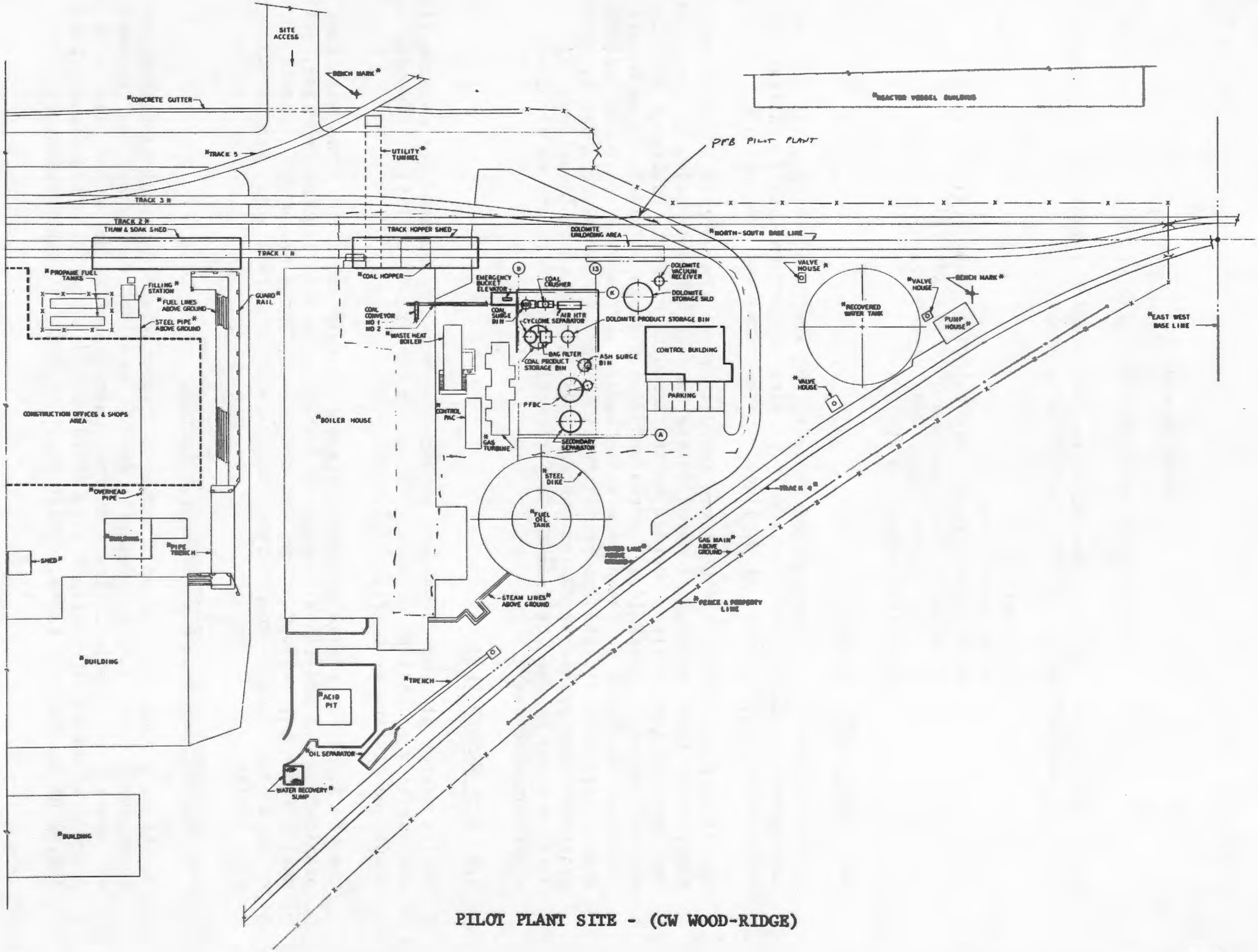
4.2 SITE MASTER PLAN

A site master plan was developed showing the areas to be used for construction, availability of utility services, temporary routing of utilities, temporary roads and storage area (Figures 4.1 and 4.2).

The PFB Pilot Plant site consists of approximately two level acres with approximately 1.5 additional acres, available for use during construction, primarily for construction laydown and temporary offices and shops. Direct truck access connects to a network of roads. Three rail spurs provide direct site access.

4.3 CLIMATOLOGICAL AND METEOROLOGICAL DATA

Tables have been prepared on a number of important climatological parameters based on 20 - 40 years of available data. They include normals and extremes of temperature, precipitation and snow, averages of relative humidity, wind speed frequency distribution, wind speed extremes precipitation amounts for storms of various durations, design dry bulb and wet bulb temperatures, etc.



PILOT PLANT SITE - (CW WOOD-RIDGE)

Figure 4.1

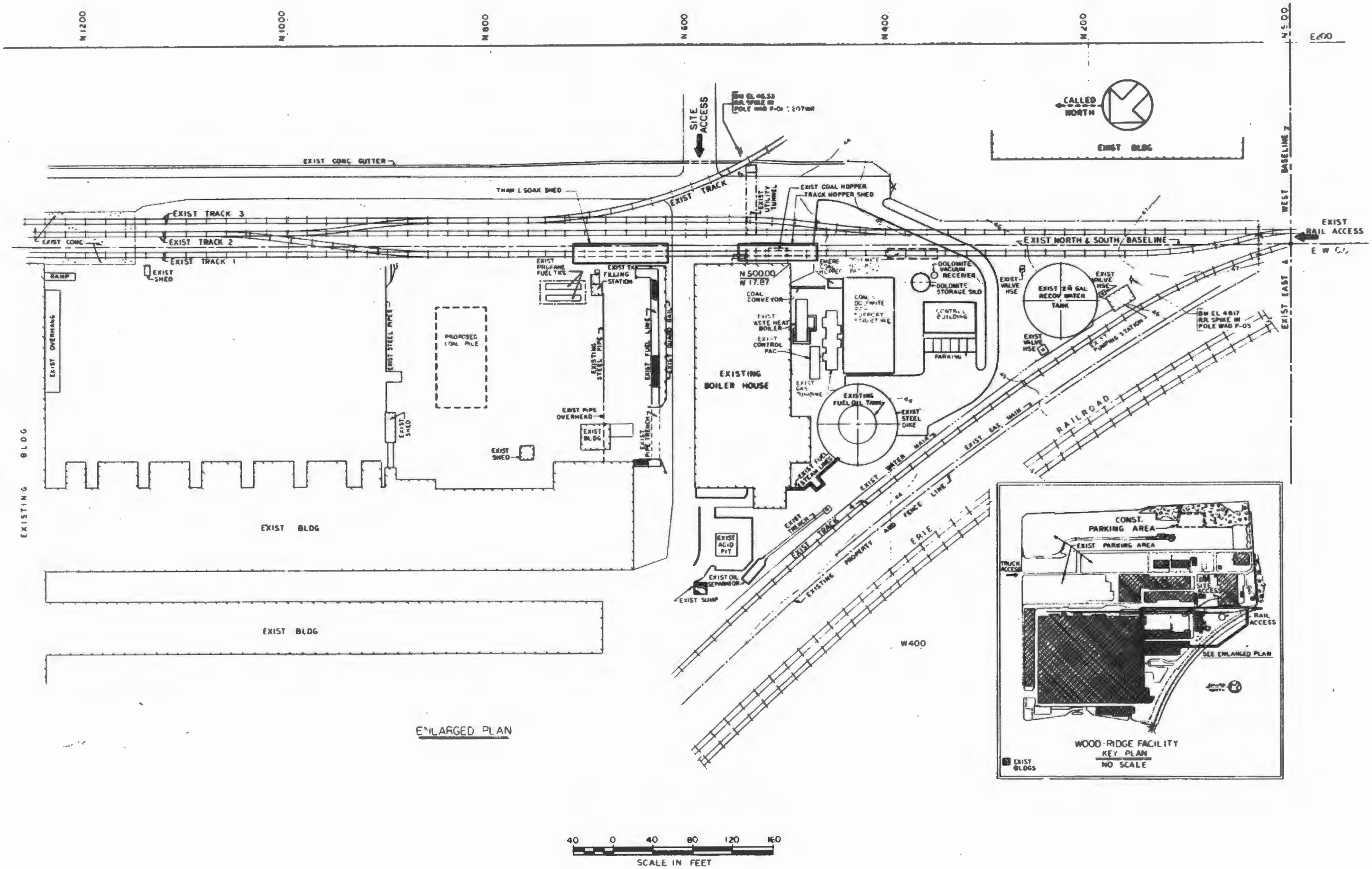


Figure 4.2

SITE MASTER PLAN

4.4 FOUNDATION INVESTIGATION AND SOIL ANALYSIS REPORT

Soil geotechnical investigation including test borings were made to determine soil characteristics and location of water table and to provide a basis for the types of support for the major structures and equipment in the pilot plant. At the site, bedrock, a red-brown sandstone, is within 11 to 20 feet of the surface. Glacial till (dense, red-brown, silty sand with gravel and sandstone fragments) topsoil and black cinders respectively, are found above the bedrock.

It is recommended that all major structures be founded either on engineered-compacted fill (after excavation and removal of topsoil and cinders) or on undisturbed glacial till or rock. The allowable bearing capacity of the compacted fill and glacial till is 8 kips per square foot. The bedrock is conservatively assigned an allowable bearing capacity of 15 kips per square foot at the bedrock surface. Groundwater is at approximately 16 feet below grade and this is below the maximum probable excavation depth.

4.5 SITE SURVEY REPORT

A topographic survey was made to establish baselines and benchmarks to be used for construction of the pilot plant. The topography of the site is relatively level at approximately El. 44 ft. The site is well removed and screened from residential areas.

The existing railroads, roads and utilities were investigated to determine their capacities and conditions and what arrangements are to be made regarding permits, licenses, etc.

The Wood-Ridge Facility located in Wood-Ridge, New Jersey, approximately 10 miles west of New York City is directly accessible by roads and railroads, and is only a short distance from port and airport facilities. Shipments over road exceeding 14 ft in height or 46 ft in length or 80,000 lb gross weight require shipping permits in the State of New Jersey (none are anticipated at this time). Published rail gross weight limits are 263,000 lb based on a standard 4-axle freight car and any shipments exceeding published line clearances are subject to railroad clearance determination procedures.

The existing coal handling and storage system is in good condition and can be used to handle and store coal and dolomite for the PFB pilot plant.

Electrical service to the Wood-Ridge Facility is provided by Public Service Electric and Gas Company.

The facility water supply is obtained from the municipal system supplied by the Passaic Valley Water Commission through a 24 in. main and from five active deep wells located on the property.

4.6 TRANSPORTATION STUDY

A study was made to determine the adequacy of local transporation systems - trucking, railroads, etc. The site is served by approximately 100 regular freight and specialized motor common carriers authorized to serve the

Section 3.0

TASK 2 - PRELIMINARY DESIGN PILOT PLANT

The preliminary design of the pilot-plant, one of the five major technical tasks of Phase I - Preliminary Engineering of the contract was not scheduled to start during the reporting period. This task will be covered during the next annual report.

Wood-Ridge, New Jersey area. Shipments over 14 ft in height, over 45 ft in length, or over 80,000 lbs gross weight must be permitted in the State of New Jersey. Permit Shipments are not limited to size or weight if clearance through the various municipalities is possible and the tire bearing pressure of the transporting vehicle does not exceed 800 lb/in. width of tire.

Daily normal freight service is available to the site on the Consolidated Rail Corporation (ConRail) Bergen County Line. Published weight limits are described to be 65,750 lb/axle, based on the distribution of a standard 40 ft 4-axle car. Published clearances on this line limit vertical height above rail to 19 ft-6 in. Height Above Top of Rail (ATR) for 6 ft-0 in. of width is a maximum of 11 ft-8 in.

Those shipments which exceed the published line clearances from any origin to the proposed site will have to be submitted to the originating carrier for clearance determination. Generally these limits are as follows:

55 ft-0 in. long
13 ft-0 in. high
10 ft-6 in. wide
100 tons

Woodbridge, NJ in the Port area. Shipments over 14 ft in height, over 8 ft [illegible] [illegible] 80,000 lbs gross weight must be permitted in the State of New Jersey. Permit shipments are not limited as to size or weight if clearance through the various routes [illegible] is possible and the tire bearing pressure of the transporting vehicle does not exceed 600 lb/in. width of tire.

Daily rail freight service is available to the site on the Consolidated Rail Corporation (Conrail) [illegible] County Line. Published [illegible] limits are [illegible] to be 65,750 lb/axle, based on the [illegible] of a standard [illegible] [illegible]. Published clearances on this line limit vertical height above [illegible] [illegible] height above Top of Rail (ATR) for [illegible] ft-[illegible] in. width to a maximum of 11 ft-8 in.

Those shipments that exceed the published line clearance from any origin to the site [illegible] will have to be submitted to the originating carrier for clearance determination. Generally, these limits are as follows:

33 ft-9 in. long
15 ft-0 in. high
10 ft-6 in. wide
100 tons

Section 5.0

TASK 5 - TECHNOLOGY SUPPORT EXPERIMENTS

5.1 PFB HEAT EXCHANGER TEST MODULE MANUFACTURE

Boiler tubes with a small number of O.D. fins are being produced by automatic welding techniques and large quantities of non-ferrous metal tubing with integral O.D. and I.D. fins are being drawn or extruded. However, tubing with the density of finning and made from the materials being considered for the PFB heat exchanger is not presently being made.

Manufacturing investigation and fabrication trials which were performed early in the program indicated that formed and welded tube construction, while probably feasible, would involve more extensive development time and effort than acceptable for the required technology rig hardware. This general method of fabrication would probably ultimately yield minimum unit cost production of large quantities of finned heat exchanger tubing but tooling cost will be high.

Brazed construction, though more expensive, was the only near state-of-the-art process available for immediate fabrication of parts. Several brazing trials and destructive and nondestructive tests were performed in selecting the braze alloy and establishing parameters to assure a sound joint. Voids in joints cannot be tolerated because of their effect on heat transfer, particularly in rig test assemblies to be used for determining design heat transfer coefficients.

5.1.1 Dorr-Oliver Test Rig Tubing

The initial rig tubing which was fabricated, incorporated O.D. fins only and was made to check heat transfer data on an existing Dorr-Oliver AFB test rig. These parts consisted of six finned tube assemblies, (Figure 5.1) all fabricated from Inco 800H material which was readily available, two parts incorporating 10 O.D. fins, two parts 15 O.D. fins and two parts 20 O.D. fins. A bare tube assembly was also included as a baseline.

The tube lengths were 6'3", fin lengths were 4'6" and tubes were 2" schedule 40 pipes. Both the tubes and fins were nickel flash plated prior to brazing. This was necessary due to the aluminum and titanium content of the alloy which readily oxidizes and prevents adequate wetting of the surfaces to be brazed.

Nicrobraze alloy 210 was selected for these assemblies but a rebraze operation was required using Nicrobraze 300 as a touch-up. It was apparent that alloys 210 and also 300 did not wet the nickel base alloys as uniformly as desired and that an alternate braze material would have to be found for subsequent rig parts.

5.1.2 NDT Inspection

Since the recording of valid heat transfer data in test rigs depends on assurance of a complete metallurgical bond between fins and tube in the fabricated

HEAT EXCHANGER TUBE ASSEMBLIES
FOR DORR-OLIVER 12" FLUOSOLIDS RIG

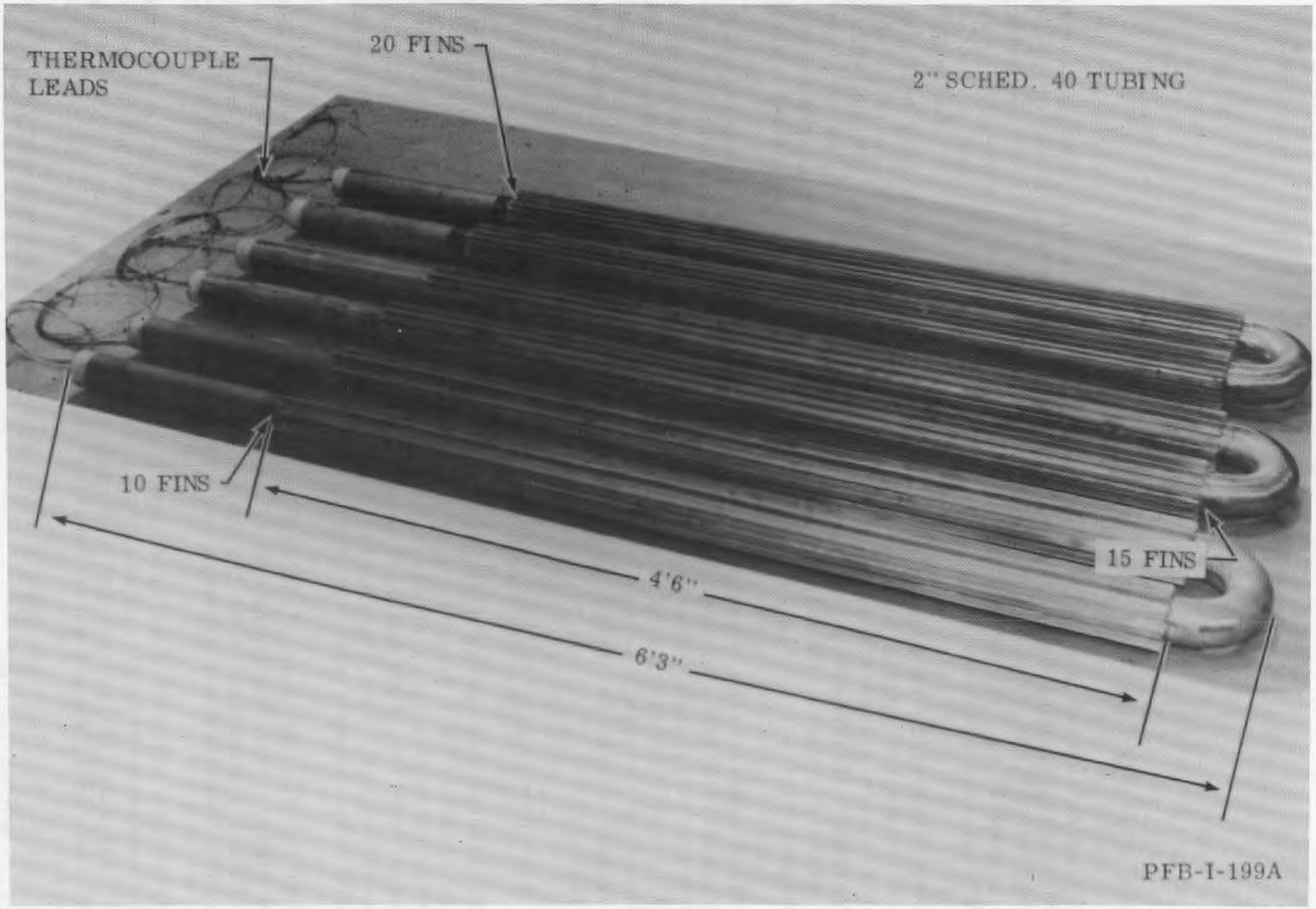


Figure 5.1

heat exchanger tube assemblies, an investigative program in the area of non-destructive test inspection utilizing ultrasonic techniques was performed to establish a fin-to-tube joint inspection technique for lack of bond. Two laboratory prepared specimens of finned tubing were used for evaluation.

Utilizing an existing ultrasonic immersion test set-up the finned tubes were placed in the water tank as shown in Figure 5.2. A 22 MHz nonfocused immersion transducer was installed such that an approximate 3/4" water path existed between the transducer face and the tube of the external fins. For this set-up, a flaw detector was used. The displayed signals are presented in filtered form easy to interpret. By moving the transducer axially along the fin and adjusting the instrument such that the combined fin wall thickness is displayed at approximately full screen on the CRT (Cathode Ray Tube) X-axis the proper instrument settings were established to enable detection of any areas along the fin tube interface where lack of bond existed. In order to establish whether the signals obtained were true, CRT display and instrument calibrations were conducted using two 0.060" diameter holes drilled into the ends of the test specimen such that one hole was located axially in the finned tube interface and the other hole close to the tube back wall. The finned tube specimen was then examined. The CRT screen displays an area where good bonding exists and where lack of bond between the fin and tube is shown as illustrated in Figure 5.3. The technique developed is capable of clearly resolving any indications of lack of bond in heat exchanger tubing with external fins. Results similar to the externally finned tubes were also obtained for an internally finned tube.

To facilitate inspection of rig tubing up to 16 ft. in length at the manufacturing site, a technique was investigated in which the finned tubes could be inspected axially with a hand held search unit which could be moved manually along the tube length while being positioned over any one fin. A prototype search unit shown in Figure 5.4 was designed and fabricated. This search unit utilizes a flowing water column as a couplant medium. The sound beam emanating from the high frequency transducer is collimated so that only a narrow sound beam enters the section of the heat exchanger tube under inspection. By having the contacting face of the search unit form a channel which slides along the one external fin, proper positioning of the search unit is ensured. In order to utilize the same prototype hand held search unit for the inspection of the internally finned heat exchanger tube, an adapter was fabricated, which, being attached to the contact area of the search unit, allows the search unit to be moved axially along the tube while the sound beam is directed at the internal finned tube region. Evaluation of the prototype hand held search unit indicated that test results could be obtained which were comparable to the inspection results obtained in the immersion tank.

Another series of tests established whether tube wall thickness measurements on finned heat exchanger tubes could be made. The requirements for this measurement exists to establish the thinning of tube wall due to erosion and corrosion and to schedule maintenance work on heat exchangers. The tube wall contact area between adjacent fins is not sufficient to allow a commercially available thickness measurement probe to be placed in contact with the tube wall. Therefore, a Transmit/Receive 4 MHz transducer element was shaped and mounted in a handle such that the probe face could be brought into intimate

GENERAL ARRANGEMENT OF ULTRASONIC INSPECTION EQUIPMENT

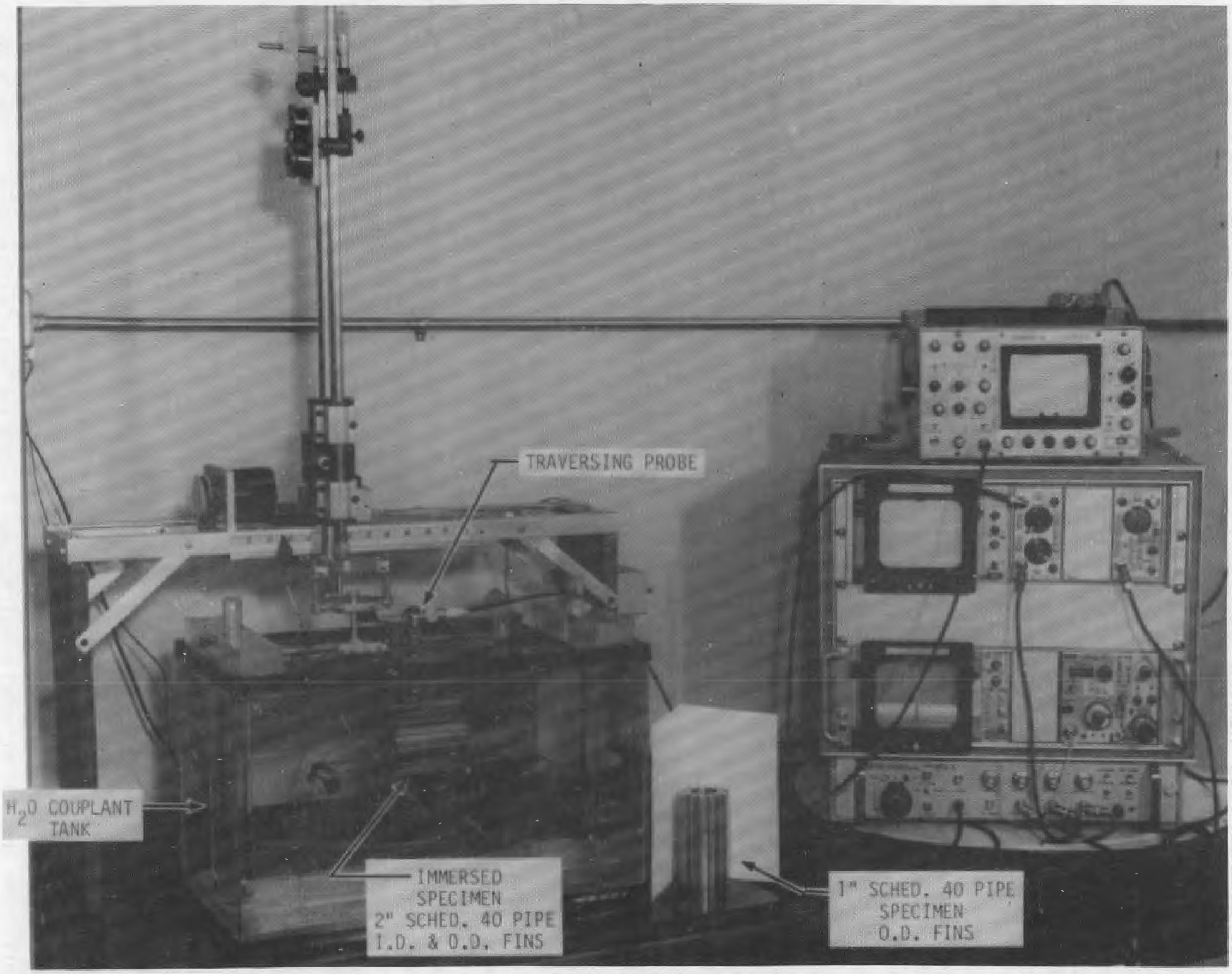


Figure 5.2

NDT INSPECTION OF FIN ATTACHMENT PFB HEAT EXCHANGER TUBE

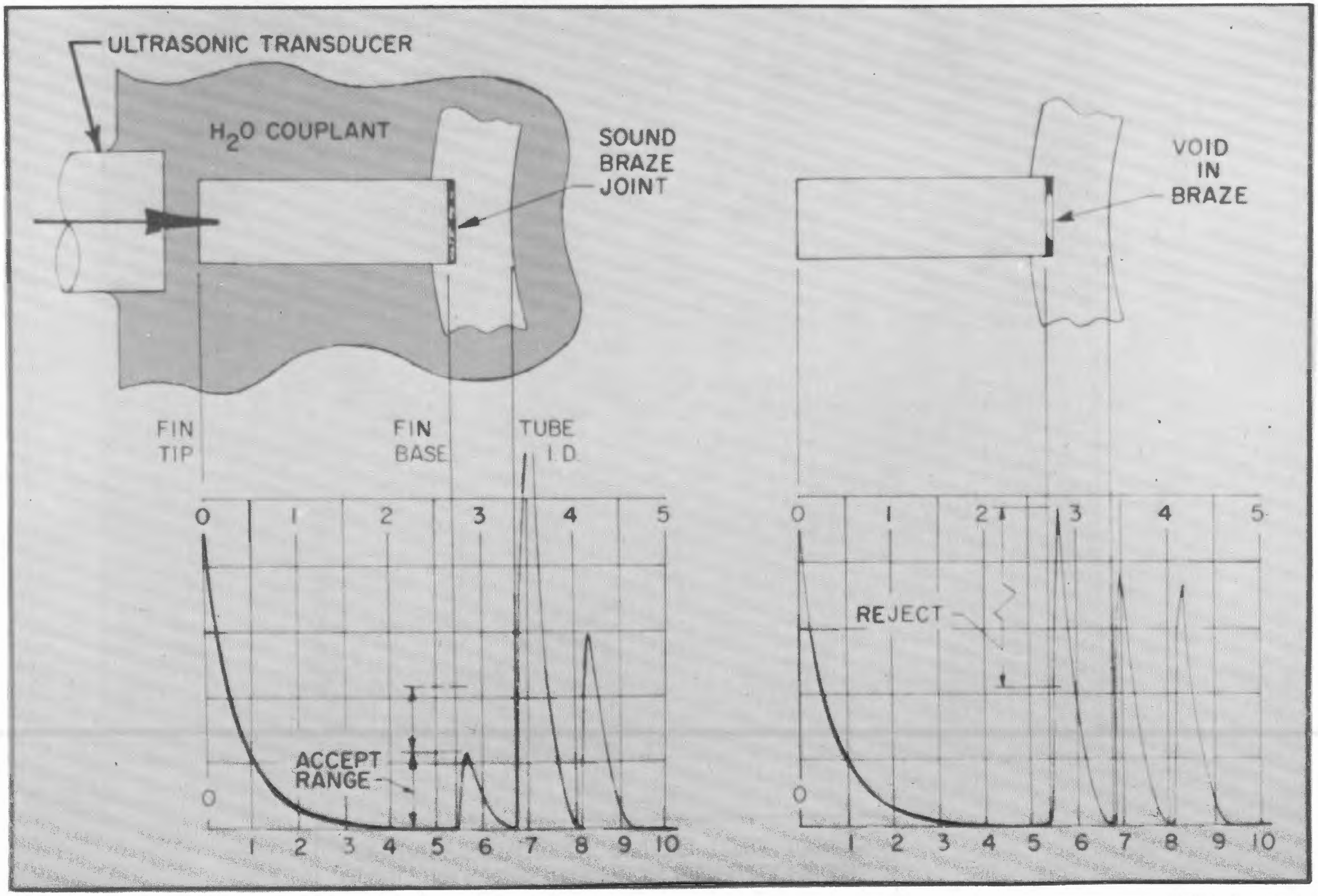


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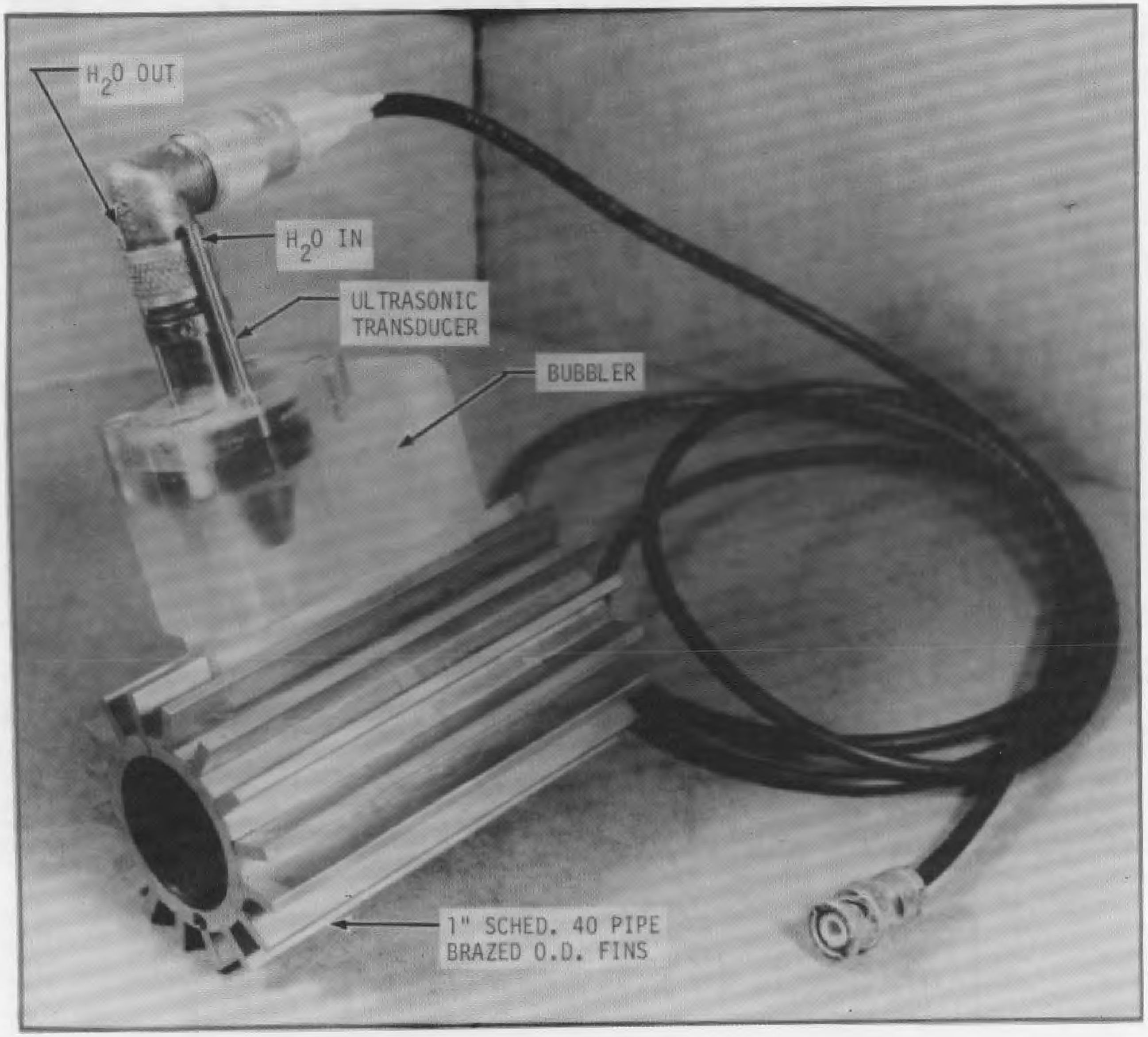
Figure 5.3

HAND TRAVERSING H_2O COUPLED PROBE FOR INSPECTION OF FIN TO TUBE JOINTS



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contact with the outside tube wall and the region between the external fins. Excellent results were obtained with this probe configuration. An ultrasonic frequency detector displays the tube wall thickness reading in digital form besides the conventional CRT screen.

5.1.3 Adams and Torrington Fin Tube Assemblies

The Adams and Torrington commercial fluid bed test specimens consist of tube-fin assemblies with fins on the O.D. only. The tubes and fins are made from a variety of material for corrosion-erosion tests at the Adams and Torrington facilities. Alloy 210 and 150 were used and provided acceptable brazed joints.

5.1.4 NRDC and SGT/PFB Heat Exchanger Tubing

The PFB combustor heat exchanger tubes are the first to incorporate I.D. as well as O.D. fins. The tube and fins are both made from Inco 600 material for erosion and corrosion resistance. Tubes are 4" schedule 40 pipe which is the final size selected for pilot and commercial PFB heat exchangers.

A pleated sheet metal I.D. fin configuration, Figure 5.5, was developed to facilitate the braze construction procedure. Heat transfer analysis indicated both thick (.01") and thin (pleated) internal fins were acceptable for the heat exchanger. Attaching thick fins to the pipe I.D. was more difficult than the pleated sheetmetal approach. A pleated fin contour was made with a pitch of .310". This pitch when rolled into tube shape gave an acceptable (.080" tight diametrically) fit with the I.D. of the tube. The .310" pitch is necessary to insure an initial good fit for 360°. A controlled amount of braze material (Alloy 150) is deposited on the flank of the I.D. fins prior to brazing. In addition the pleated fin segments are resistance tack welded in place.

The O.D. fins are then tack welded in place and braze alloy is placed along one side of the fins to facilitate determination of adequate coverage by visual examination after brazing.

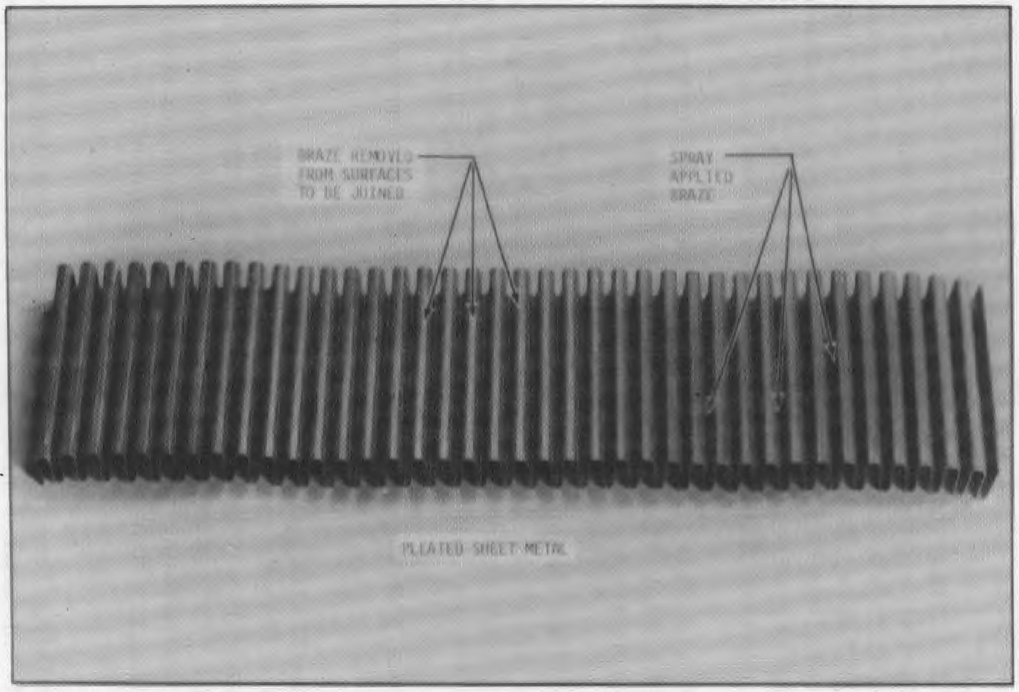
With braze applied on only one side of the O.D. fins, its appearance on the opposite side after it flows into joint constitutes the prime assurance that bond is complete. As part of the process approval, joints are destructively analyzed to confirm this and ultrasonic inspection of selected samples is made.

A tube specimen showing the final configuration after brazing is shown in Figure 5.6.

In addition to brazed tube assemblies, the possibility of extruding an acceptable I.D./O.D. finned section in materials required for a PFB coal combustor environment was investigated. An extrusion experiment was conducted at Curtiss-Wright's Metal Processing Division in Buffalo. Results were encouraging but significant development will be necessary to accurately assess the capabilities of this fabrication process. A cross-section of the extruded tube is shown in Figure 5.7.

The most promising immediate alternate to brazing tube assemblies, appears to be casting of integral finned tubes. Precision cast specimens were made of

HEAT EXCHANGER TUBE
INTERNAL FIN SECTION



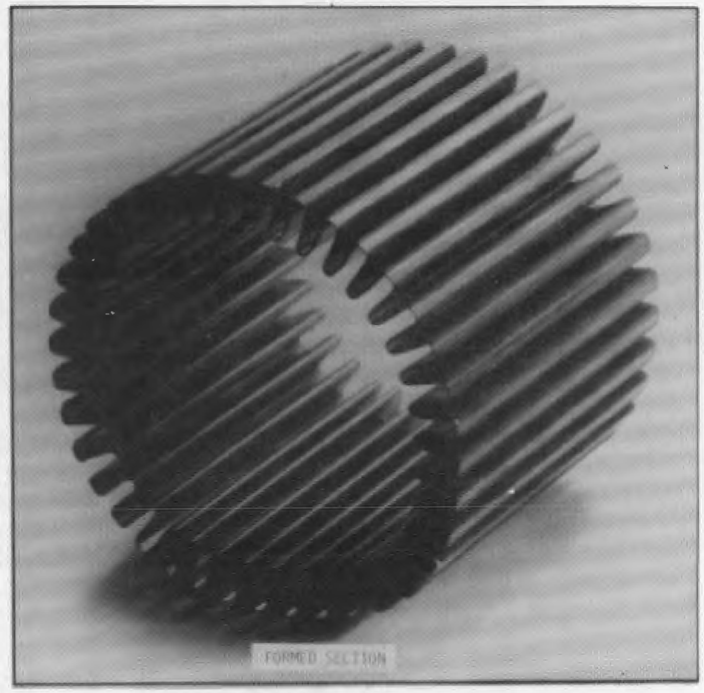


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Figure 5.5

SAMPLE 4" SCHED. 40
HEAT EXCHANGER TUBE
MATERIAL 18-8 S.S.

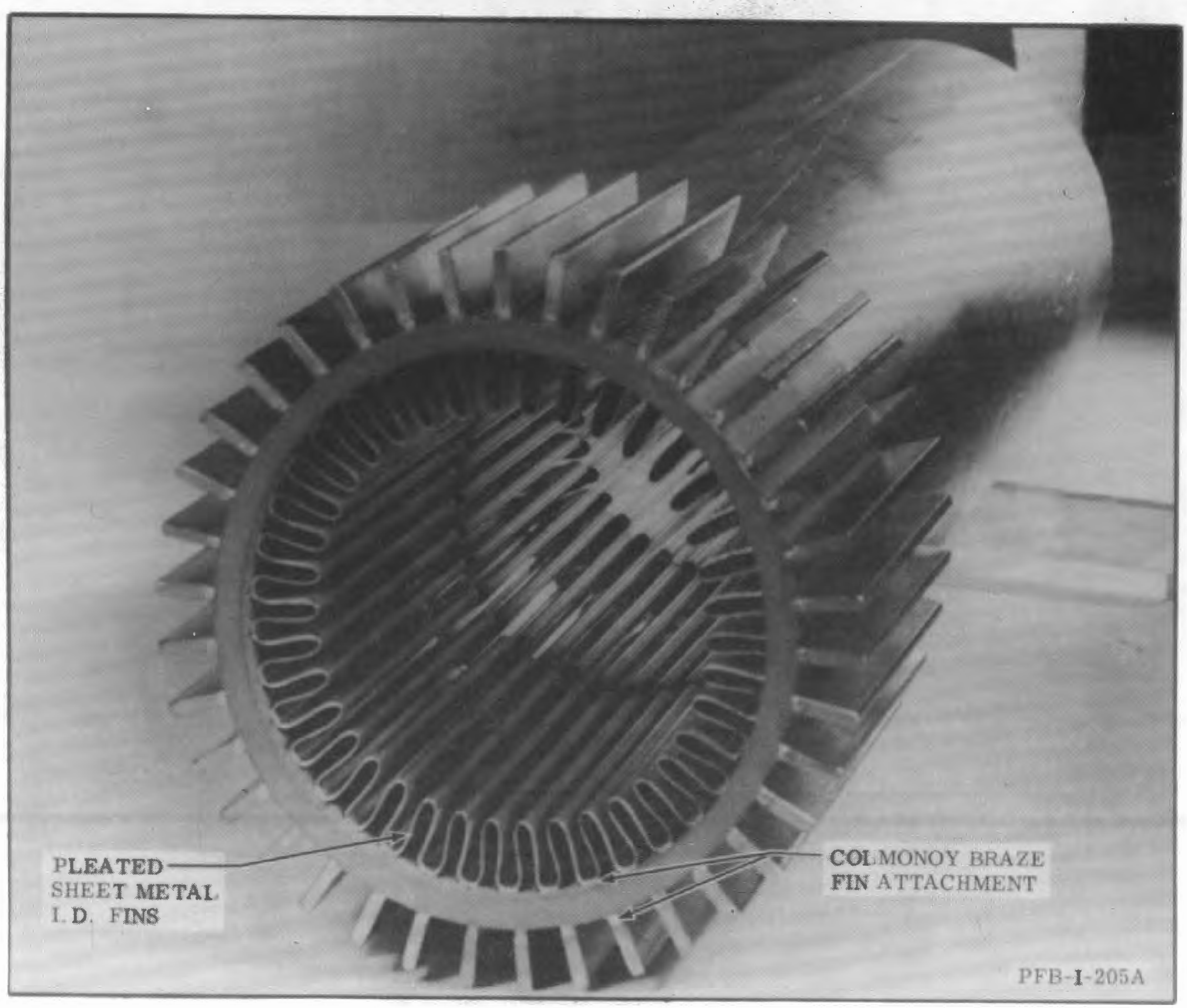

Figure 5.6

HEAT EXCHANGER TUBE FABRICATION DEVELOPMENT

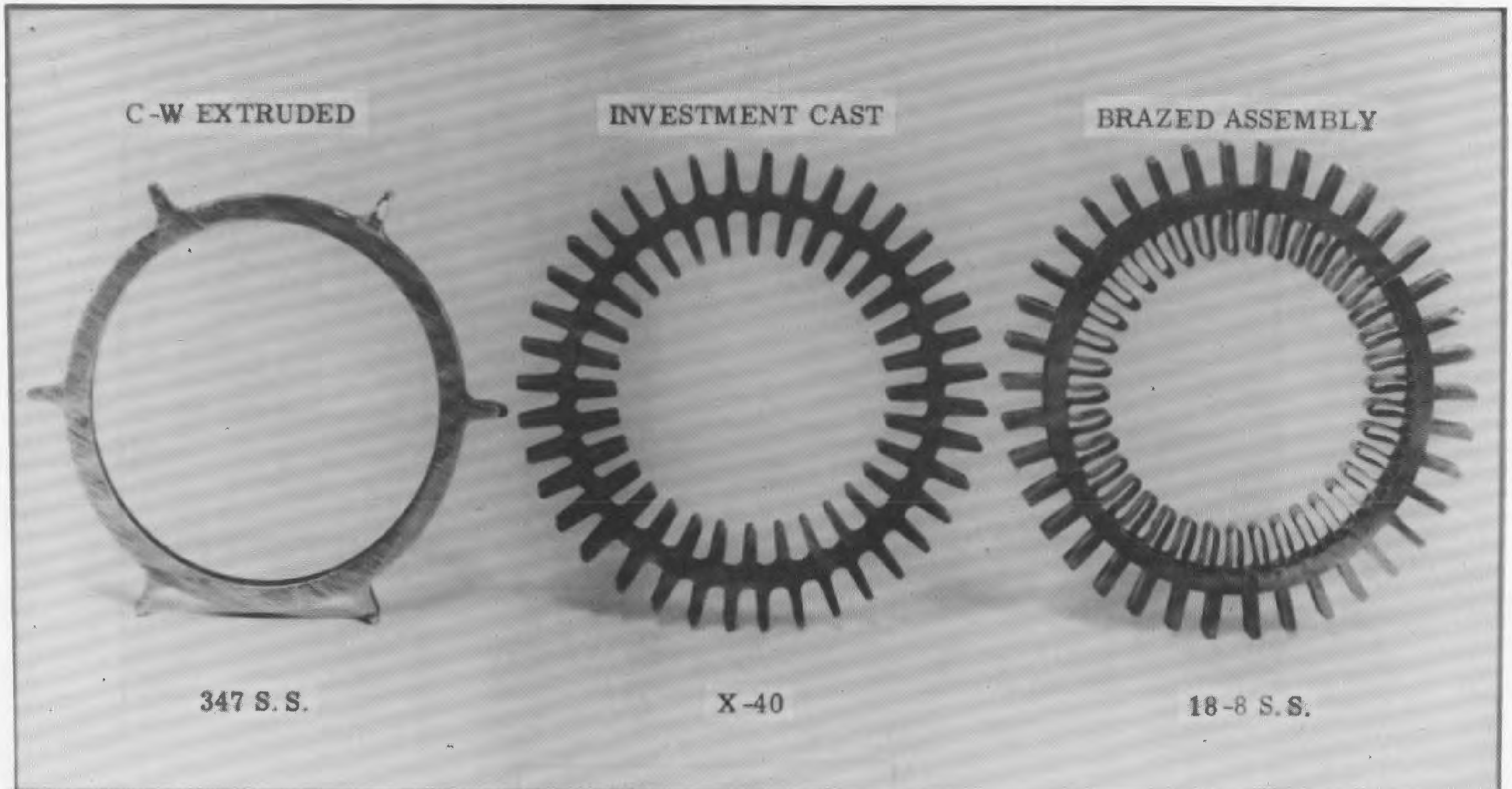

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Figure 5.7

progressively longer sections starting with a 9-1/2" piece and ending with a 30" section, Figures 5.7 and 5.8. Soundness of the X-45 (Stellite 31) material being used for these prototypes and detail definition have both been maintained to adequate standards. Longer sections are desirable for joining into complete heat exchanger tube assemblies and this remains the prime objective of continuing efforts with this process.

In addition, centrifugal cast specimens have been made which could have lower unit cost and modest expenditure for tooling compared to precision cast tubes.

Casting continues to be pursued as a possible backup for brazed tube fabrication and to obtain data applicable to pilot and commercial plant pricing analyses.

5.2 HEAT TRANSFER TESTS

5.2.1 Dorr-Oliver 12" Diameter Atmospheric Fluidized Bed Combustor

Single tube elements representative of the PFB heat exchanger were tested in the existing Dorr-Oliver 12" diameter atmospheric fluid bed combustor to obtain bed side heat transfer characteristics. Four different heat exchanger tubes were evaluated. The tests were conducted on an isolated U-tube immersed in a fluidized bed combustor burning a high sulfur coal with either dolomite or limestone used as the sulfur sorbent. The combustor was operated at atmospheric pressure, 1650°F bed temperature and fluidizing velocities up to 3.25 fps.

The primary objectives of the atmospheric combustor test program were to obtain basic information on bed-to-tube heat transfer coefficients as a function of metal skin temperature, fluidizing velocity (space rate), bed particle size distribution and fin height and fin spacing for several vertical heat exchanger tube configurations. Secondary objectives were the evaluation of the degree of bed decrepitation upon calcination, bed elutriation rate and the combustion efficiency. A summary of the tests to be conducted is shown in Table 5.1.

The single pass U-shaped tube assembly with external fins (Figure 2.16) was selected for evaluation to provide a relatively simple configuration to fabricate and thereby facilitate early evaluation of tube performance. This configuration serves adequately for determination of bed-to-tube heat transfer coefficient and all connections are at the bottom of the rig minimizing the extent of facility modifications required.

The cooling tubes were made from 2" schedule 40 pipe of 800H alloy material largely based on material availability. Heat transfer tubes containing 0, 10, 15 and 20 longitudinal fins (Figure 5.1) were used. The outside metal skin temperatures were measured with thermocouples embedded in the tube metal. Air and water were each used as cooling media. Air was preheated to 500-1000°F in an auxiliary burner before entering the cooling tube to simulate design inlet temperatures.

A flow diagram of the combustor is shown in Figure 5.9 and Figure 5.10 is a photograph of the actual installation. The stainless steel combustor is

PRECISION CAST 4" SCHEDULE 40 HEAT EXCHANGER TUBE
INTEGRAL FINS, X-45 MATERIAL

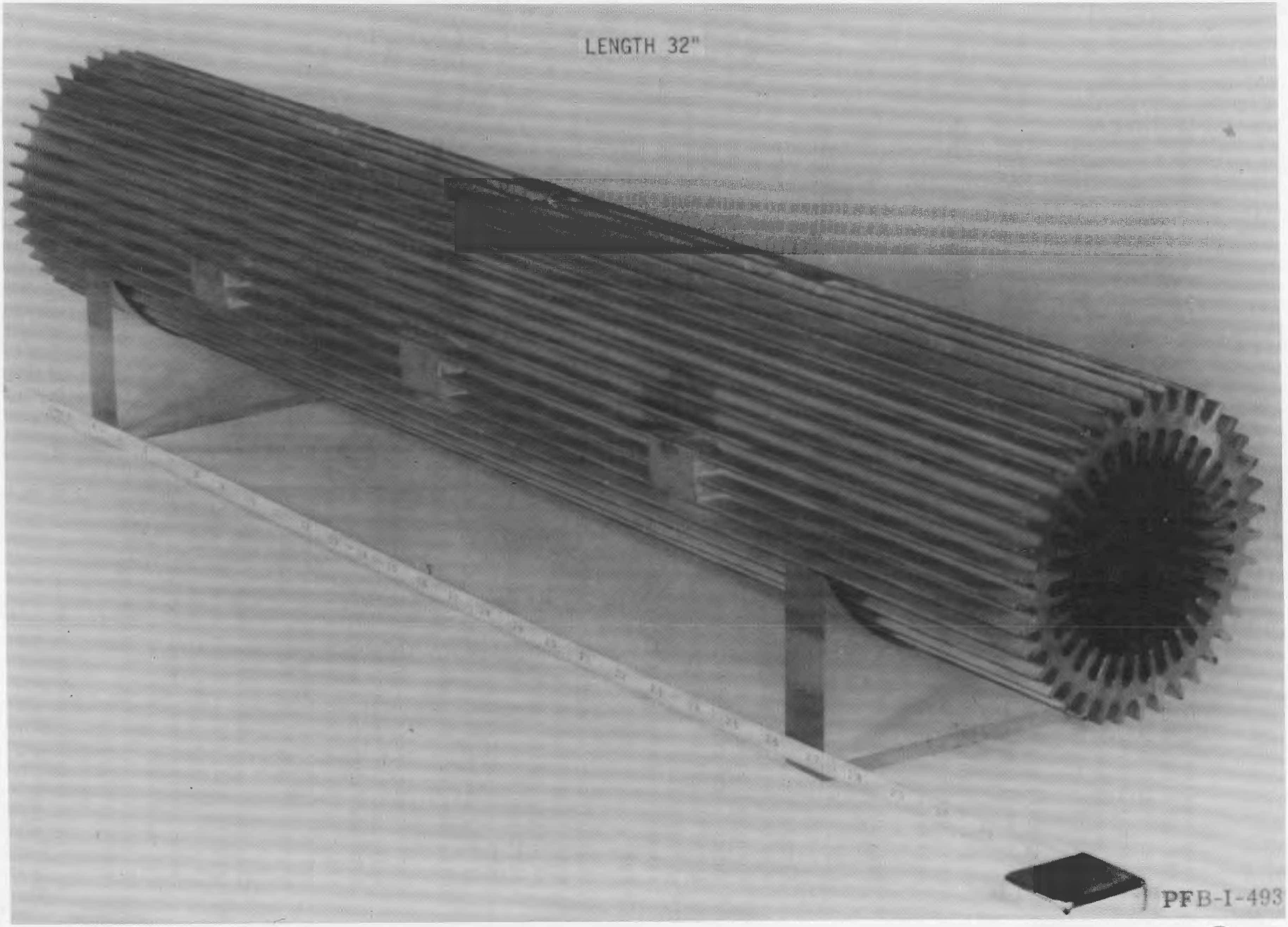

Figure 5.8

TABLE 5.1

DORR-OLIVER 12" DIAMETER ATMOSPHERIC FLUOSOLIDS REACTOR

HEAT EXCHANGER TUBE OPTIMIZATION

HEAT EXCHANGER TUBE			BED	
1 NO. OF FINS (SPACING)	1 HEIGHT OF FINS INCHES	1 COOLING AIR IN TEMP °F	1 COAL & DOLOMITE PARTICLE SIZE INCHES MAX	2 SPACE RATE FT/SEC
BARE	0	500 1000	-.250	2.15, 3.15, 3.20 2.15, 3.15
10	.6	500 1000	-.250	SAME
10	.6	500 1000	-.023	SAME
10	.4	500 1000	-.023	SAME
10	.2	500 1000	-.023	SAME
15	.6	500 1000	-.250	SAME
20	.6	500 1000	-.250	SAME
20	.4	500 1000	-.250	SAME
20	.4	500 1000	-.023	SAME
20	.2	500 1000	-.023	SAME

NOTES:
1 PRIMARY VARIABLE INVESTIGATED
2 SECONDARY VARIABLE
3 CONSTANTS: BED TEMP 1650°F
Ca/S RATIO = 2
% EXCESS AIR RANGE 15-30%

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REACTOR FLOW DIAGRAM

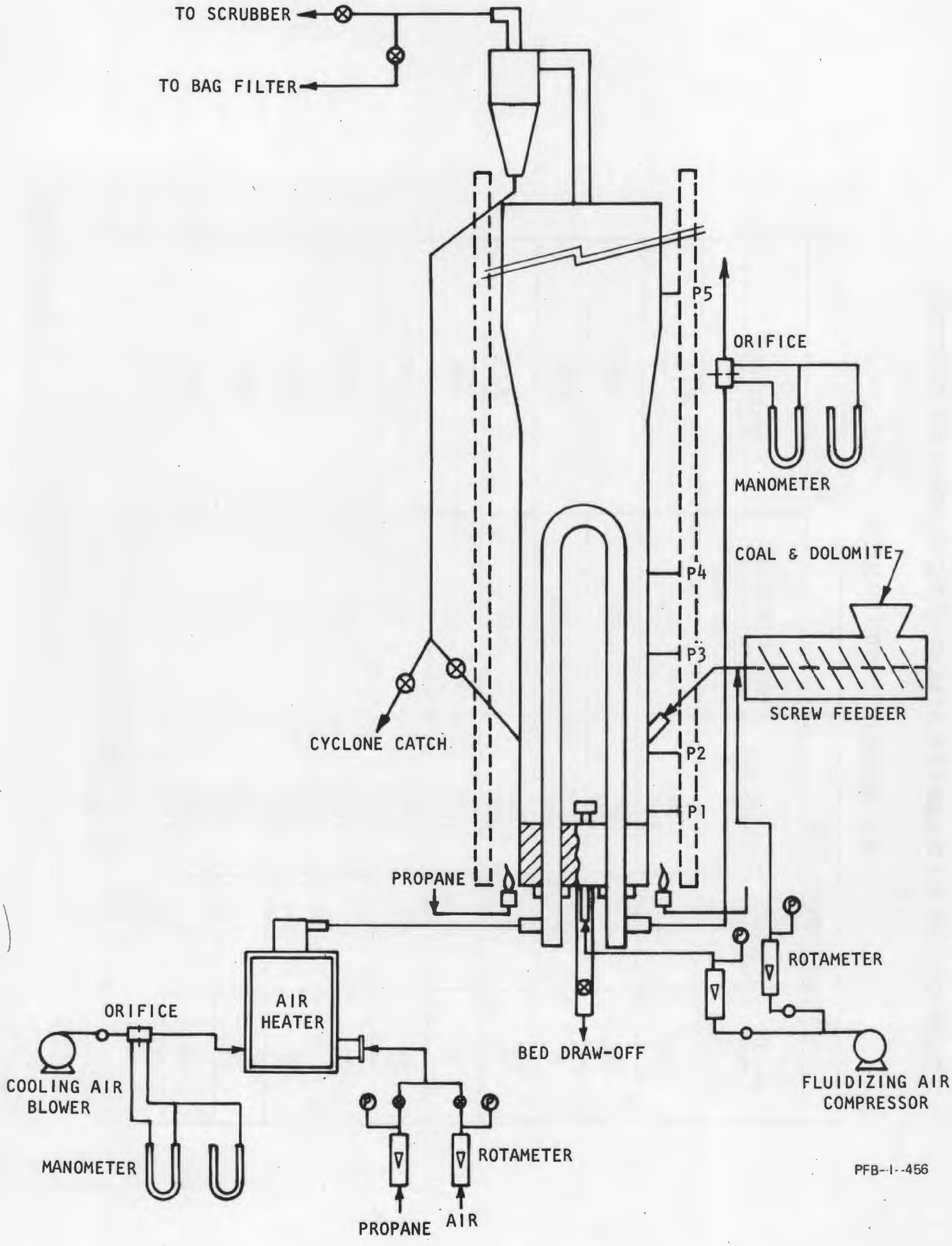

Figure 5.9

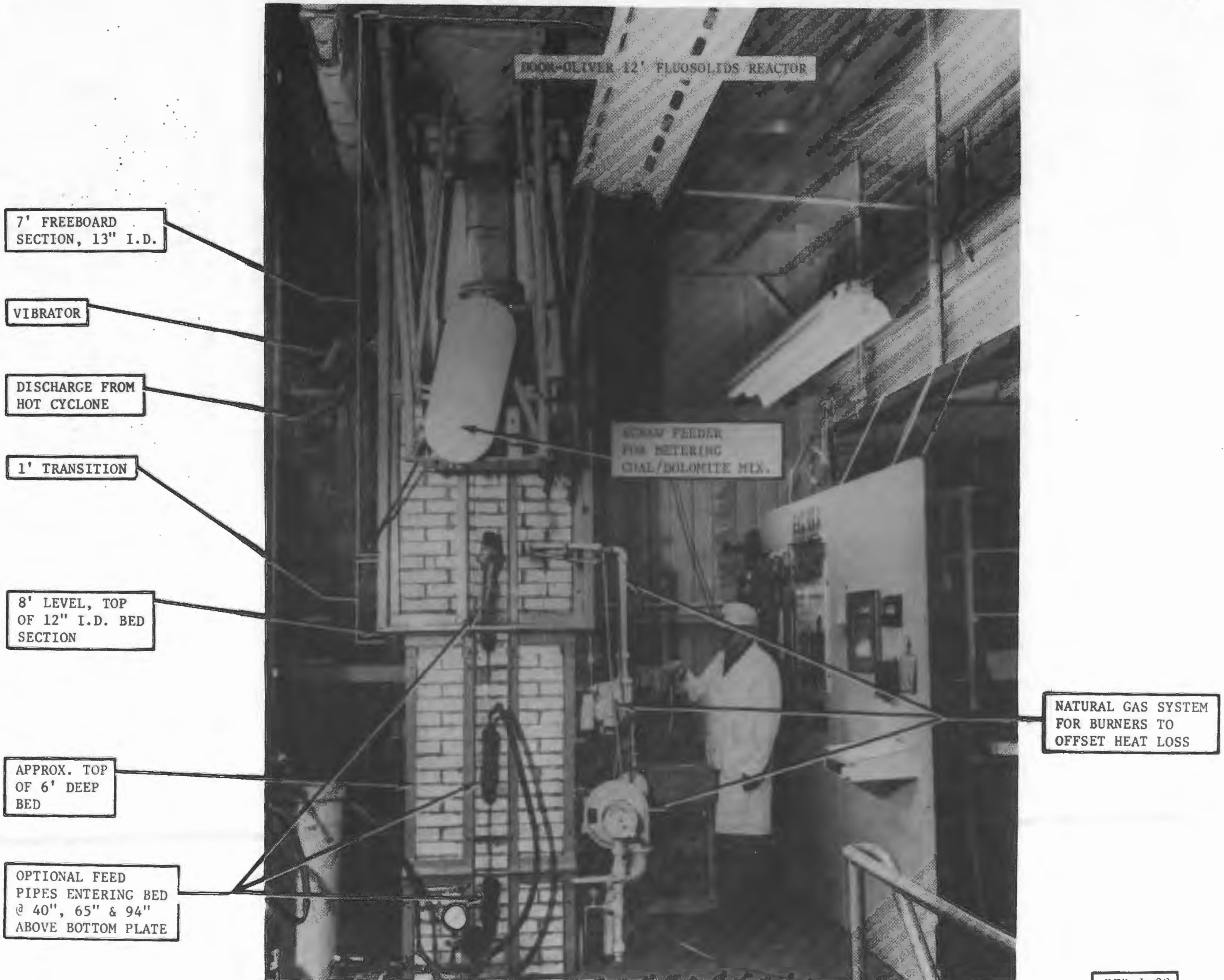
DOOR-OLIVER 12' FLUOSOLIDS REACTOR
7' FREEBOARD SECTION, 13" I.D.
VIBRATOR
DISCHARGE FROM HOT CYCLONE
SCREW FEEDER FOR METERING COAL/DOLOMITE MIX.
1' TRANSITION
8' LEVEL, TOP OF 12" I.D. BED SECTION
NATURAL GAS SYSTEM FOR BURNERS TO OFFSET HEAT LOSS
APPROX. TOP OF 6' DEEP BED
OPTIONAL FEED PIPES ENTERING BED @ 40", 65" & 94" ABOVE BOTTOM PLATE
PFB-I-32

Figure 5.10

mounted inside a chimney built of insulating bricks, and is heated externally by hot combustion gas from gas burners to hold the fluidized bed at reaction temperature, and offset heat losses.

Fluidization air is blown into the bottom of the fluid bed through a removable windbox containing an air distributor. Solids are fed into the reactor using the side feed tube located 40 inches above the bottom plate. A screw feeder is used for accurate solid feed metering. The bed product is periodically discharged through an underflow valve to maintain a constant bed level. Stack gases containing elutriated solids are passed through a cyclone mounted at the top of the reactor and finally to a gas scrubber. The bottom products of the cyclone are then recycled back to the reactor.

Tests are continuing, however some preliminary results are presented as follows:

The gas-side heat transfer coefficient for the bare tube was found to be higher than the coefficients generally reported in the literature (i.e. 125 vs 70 Btu/hr-ft^2 °F). The higher coefficient can be attributed to differences in particle size of the atmospheric bed, largely a result of recycling the collected solids of the cyclone. By recycling the fines, only the smallest micron size particles are not kept in the bed. It is well known that bed-to-tube heat transfer coefficients are dependent on the size of the bed particles. This dependency is shown in Figure 5.11 for the present data and other published studies.

The effect of fin height is summarized in Figure 5.12 for the tube with 20 fins. Note that the film coefficient must equal the bare tube coefficient when the fin height is reduced to zero.

Both dolomite and limestone were used as sorbents. The heat transfer characteristics with these two materials are shown in Figure 5.13. The poorer performance of limestone can be attributed to its particle stability. The limestone did not decrepitate nearly as much as the dolomite. Therefore, the bed was much coarser with limestone and the heat transfer, consequently, lower.

5.2.2 Pressurized Fluidized Bed Combustor/Heat Exchanger Rig (NRDC)

A reduced height heat exchanger tube bundle with identical tube cross-section as designed for the commercial and pilot plants has been designed for test in the existing NRDC PFB combustor rig at pilot plant operating conditions. The NRDC facility, Figure 5.14, provides the initial opportunity to obtain heat transfer data for the heat exchanger tube design at full design pressure and temperature.

The objectives of the heat exchanger test are to determine heat-transfer characteristics, and temperature distribution within the bed and freeboard. In addition, measurements will be taken which will permit an evaluation of combustion efficiency, bed behavior regarding clinker information, sulfur sorbent performance, concentration (ppm), chemical composition and particle size distribution of the particulate matter present in the gas stream from the bed, from the primary cyclone and from the secondary cyclone and fouling, corrosion

EFFECT OF PARTICLE SIZE
ON HEAT TRANSFER COEFFICIENT

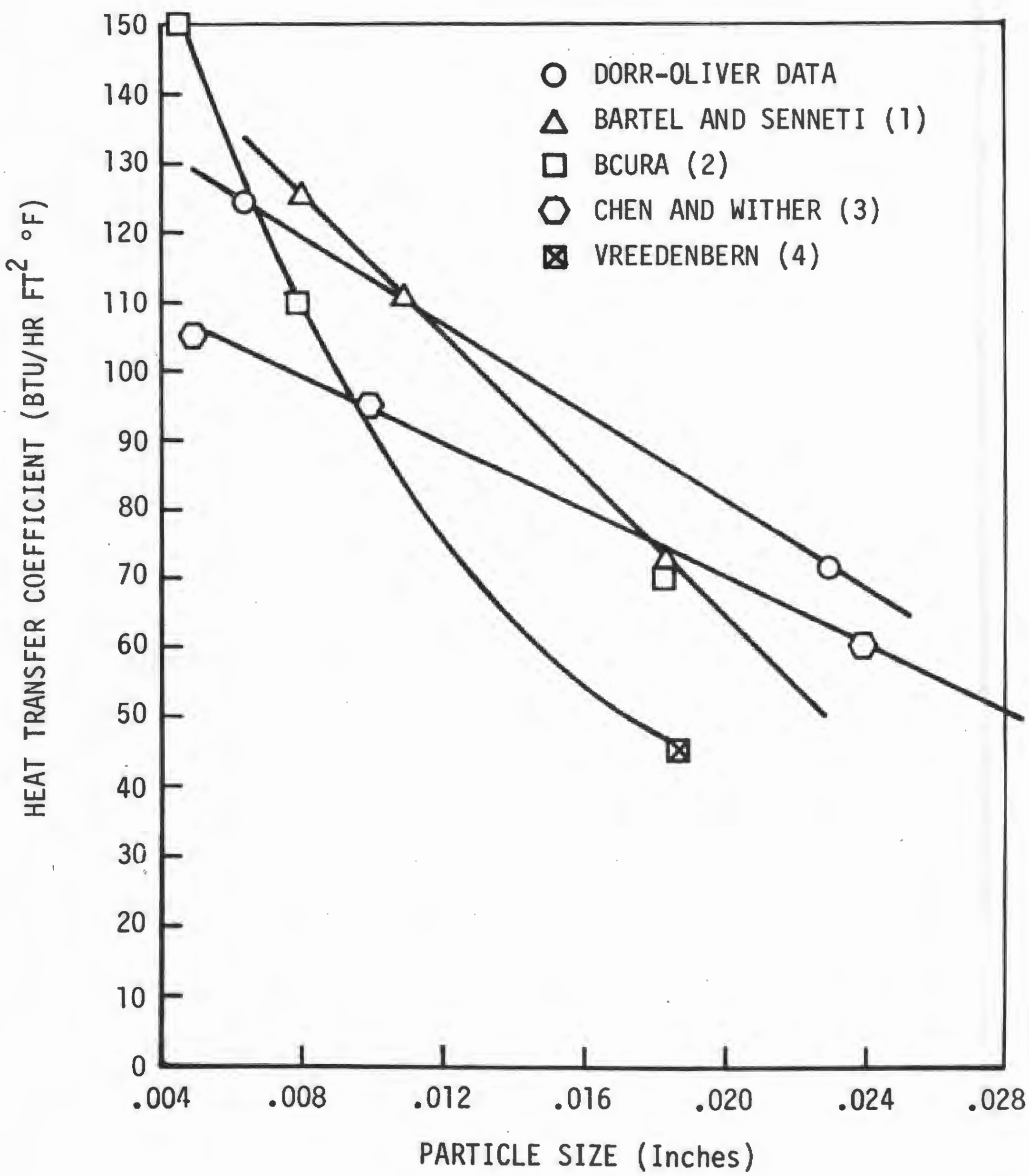

Figure 5.11

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EFFECT OF FIN HEIGHT ON HEAT TRANSFER COEFFICIENT

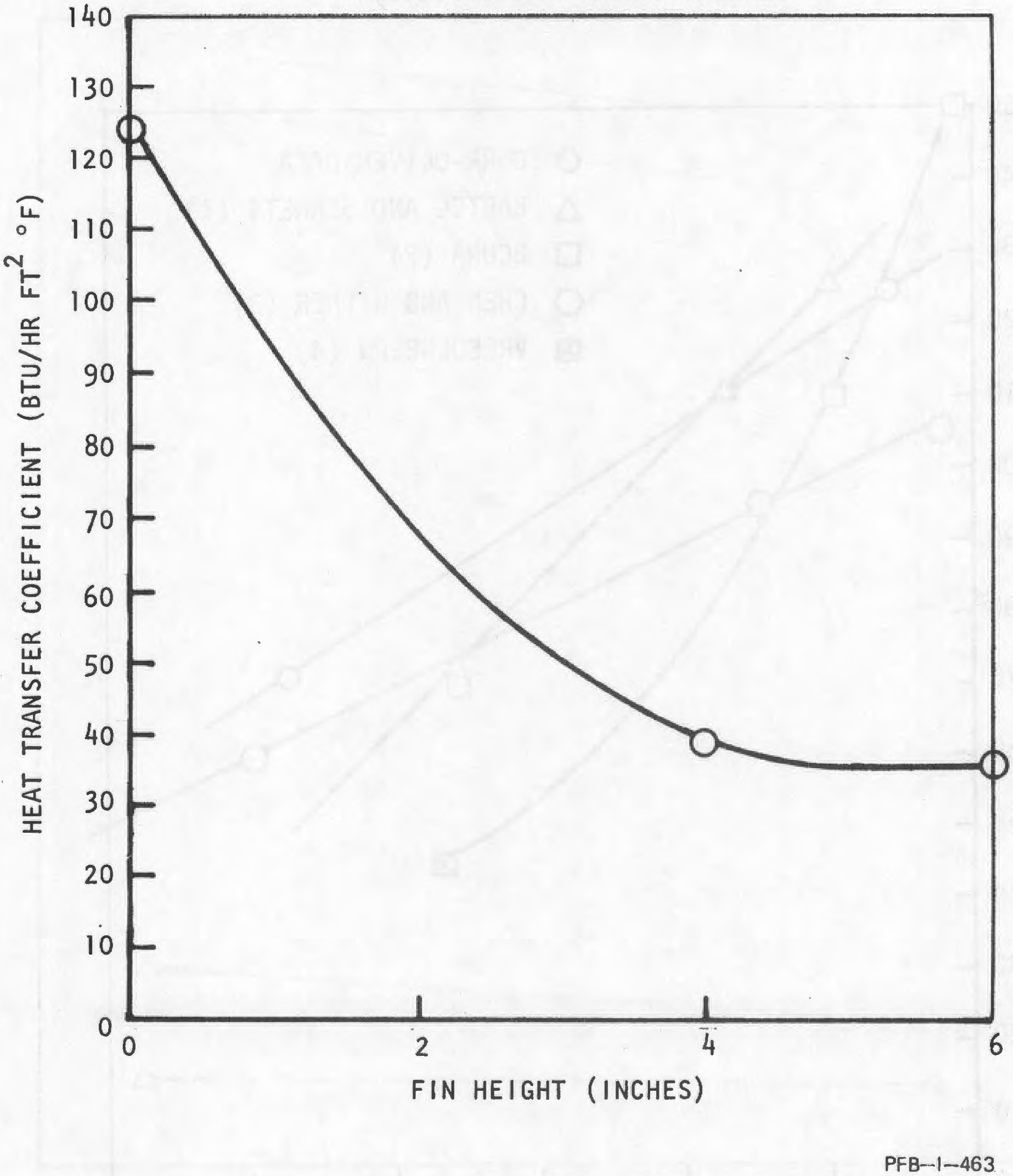


Figure 5.12

EFFECT OF PARTICLE SIZE ON HEAT TRANSFER

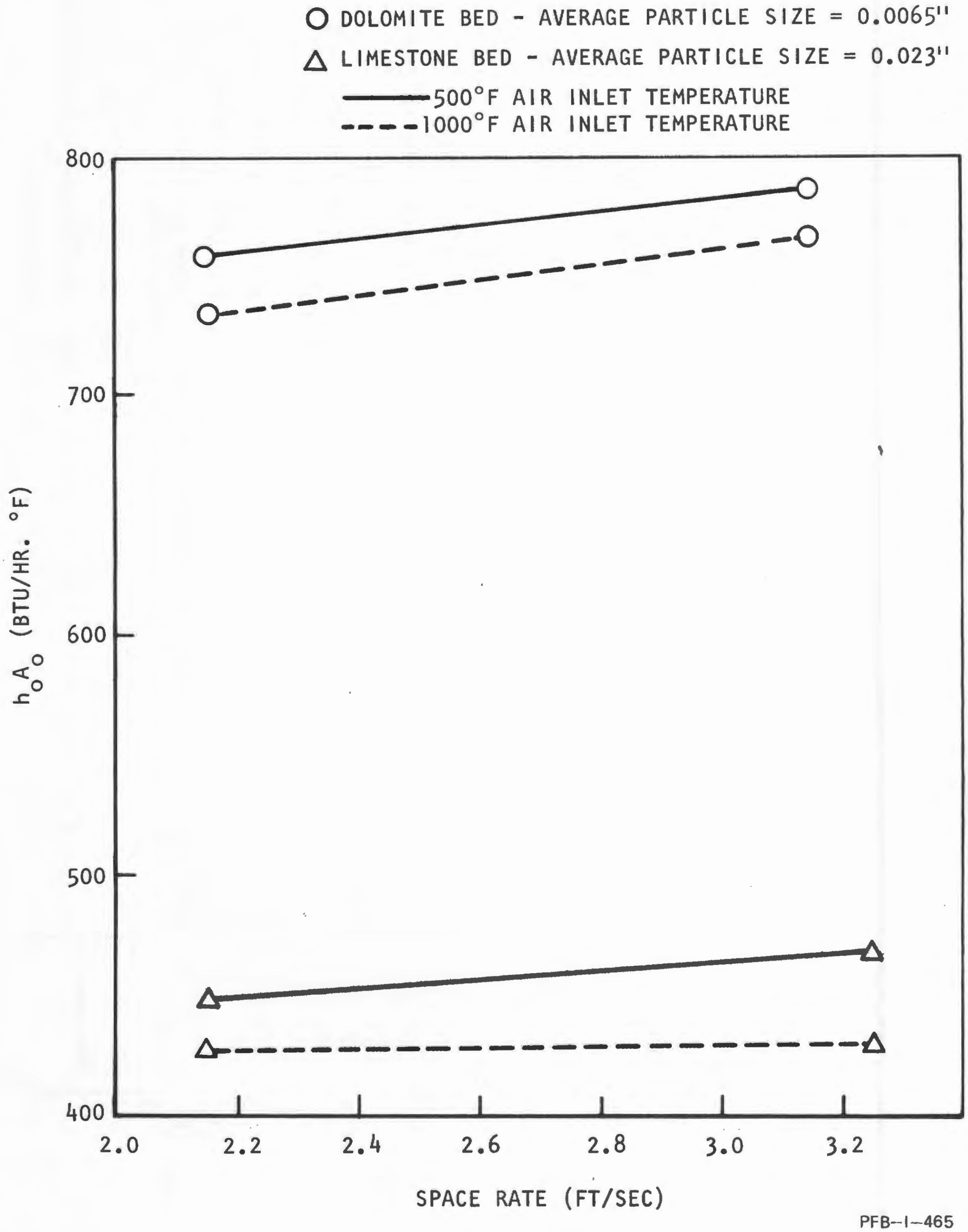
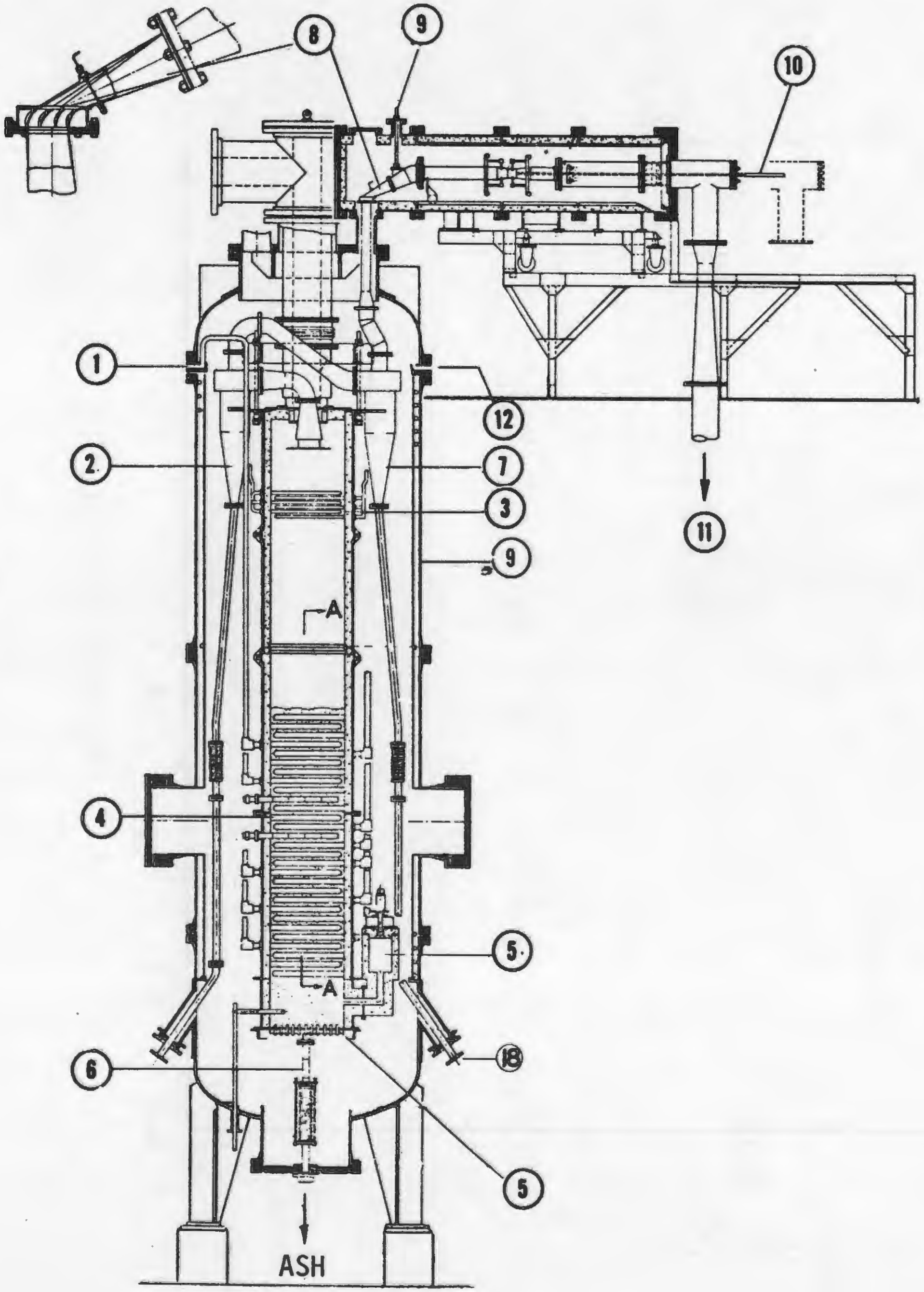


Figure 5.13

ARRANGEMENT OF FLUID BED COMBUSTOR MK III



NOTES

1. WATER SUPPLY TO WATER-COOLED CIRCUITS
2. FIRST-STAGE DUST COLLECTING CYCLONE
3. FREEBOARD COOLING CIRCUITS (TO CONTROL ANY RISE IN GAS TEMPERATURE)
4. MAIN TUBE BANK. SURFACE AREA IN USE IS VARIED TO OBTAIN DESIRED BED TEMPERATURE
5. AUXILIARY GAS BURNER (FOR START-UP)
   DISTRIBUTOR PLATE
6. ASH OFF-TAKE FROM BED
7. SECOND-STAGE DUST COLLECTING CYCLONE
   PRESSURE SHELL
8. CASCADE AND TARGET RODS
9. SAMPLING POINT FOR ALKALI CONTENT OF GASES
10. DUST SAMPLING AND O_2,CO_2,CO probe
11. TO PRESSURE LET-DOWN VALVE
12. AIR SUPPLIES

PFB-I-58A

Figure 5.14

and erosion of target rods placed behind an existing cascade. Metallurgical inspection of the tested tube bundle will also be made.

The design of the test heat exchanger assembly is shown in Figure 5.15 and Figure 5.16 is a photograph of the assembly. The design is for a 7-1/2 foot deep bed and includes seven vertically oriented bayonet type cooling tubes. Four of the tubes are water cooled and serve only to control bed temperature. The remaining three tubes are connected in series and will be cooled with air at 200°F inlet temperature. The three air cooled tubes are connected in series to simulate the cooling air temperature conditions that will exist in the 16 foot deep pilot plant bed. The tube length is the maximum that can be accommodated in the NRDC rig.

A total of eight tuyeres are interspaced among the cooling tubes in the bed baseplate. Flow to the bed at the design condition is 1.7 pps at an inlet pressure of 87 psia. The bed will be operated at 1650°F with a 2.6 fps space velocity. Predicted cooling air discharge temperatures for the heat exchanger are shown in Figure 5.17.

Instrumentation is provided which will permit an extensive survey of heat exchanger tube metal temperature (fin and tube walls) and tube cooling air temperature. Installation and testing of the heat exchanger tube bundle are due to get underway within the next several months.

5.3 MATERIALS EVALUATION

5.3.1 Commercial Fluid Bed Corrosion/Erosion Material Tests

Arrangements were made to install test fixtures incorporating various candidate PFB heat exchanger tube materials in two Dorr-Oliver designed commercial fluidized beds. One bed is a municipal sewage sludge incinerator in Torrington, Conn., and the other is a Pfizer Co. limestone calciner in Adams, Mass. The environments in these two beds should bracket conditions expected in the coal/dolomite PFB combustor and yield early data relative to the long term erosion/corrosion of the materials selected for test. In both cases, four tube specimens were incorporated in the tube bundles, each tube of a different material as follows:

2" Sch. 40 Incolloy #800H, Fins 800H
2" Sch. 40 Inconel #601, Fins #601
2" Sch. 40 Inconel #690, Fins as follows:

Upper Half Stellite Alloy #188
Lower Half Inconel Alloy #690

2" Sch. 80 Type 304 S.S., Fins 304 S.S.

NRDC PFB RIG HEAT EXCHANGER

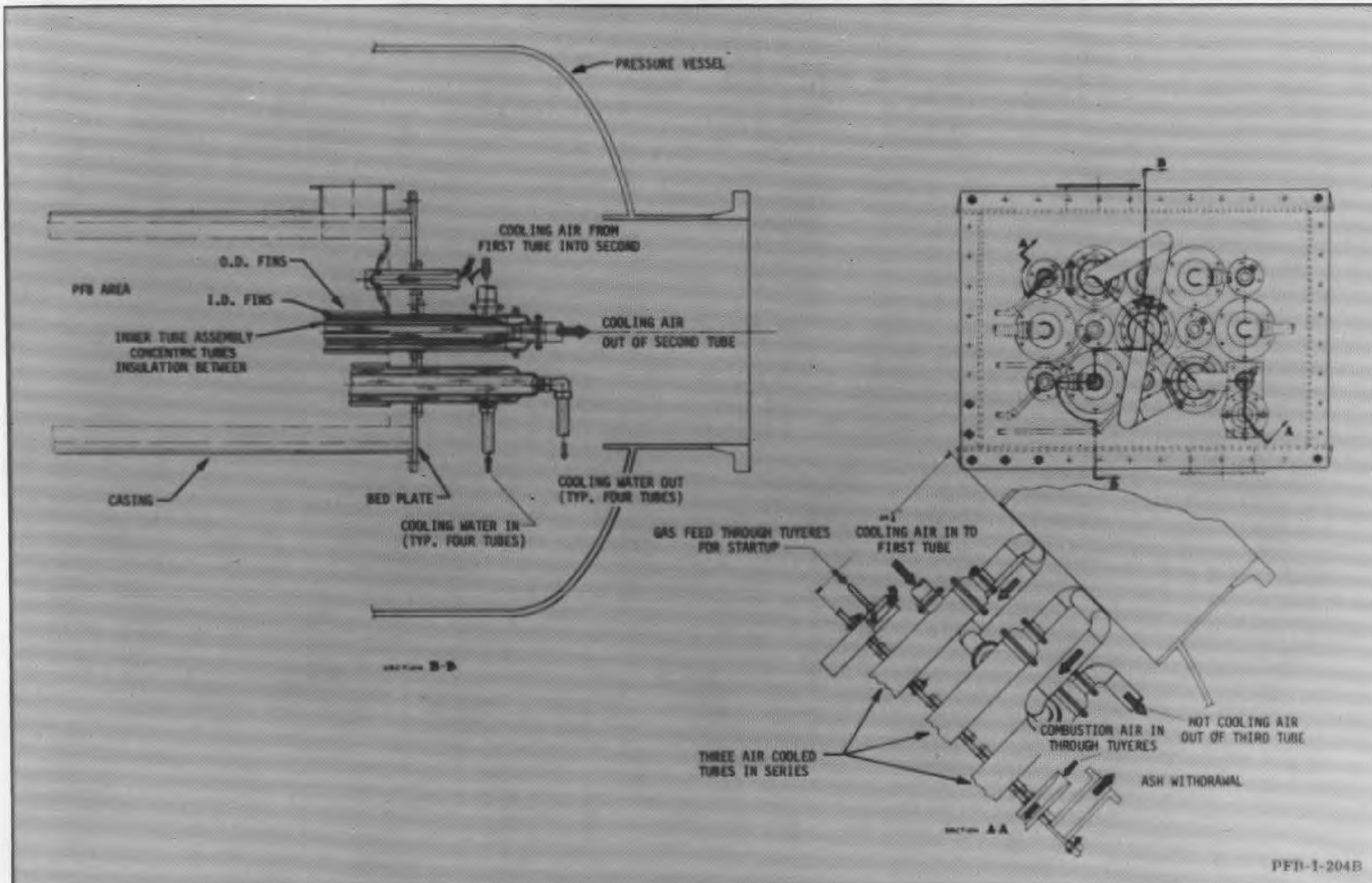


Figure 5.15

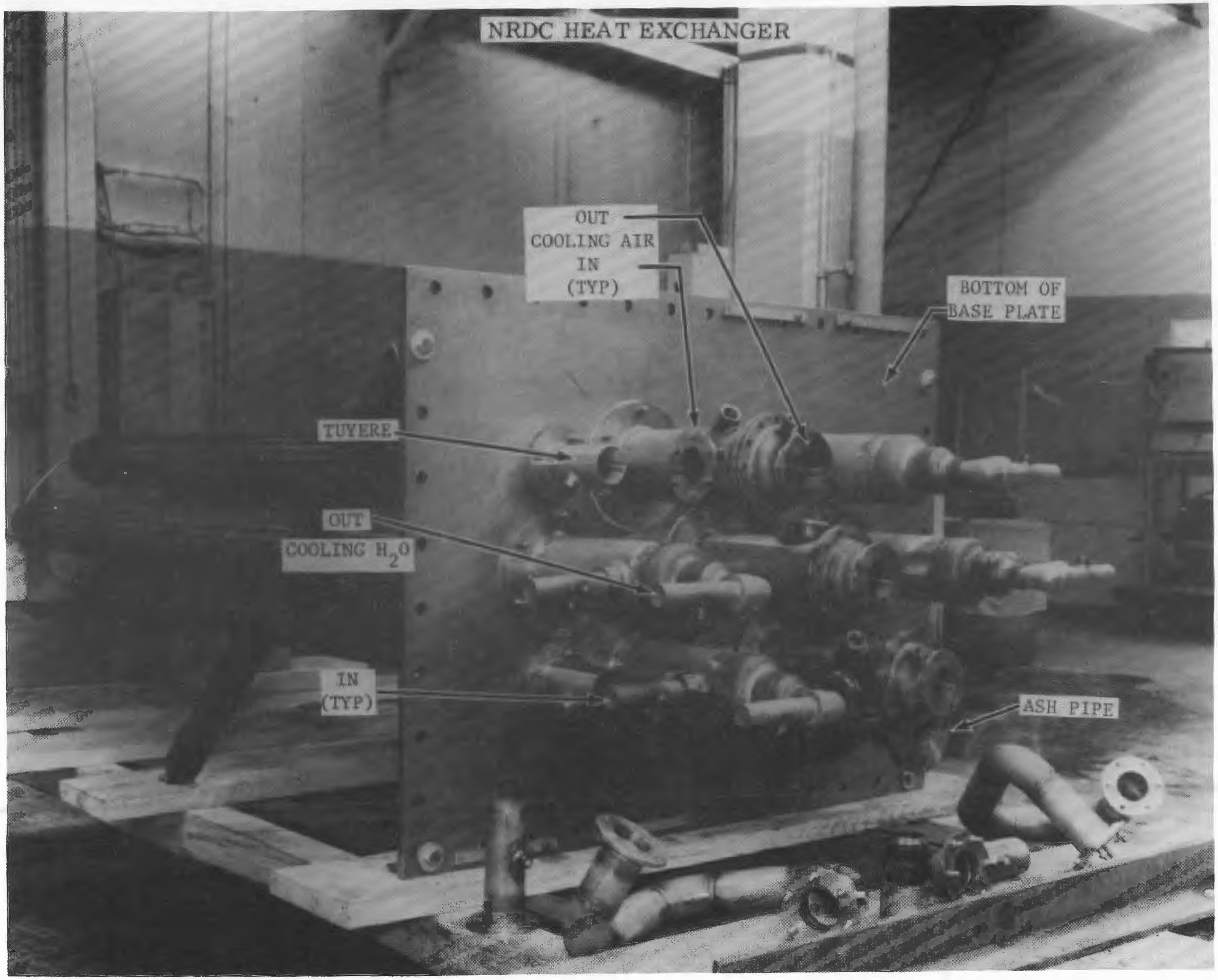

NRDC HEAT EXCHANGER
OUT
COOLING AIR
IN
(TYP)
BOTTOM OF
BASE PLATE
TUYERE
OUT
COOLING H2O
IN
(TYP)
ASH PIPE

Figure 5.16

FINNED TUBE COOLANT DISCHARGE TEMPERATURES
NRDC RIG — 3 COOLANT TUBES IN SERIES

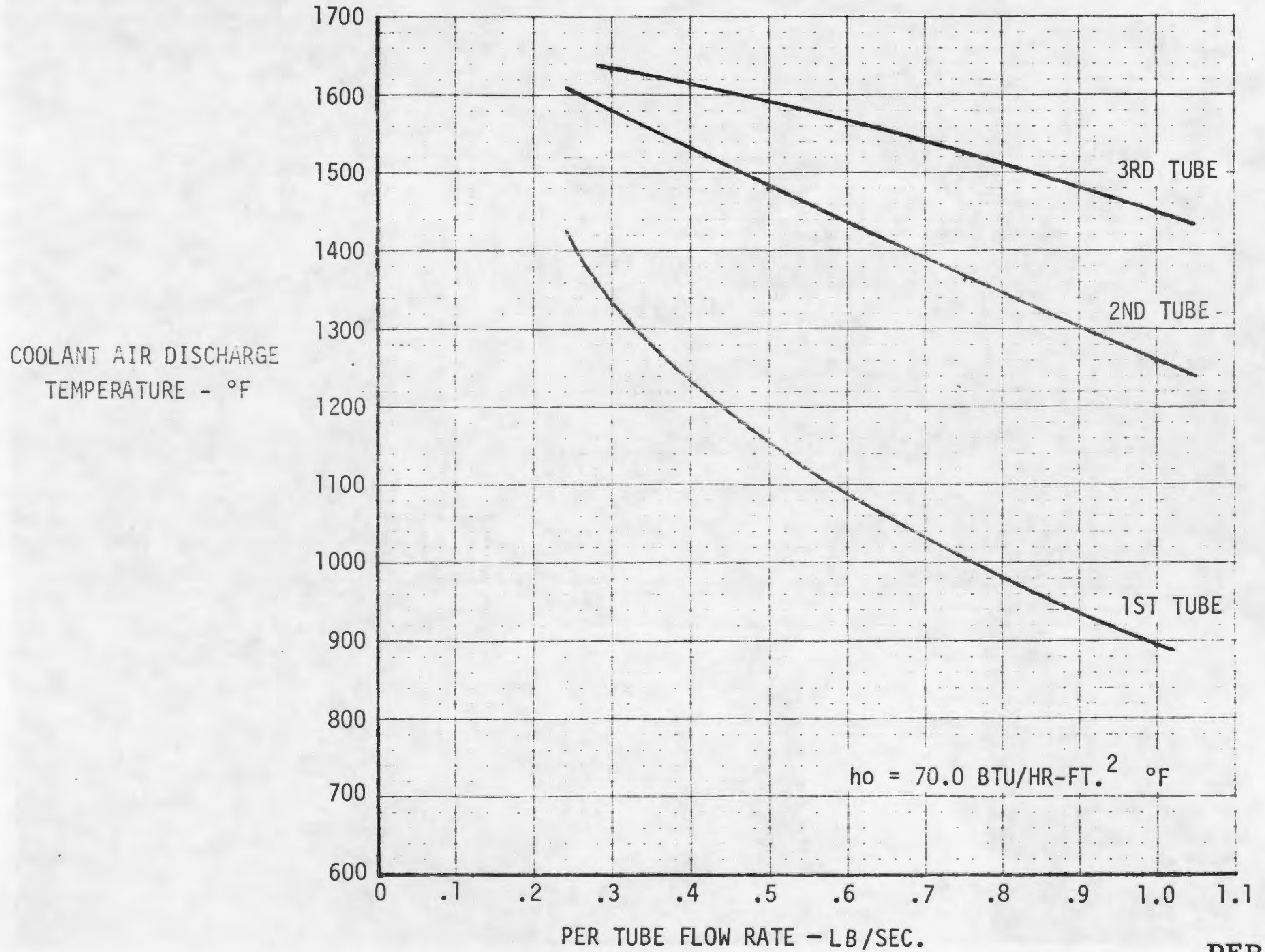


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Figure 5.17

5.3.1.1 Limestone Calciner

The calciner is fired with oil containing sulfur and, except that the bed is limestone instead of dolomite, and the system is only slightly above atmospheric pressure, the conditions for obtaining useful material data will be representative of those expected in the PFB combustor. Other differences between the calciner and PFB combustor which must be considered in evaluating the data include: (a) the calciner operating temperature range is 1460 - 1600°F slightly lower than the 1650°F PFB design point condition although 1650°F is possible during momentary excursions in the calciner.

Calciner fuel injection occurs in the "Calcining Chamber", see Figure 5.18. This is the next chamber below the 3rd Preheat Chamber where the specimen tubes are to be located. Since no combustion processes are taking place in the 3rd Preheat Chamber, a fairly uniform temperature distribution can be expected in the bed. In the PFB, the tubes may be exposed to possible local hot spots at coal injection points, but the overall bed temperature distribution should also be uniform.

Since the calciner bed is much shallower than the PFB, the specimen fin tubes are necessarily short (Figure 5.19). Therefore, a stabilized flow pattern up past the specimen tubes may not be fully established and the erosion pattern may be partially due to end effects and conditions occurring in the nominal fluid bed "surface".

The four fin tube specimens,(Figure 5.19), are supported by two 3 inch schedule 80 pipes welded to a heavy cover plate clamped to the calciner man-hole nozzle. The lower 10 inches of the fin tubes are submerged in the bed. The fins for two of the four tubes extend approximately 2-1/2 inches above the nominal upper surface of the bed in order to study the effects occurring in the space above the bed.

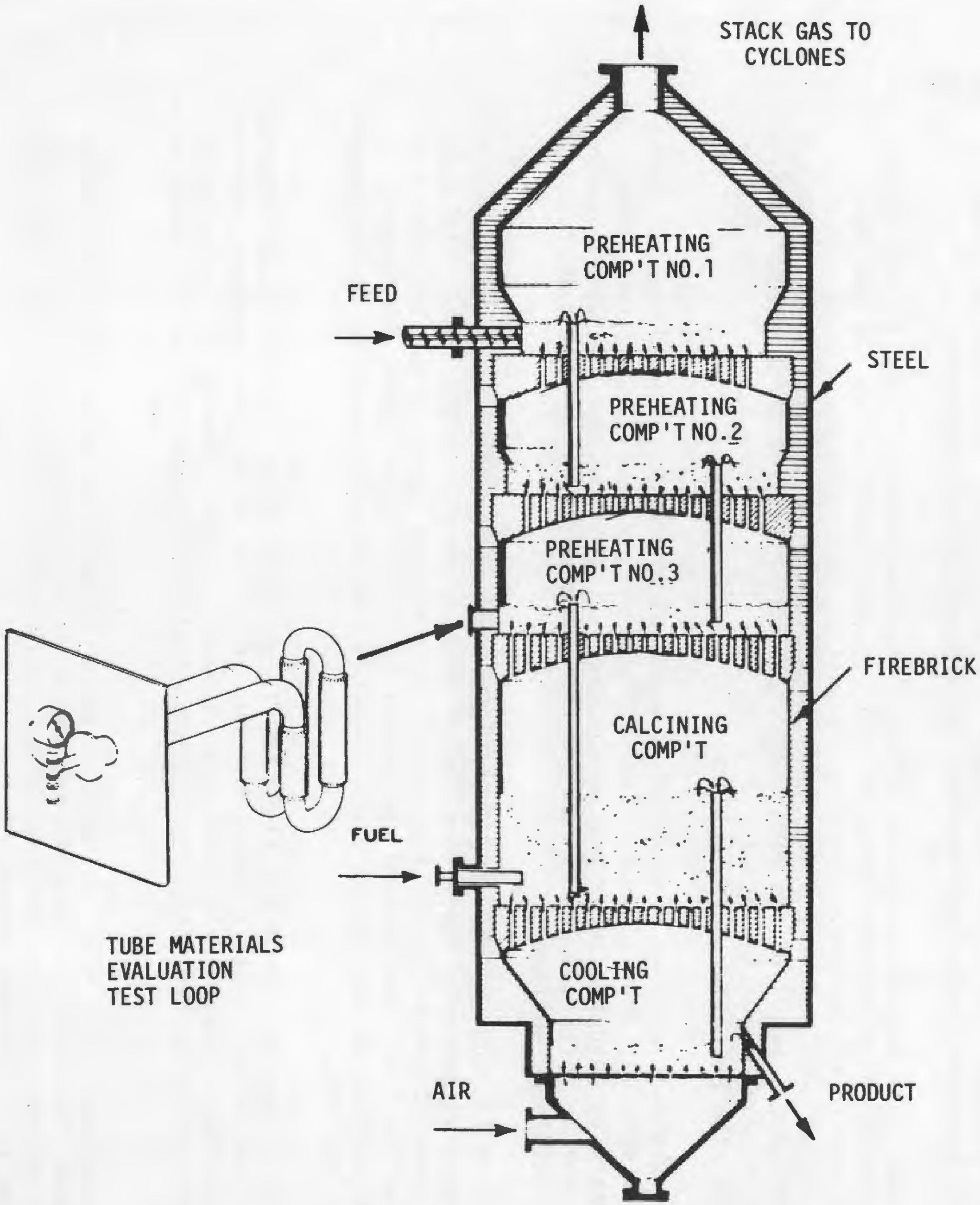
The test loop is welded gas tight and is provided with a pressure gage and vent valve in order to detect the occurrence of a hole in the tubing caused by erosion without removing the tube from the unit. Since there is no coolant circulation through the tubes, the specimens will be essentially at bed temperature.

The test specimens will be installed soon and will be exposed for the typical calciner run which is normally 130 days. At the conclusion of the test, the tube specimens will be examined metallographically to determine the mechanism and depth of surface attack.

5.3.1.2 Sand Bed Incinerator

The sand bed should provide an accelerated evaluation of relative data among the tube materials tested. The environment in the sand bed is more severe than conditions in the PFB combustor, both from the erosion standpoint and the corrosion factor.

Figure 5.18



FLUO SOLIDS LIME KILN

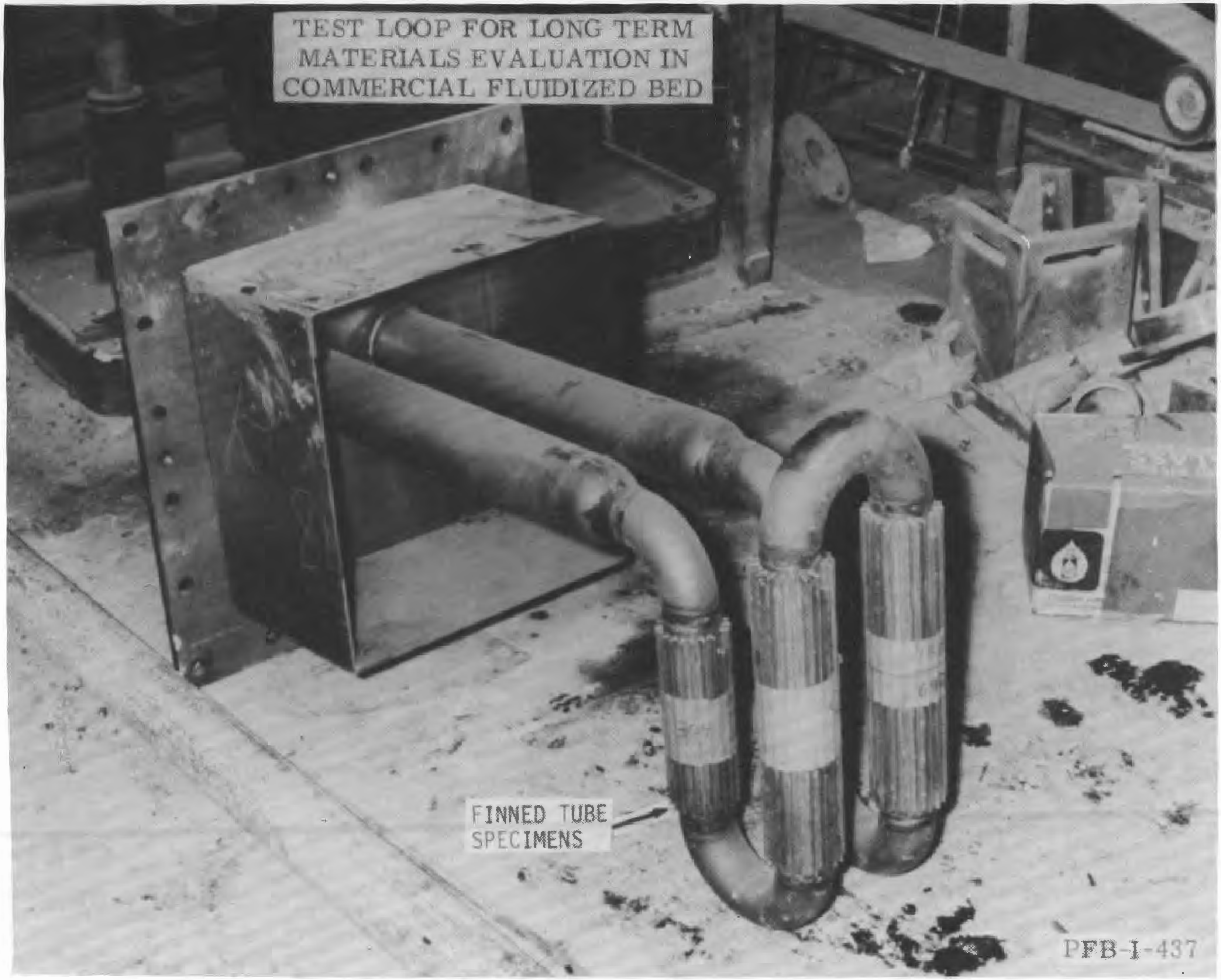

TEST LOOP FOR LONG TERM
MATERIALS EVALUATION IN
COMMERCIAL FLUIDIZED BED
FINNED TUBE
SPECIMENS
PFB-I-437

Figure 5.19

The fluid-bed particles in the sewage incinerator installation are harder than limestone or dolomite and the products of combustion of sewage have a wide range of corrosive elements. Since it would be difficult to determine which effect is more predominant, the value of the test is principally in its comparison of candidate materials in identical conditions which are believed to be more hostile than those to be encountered in the PFB combustor.

The tube specimens will be installed in the Torrington incinerator which has a 5 foot deep sand bed operating in the 1500 - 1600°F range. Figure 5.20 shows the complete assembly of test loops with four fin tube specimens. The lower four feet of the fin tubes are submerged in the bed. The fins extend approximately two feet above the nominal upper surface of the bed in order to study the effects occurring in the space above the bed.

In addition, the vibration environment of the specimen heat exchanger tubes which are representative of the size and comparison of the PFB tubes will be recorded.

The instrumentation that will be used to evaluate the dynamic environment will be primarily accelerometers. Displacement pickups will be used to investigate the low frequency range 10 to 100 cps (in this frequency range, accelerometers are not sensitive enough to detect small amplitudes). High temperature weldable strain gages will be used on the specimen heat transfer tubes to measure tube vibratory stresses.

The test specimens will be removed, photographed and fin and tube thicknesses will be measured by sonic gage and mechanical techniques and reinstalled at approximately 1 and 4 months after initial installation.

The total test period will be 7 months unless the condition of the test specimens indicate additional operating time is desirable.

At the conclusion of the test, the tube specimens will be metallographically examined to determine mechanism and depth of surface attack.

5.3.2 Erosion Evaluation of PFB Heat Exchanger Tube Materials

An existing laboratory-size atmospheric fluidized bed, heated by a furnace, has been operated at 1600°F to determine the erosion resistance of fin and tube materials in a fluid bed environment simulating the temperature and velocity conditions of the PFB combustor. The bed contained samples of candidate alloys, weldments, braze joints, and protective coatings. The aluminum oxide bed material was fluidized by air at the fluidizing velocity planned for the PFB combustor. Measurements of weight loss, dimensional change, change in surface roughness and metallographic examination have been made to determine erosion resistance following 1000 hour exposure tests. The test rig consists of a six inch diameter, externally heated bed of alumina, fluidized by preheated air. The material samples were suspended vertically in the fluidized alumina and removed periodically for inspection.

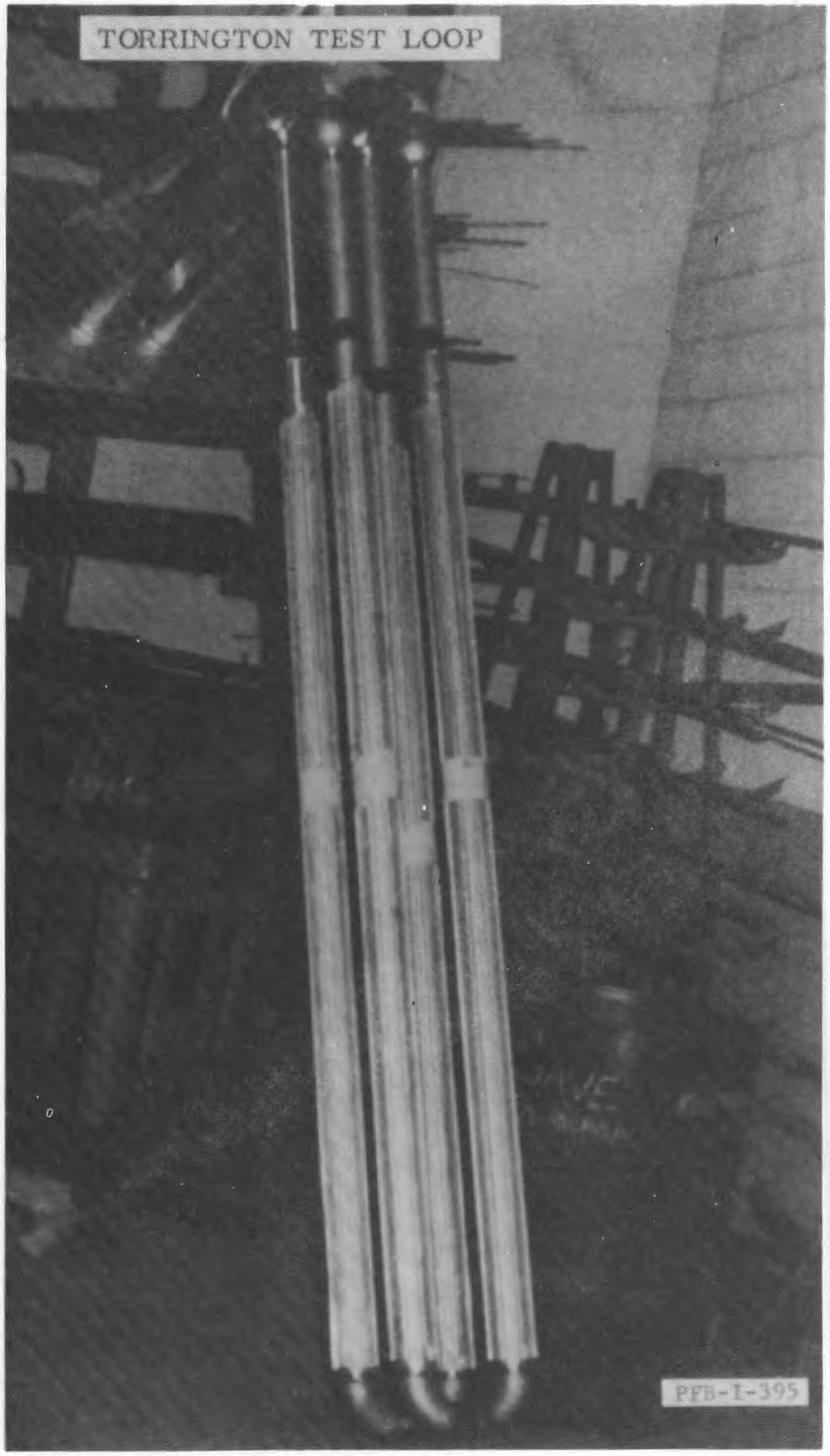


Figure 5.20

For the first test, a group of cobalt base and nickel base alloys was selected for testing which included compositions giving strengths and corrosion resistances over a broad range. The materials included Stellite 6B, Haynes 188, Incoloy 800, Inconel 601, Inconel 690, Inconel 617 and Haynes 556.

Analysis of the results of the first test revealed that the velocities encountered in the fluidized bed were too low to result in measurable erosion. Weight changes were extremely small and could be attributed to oxide spalling when samples were removed for measurements.

The metallographic results showed that, in general, samples built-up oxide layers about 1/2 to 1 mil thick which were relatively continuous and adherent. No catastrophic attack was in evidence on any specimen.

Test No. 2 subjected weld beads (Inconel and Stellite 25 weld wire) and braze areas (Colmonoy 150) to the bed environment. One-thousand (1000) hours of exposure caused virtually no effect other than a very thin (almost invisible at 400X) oxide layer formation on the weld. The braze developed an oxide layer to which fine alumina adhered. This layer is thought to be Boron oxide which forms as a result of the Boron coming out of solution upon brazing.

Test No. 3 subjected samples coated with several types of potential protective coatings to the bed conditions. Included were Plasma Sprayed Stellite 31 Composition, Plasma Sprayed Co-Cr-Ni-Ta-Al-Y, Plasma Sprayed Graded Zirconia (Calcia Stabilized), Vapor Deposited Co-Cr-Al-Y, High Velocity Plasma Stellite 31 and High Velocity Plasma Co-Cr-Ni-Ta-Al-Y. This test has completed the 1000 hour run and a visual examination shows no unusual effects. The coatings appear to behave in the same manner as the base alloys, i.e., formation of tight adherent oxide layers. Metallographic examination is proceeding.

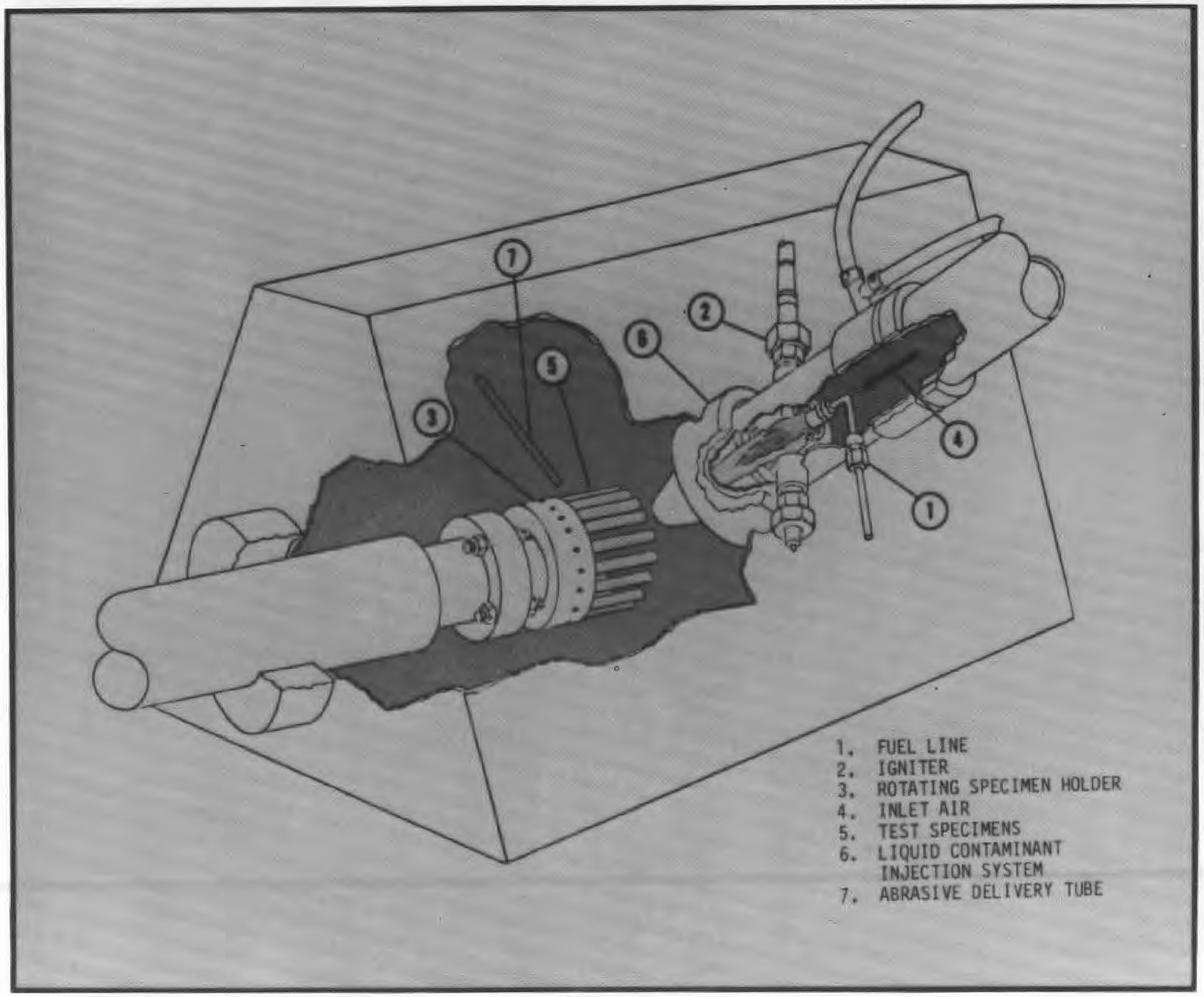
5.3.3 Turbine Materials Corrosion/Erosion Evaluation

The PFB combustor is expected to produce particulate and gaseous substances which could be detrimental to gas turbine blade and vane materials. A turbine material test program was undertaken to determine the resistance of current materials as well as alternative alloys and coatings, to the effects of combined corrosion and erosion of a simulated PFB gas stream.

The test rig used is an existing facility at Curtiss-Wright, (Figures 5.21 and 5.22).

The simulated PFB gas stream environment is created through the combustion of a sulfur doped jet fuel into which alkali metal contaminants (sodium and potassium) are injected to create the corrosive environment. Rod shaped specimens of the turbine alloys and coatings under evaluation rotate through the hot gas environment at 1600°F and are cycled in and out of the flame to simulate turbine start-up and shutdown conditions. In addition to exposure to a corrosive environment, the test specimens are subjected to erosion due to impingement from a high velocity abrasive laden gas stream during elevated temperature exposure.

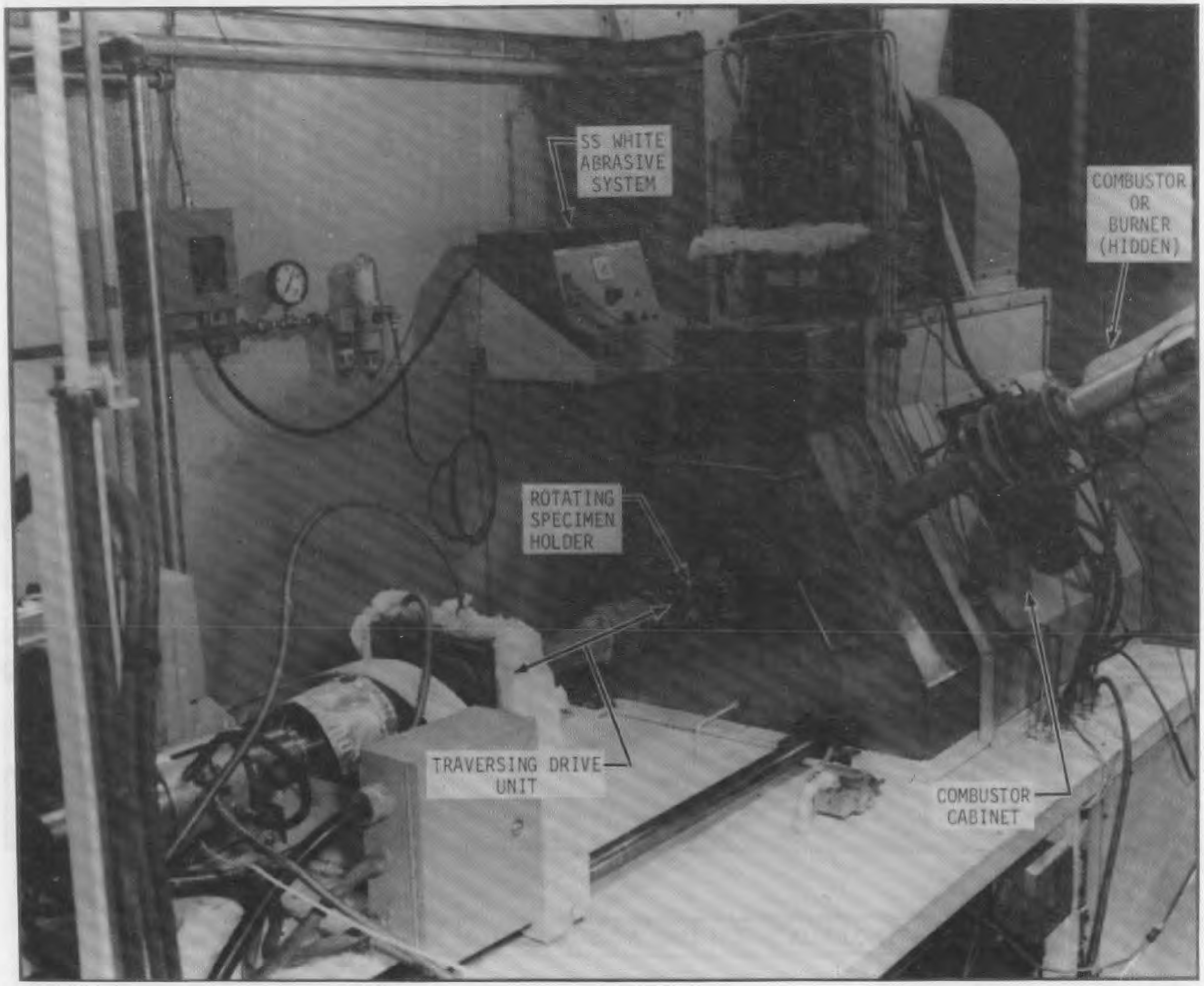
SCHEMATIC ILLUSTRATION OF HOT CORROSION TEST RIG HEATING CHAMBER



PFB-I-78B

Figure 5.21

HOT CORROSION/EROSION RIG
(TURBINE MATERIALS EVALUATION)



PFB-1-10B

Figure 5.22

High levels of contaminants and erosive media have been utilized in this test program in order to accelerate the testing to obtain relative corrosion-erosion data for the various turbine alloys and coatings under evaluation. It is estimated that the test conditions are two to three orders of magnitude more severe than conditions the actual PFB turbine will be exposed to.

Three different tests have been completed to date. In these three tests the corrosion-erosion resistances of the turbine alloys under test have been determined utilizing three different erosive media while maintaining the alkali metal contaminants at one level. Ten micron alumina was utilized in test No. 1 while ten micron silica and three micron silica were used in Tests No. 2 and 3, respectively. Table 5.2 lists the test conditions of all three tests as well as the conditions expected in the PFB gas stream.

Preliminary results have shown that the turbine alloys under evaluation experience rapid metal loss due to erosion from ten micron alumina and ten micron silica particulate at flux levels of 3 grains/in^2/sec and particle impact velocities of 300 fps. Turbine alloy erosion is significantly reduced when subjected to three micron silica particulate.

Aluminide diffusion coatings, utilized to protect turbine alloys from corrosion, provide a hard protective surface which has better resistance to erosion than the base alloy themselves.

The cobalt base alloy FSX 414 has better resistance to corrosion and particulate erosion than the nickel base alloys evaluated in this program.

The ranking of the alloys/coatings, in terms of corrosion-erosion resistance, evaluated in this program is as follows:

Best:	S-31 + CW-3 aluminide coating IN 738 + CW-3 aluminide coating FSX 414
Intermediate:	U-710 IN-738 IN-792, U-500
Poorest	U-700

Preliminary conclusions from these tests are as follows:

Particulate matter in the PFB gas stream entering the turbine should be limited to less than three microns in size in order to reduce turbine component erosion effects.

Cobalt base alloys should be utilized as vane alloys where possible.

Aluminide diffusion coatings should be utilized on turbine blades and vanes to improve component erosion resistance.

Udimet 700 first stage turbine rotor blades should be replaced with Udimet 710 alloy blades because of the improved corrosion resistance of the U-710 over U-700.

TABLE 5.2

CORROSION-EROSION TEST CONDITIONS

	Test #1	Test #2	Test #3	Expected PFB Environment
Test Specimens	U-700, U-710, U-500, IN738 IN738+CW-3, S-31+CW-3	U-700, U-710, U-500, IN738, IN792, FX 414 IN738+CW-3, S-31+CW-3	Same as Test #2	
Metal Temperature	1600 ± 25°F	1600 ± 25°F	1600 ± 25°F	1600 ± 25°F
Particulate, Size and Composition	10 Micron Al_2O_3	10 Micron SiO_2	3 Micron SiO_2	< 2 Micron, Mix of SiO_2, Al_2O_3, Fe_2O_3, C, $CnSO_4$, CnO, MgO
Leading Edge Impact Velocity	300 fps	300 fps	300 fps	300-500 fps
Particulate Flux	3.0 grains/ in^2/sec	3.0 grains/ in^2/sec	3.0 grains/ in^2/sec	0.03 grains/ in^2/sec
Alkali Metal Content				
Sodium	5 PPM	5 PPM	5 PPM	< 1.5 PPM
Potassium	2 PPM	2 PPM	2 PPM	< 0.5 PPM
Sulfur	0.3%	0.3%	0.3%	0.3%

5.4 SGT/PFB OPERATING PARAMETERS RIG

To provide experimental test evaluation of key system components, procedures, and operations in support of the Pilot and Commercial Plant program tasks, a Small Gas Turbine/Pressurized Fluidized Bed Combustor (SGT/PFB) test rig is to be installed at Wood-Ridge, New Jersey. The design includes a scaled PFB combustor having a bed depth and freeboard height equal to the proposed Commercial and Pilot Plant Combustor and having the capability to operate at up to 6.5 atmospheres pressure and 1750°F bed temperature. The rig is designed to evaluate system performance and operating procedures including:

a. PFB Combustor
   1. Combustion Efficiency
   2. Temperature Distribution
   3. Sulfur Retention
   4. Stability

b. Heat Exchanger Core
   1. Effectiveness
   2. Material Evaluation

c. Hot Gas Clean Up Evaluation
   1. State-of-the-Art Equipment - First Stage
   2. Advanced Clean Up System - Second Stage

d. Turbine
   1. Material Evaluation
   2. Particulate and Corrosion Gas Tolerance Estimate

e. Operation at Off-Design
   1. Power Change Characteristics and Off-Design Performance
   2. Bed Stability at Low Combustion Intensity
   3. Operation at Higher Fluidizing Velocities
   4. Shutdown Procedure

A performance analysis was conducted to identify the capacity and operating range requirements for the SGT/PFB combustor to obtain a sufficiently broad range of test variables. The PFB operating conditions for the design point and the maximum operating capability are defined in Table 5.3.

TABLE 5.3

SGT/PFB OPERATING CONDITIONS

		Design Point	Maximum
Bed Pressure.	psia	94.4	94.4
Temperature	°F	1650	1750
Fluidizing Velocity	fps	2.7	5.0
Bed Height.	ft	16	16
Bed Airflow	pps	2.29	4.2
Coal Flow	pph	586	1130
Excess Combustion Air	%	30	35
Dolomite Flow . . . . (1.5 ca/S to 2.0 Ca/S)	pph	213-284	394-526
Cooling Airflow	pps	4.6	8.5
Inlet Air Temperature	°F	506	506

5.4.1 SGT/PFB Test Rig Arrangement

The general arrangement of the SGT/PFB operating parameters test rig is shown conceptually in Figure 5.23 and a simplified flow diagram of the rig is shown in Figure 5.24. The rig includes a scaled version of the pilot plant PFB combustor and heat exchanger, 1st stage cyclone and ash removal system, an Aerodyne 2nd stage clean-up system, a small gas turbine (Rover) engine/electric generator, coal and dolomite receiving, storage, transport and injection system, computer control and data logging system and on-line gas analysis monitoring and instrumentation to provide performance and operating data. The conceptual drawing of the rig shows a gravel bed filter system for the 2nd stage gas clean-up device as an indication of available site space for testing advanced components.

The rig design criteria include:

PFB Combustor/Heat Exchanger - The combustor I.D. was set at 3 feet which is estimated to be the minimum required to provide acceptable vessel heat losses in proportion to the heat released through coal combustion and also the minimum considering the desirability to have a uniform bed condition around the heat exchanger, i.e., affected insignificantly by vessel internal wall boundaries. The PFB combustor is designed to have the same bed depth and freeboard height as the pilot plant PFB combustor to accurately model the heat exchanger and combustor performance.

PFB combustor construction is designed to facilitate development testing and includes multiple access ports, instrumentation ports, and disassembly flanges to increase test flexibility.

Hot Gas Clean-Up - Primary cyclone and secondary cyclone particulate removal are provided in a reduced scale of the pilot plant design. Primary cyclone collected solids can be returned to the PFB at several depth locations or discharged to a hopper.

Gas Turbine - A small gas turbine is provided through which a portion of the mixed PFB combustion gas and heat exchanger air is expanded. The turbine will operate in the hot gas stream which is a simulation of the pilot plant turbine operating condition and turbine erosion and corrosion will be monitored.

Material Handling - Coal preparation and injection equipment was selected to permit testing a range of coal types and particle sizes. Sulfur sorbent handling equipment was selected assuming sized dolomite or limestone is received for test.

Control and Instrumentation - The rig was provided with a computer control system to facilitate data logging and performance calculation as well as to permit simulation of pilot plant control operation to develop start-up, steady state and shutdown procedures and system operating parameters.

Instrumentation is provided at numerous stations to monitor process variables, component and system performance, and solids, gas and particulate analyses.

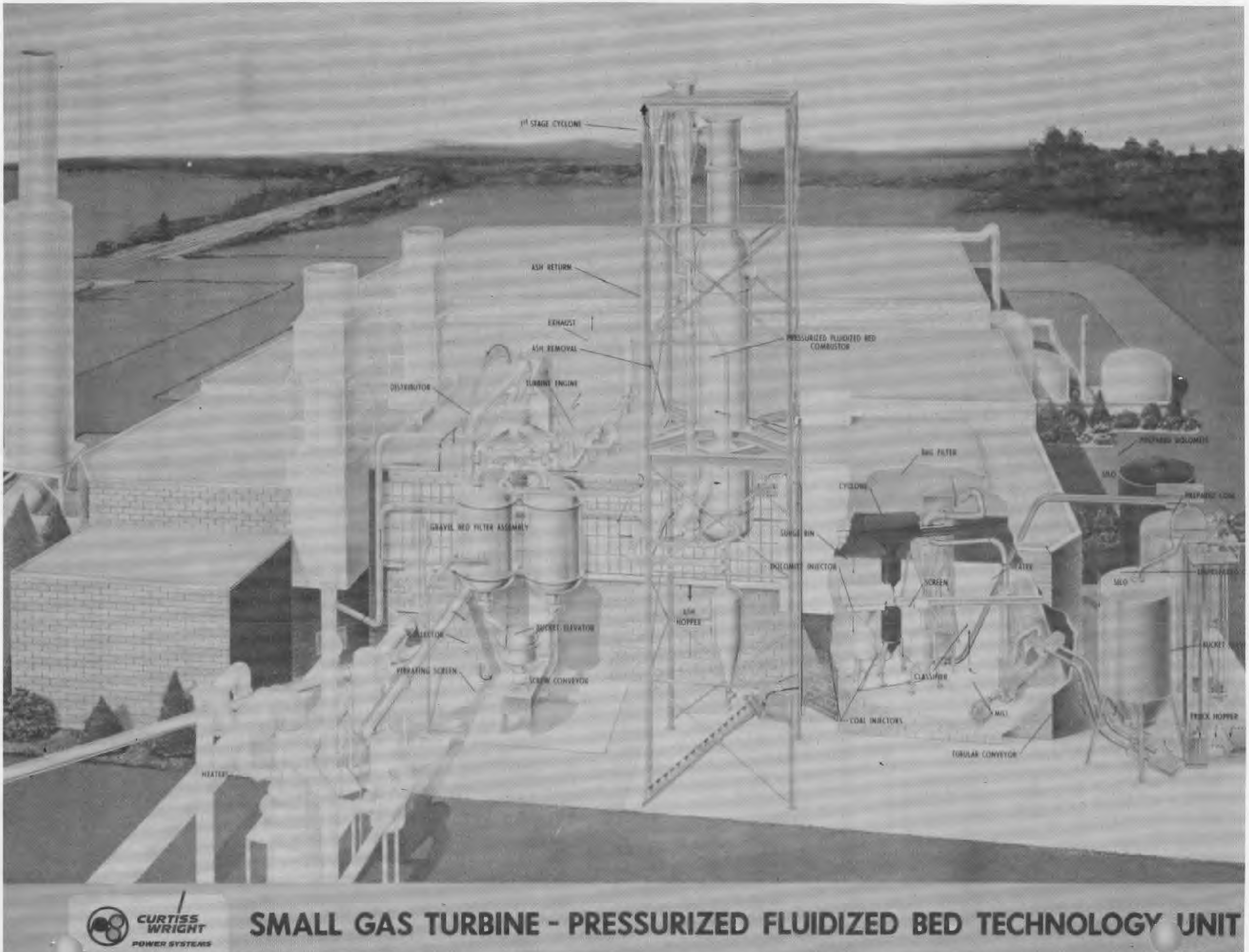

1st STAGE CYCLONE
ASH RETURN
EXHAUST
ASH REMOVAL
PRESSURIZED FLUIDIZED BED COMBUSTOR
DISTRIBUTOR
TURBINE ENGINE
GRAVEL BED FILTER ASSEMBLY
BUCKET ELEVATOR
VIBRATING SCREEN
SCREW CONVEYOR
HEATER
ASH HOPPER
BAG FILTER
CYCLONE
SURGE BIN
DOLOMITE INJECTOR
SCREEN
CLASSIFIER
COAL INJECTORS
MILL
TUBULAR CONVEYOR
PREPARED DOLOMITE
SILO
PREPARED COAL
SILO
TRUCK HOPPER
CURTISS WRIGHT
POWER SYSTEMS
SMALL GAS TURBINE - PRESSURIZED FLUIDIZED BED TECHNOLOGY UNIT

Figure 5.23

SGT/PFB FLOW DIAGRAM

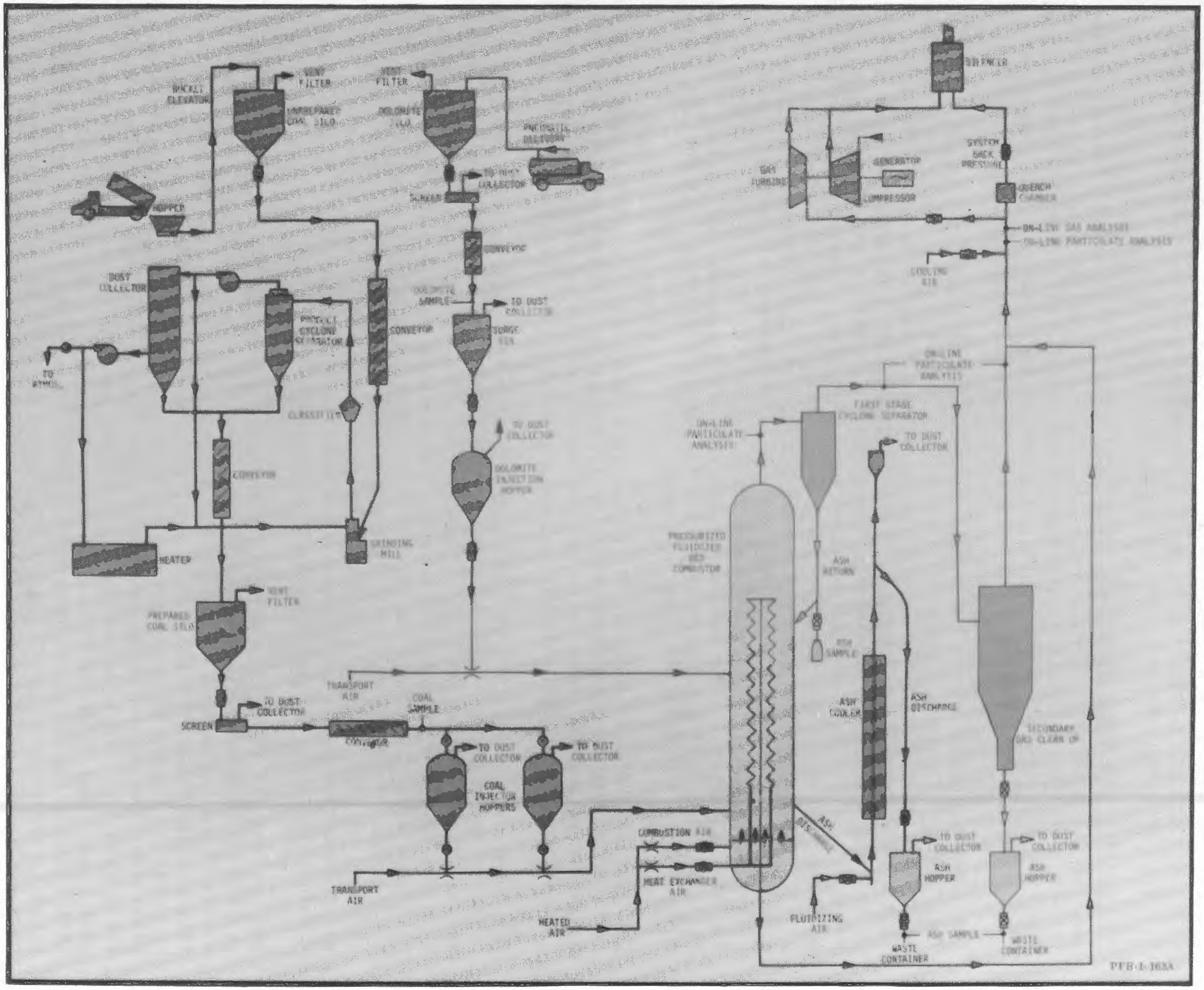


Figure 5.24

5.4.2 Component Design and Analysis

5.4.2.1 PFB Combustor and Heat Exchanger

The SGT/PFB combustor design was initiated with preliminary design and analysis effort concentrating on a number of alternate design arrangements for the vessel distributor and heat exchanger assembly and refractory insulating liner. The PFB general arrangement, Figure 5.25 shows the assembled PFB combustor with the detail components which make up the complete assembly.

The center section of the PFB combustor is a 5 foot diameter vessel 24 feet in length with weld neck flanges at both ends. The vessel is lined with castable refractory insulation; the I.D. of the castable liner is 3 feet. There are 3 coal nozzles providing 3 heights for injecting coal, one dolomite feed nozzle, 15 thermocouples and 5 pressure connections. Provisions are incorporated for three ash return ports to return the fires from the primary cyclone to the PFB at three heights. Ash sample ports are provided for the two upper ash return ports. Ash is removed from the center section through an opening located above the lower flange face. Removed ash is cooled in a fluidized, water jacketed, cooling pipe system rising parallel to the PFB center section. Fluidizing air exits the cooling system through a cyclone and vented to a dust collector. Cooled ash is removed from the upper section of the cooling system and piped to a pressurized lock hopper.

The ash lock hopper vessel is 30 inches in diameter with a dished head enclosure and a 30 degree included angle conical section. Provisions are made for a high level and low level material indicator, thermocouple insertion, pressurization port, vent port and air stimulator nozzles to facilitate ash flow.

The lower section of the PFB combustor shown in Figure 5.26 consists of a distributor and heat exchanger assembly which is mounted on the lower base vessel with a radial centering joint. The distributor is a box type structure made of a top plate, a cylindrical section, two webs, a bottom plate, nine flanged pipe spools, and a flanged section. The top plate has provisions for 12 tuyeres and 9 cooling air tube assemblies. The cooling air tubes are constructed of schedule 40 pipe with fins equally spaced on the OD of the pipe, and convolutions made from sheet stock equally spaced on the ID of the pipe. Within this tube is a double walled insulated tube.

The cooling air flows up through the channels formed by the ID convolutions and the OD of the insulated tube, then turns and flows down the ID of the insulated tube. There is no mechanical attachment between the ID of the outside tube and the OD of the insulated tube, thus permitting independent thermal movement of the outer tube and the insulated tube. The outer cooling air tubes are flanged and mount to flanged pipe spools on the distributor assembly. The 9 insulated center tubes are flanged and mounted to a flanged double dished manifold which is bolted to the lower vessel. The inside area of the heat exchanger manifold which receives the 1600°F heated air is insulated and lined so that the external skin of the manifold is maintained at the same temperature as the distributor assembly. Thus, the radial thermal expansion of the distributor assembly and the heat exchanger manifold are the same.

SMALL GAS TURBINE RIG
GENERAL ARRANGEMENT

PRESSURIZED FLUIDIZED BED COMBUSTOR AND ASH COOLER ASSEMBLY

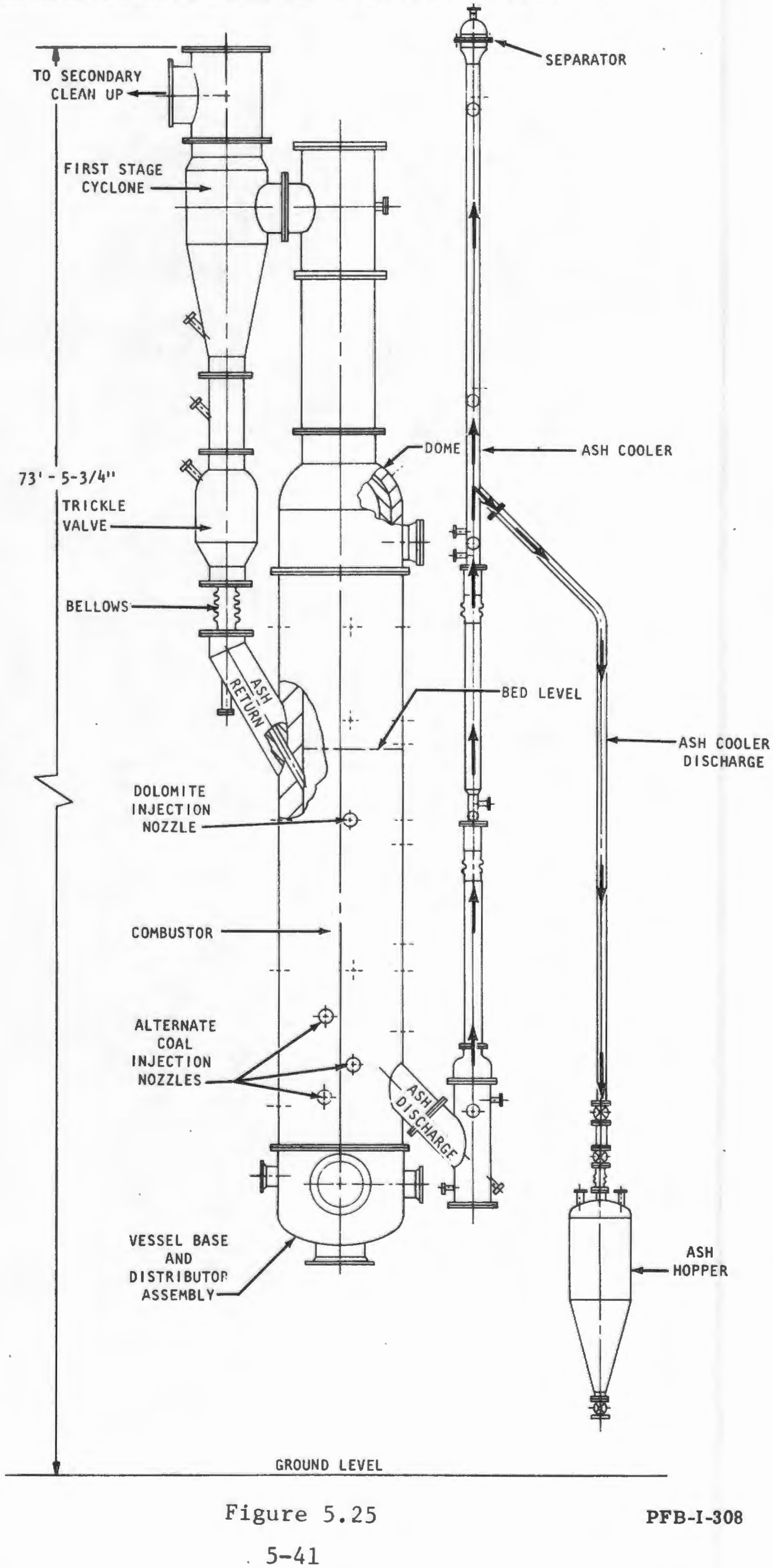


Figure 5.25

PFB-I-308

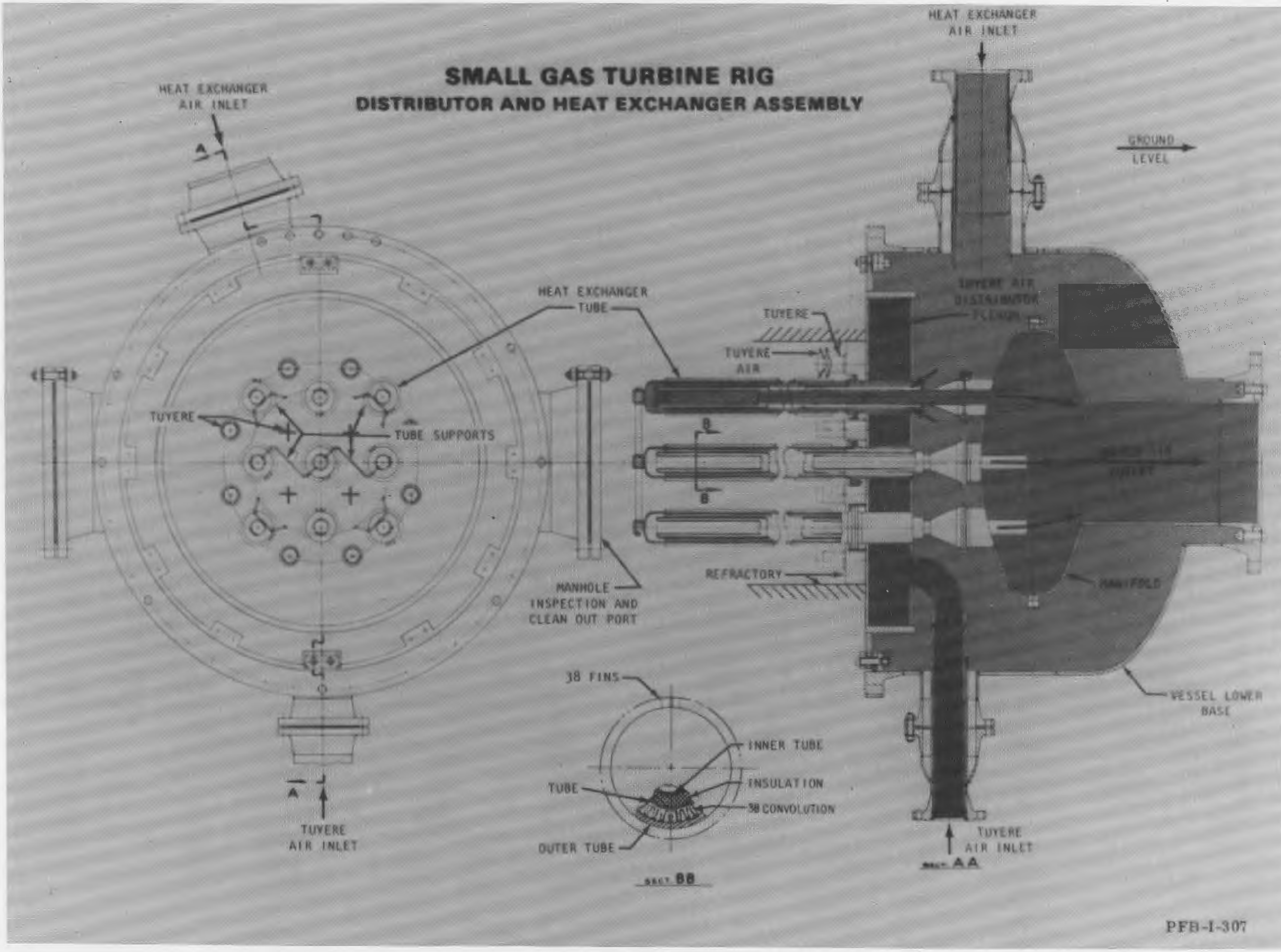

SMALL GAS TURBINE RIG
DISTRIBUTOR AND HEAT EXCHANGER ASSEMBLY
HEAT EXCHANGER AIR INLET
HEAT EXCHANGER AIR INLET
GROUND LEVEL
HEAT EXCHANGER TUBE
TUYERE
TUYERE AIR
TUYERE
TUBE SUPPORTS
REFRACTORY
MANHOLE INSPECTION AND CLEAN OUT PORT
MANIFOLD
VESSEL LOWER BASE
38 FINS
INNER TUBE
TUBE
INSULATION
38 CONVOLUTION
OUTER TUBE
SECT BB
TUYERE AIR INLET
TUYERE AIR INLET
SECT AA
PFB-I-307

Figure 5.26

The tuyere air enters the distributor plenum thru a 4 inch pipe. The bed cooling air enters the lower vessel thru an 8 inch pipe and enters the cooling air tubes from the lower side of the distributor assembly. The bed side surface of the distributor assembly is protected with castable insulation.

The nine heat exchanger air tubes are instrumented to measure fin tip and tube wall metal temperatures at three vertical height locations. The temperature of the heated air within each heat exchanger air tube is measured in the vicinity where it changes direction from vertical to downward flow. The heat exchanger outlet air temperature to the heat exchanger is measured at four locations. The upper and lower distributor plates are instrumented with a total of four (4) thermocouples. The distributor mounting flange lower face is instrumented with six thermocouples. A pressure probe to measure tuyere air pressure is installed thru the lower PFB vessel into the distributor.

The lower freeboard of the PFB consists of a 5' spherical dome and 5' cylindrical section with castables. The outlet opening from the freeboard is a 36" ID pipe.

An inspection port is provided on the cylindrical section and one pressure probe port is provided in the spherical section.

The upper freeboard consists of a tee and a pipe section. The section is made of 36" ID pipe.

Combustor Gas Particulate Removal - The first stage primary cyclone is a conventional cyclone separator with an inlet tangentially exiting into a swirl chamber with a clean air exit pipe and an ash return port. The basic vessel is 9-1/2 feet ID with castables. The first stage primary cyclone is bolted to the upper freeboard tee. The overall length of the primary cyclone is just under 10 feet.

The 1st stage cyclone collected particulate is returned to the PFB combustor, then the ash return spool and pipe lined with castables. The length of the spool piece is tailored at assembly to accommodate the accumulated tolerances encountered in mounting the ash return loop which includes the pressurized fluidized center section, the spherical freeboard section, upper freeboard tee section, primary cyclone, trickle valve assembly and the ash return expansion joint assembly.

The ash return trickle valve assembly is a vessel lined with castables. Inserted in the vessel is a trickle valve assembly. A weld neck flange is provided for inspection of the trickle valve assembly. A blowout pipe is provided above the mitered joint in the trickle valve assembly. The blow through nozzles located in the trickle valve assembly, ash return spool and the primary cyclone are activated by a timer and solenoid valves.

An expansion joint is provided between the trickle valve assembly and the center section of the pressurized fluidized bed ash return nozzle. The assembly consists of an expansion joint welded to ASME Code type flanged and dished spun heads. A Van Stone flange is utilized to eliminate angular misalignment tolerances between the mounting flange of the trickle valve assembly and the ash return nozzle flange of the PFB center section. The dished heads contain castables. A pipe insulated on the OD is inserted in the expansion joint and becomes the passage for the ash.

An evaluation of potential second stage gas cleanup systems was conducted. Based upon present day technology of high temperature,high pressure gas cleanup systems in conjuction with latest available data for estimated first stage cyclone effluent,it was concluded that a cyclone separator would meet design requirements. The SGT/PFB rig provides the opportunity to confirm the first stage cyclone effluent and evaluate the most promising second stage cleanup system. Additional 2nd stage hot gas cleanup concepts or systems appear potentially attractive, such as:

a. Mesh Filter (metal or ceramic bag)
b. Pebble bed filter
c. Granular bed filter
d. Electrostatic precipitator

Considering the present level of industrial gas cleaning experience with each system and the additional required development to apply these devices to a high pressure, high temperature system, the cyclone has been selected for the SGT/PFB 2nd stage hot gas cleanup. The design layout of this cleanup system which will be installed for evaluation in the SGT rig is shown in Figure 5.27. Gas enters the vessel tangentially and is subjected to conventional cyclonic separation. The gas flow entering the final stage is divided into two separate gas streams (primary and secondary) by means of an orifice plate. The primary flow enters through a central set of turning vanes at the base of the cylindrical second stage unit. The secondary flow enters around the circumference of the second stage at the top through tangential inlet nozzles. As particles in the rising primary flow are thrown outward towards the wall they are swept downward towards the collection hopper by the secondary flow.

5.4.2.2 Small Gas Turbine

The discharge line from the secondary cleanup connects to a "Y" section combining with the PFB combustor heat exchanger discharge line. The "Y" section connects to a tee section which has an isokinetic flow branch leg leading to a Rover gas turbine engine. Only a portion of the total flow (1.4 pps) flows to the engine. The straight through path receives the remainder of the PFB flow which is cooled in a water quench chamber. The cooled mixture flows through an exhaust silencer.

The flow for the Rover gas turbine engine leaves the tee section and is cooled to 1530°F with dilution air. It then flows through a ball valve which can be closed to prevent flow through the turbine loop and is piped to the Rover gas turbine engine. The hot gas enters the turbine section of the engine, as shown on Figure 5.28, and drives the gas turbine compressor and electric

SMALL GAS TURBINE RIG
AERODYNE CYCLONE SEPARATOR
SECOND STAGE CLEAN UP

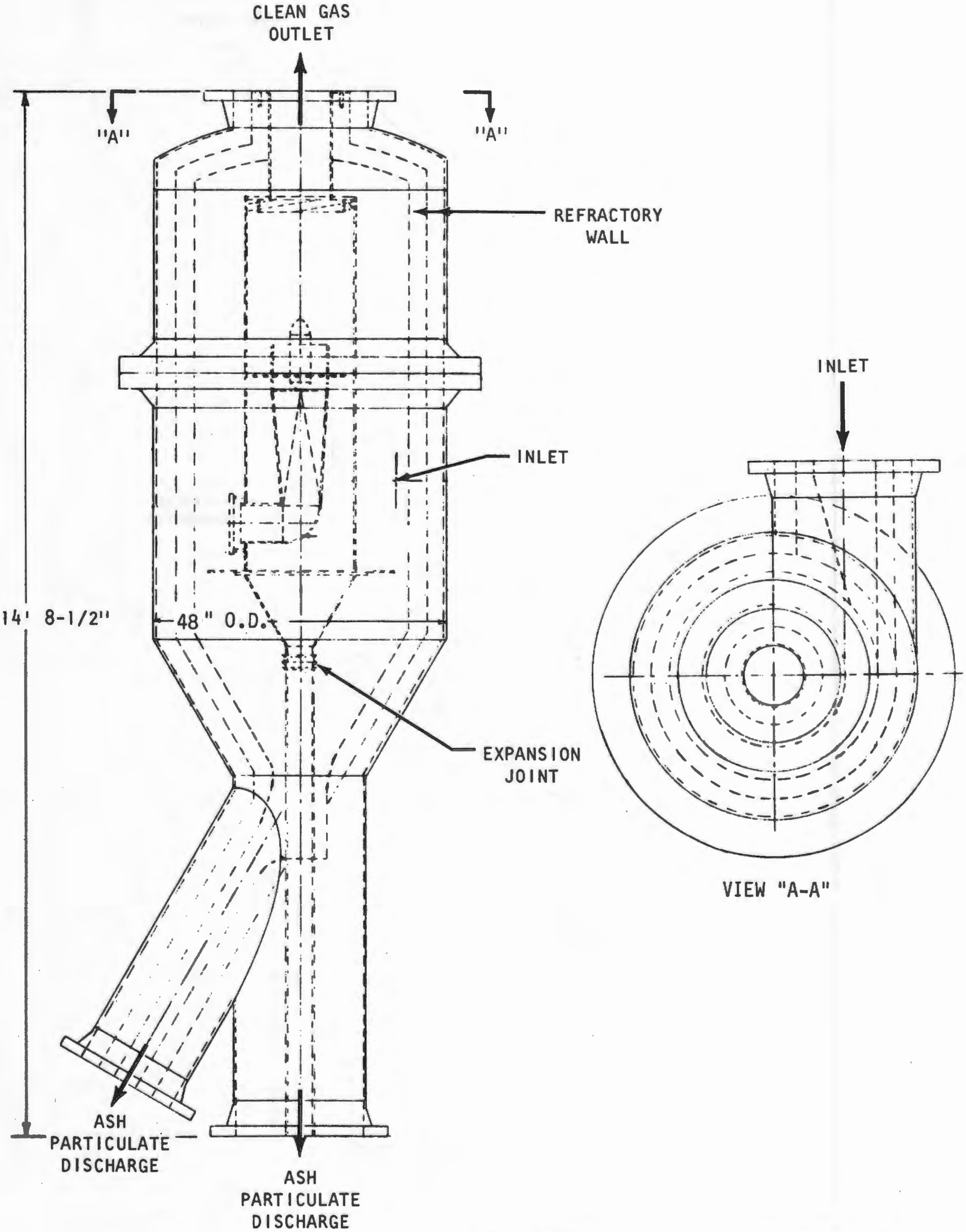


Figure 5.27

PFB-I-304

SMALL GAS TURBINE TECHNOLOGY RIG
ENGINE AIR MODIFICATIONS

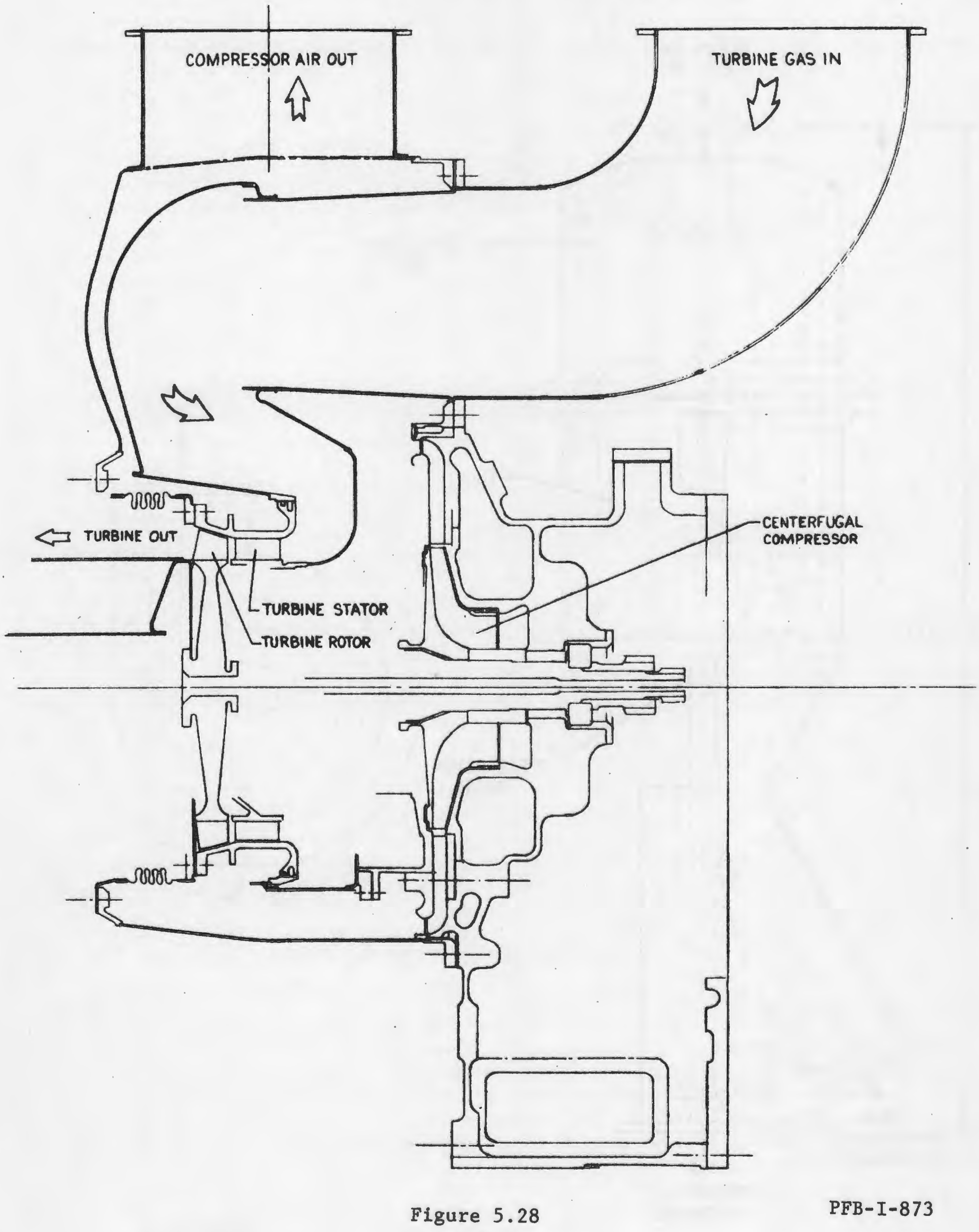


Figure 5.28

PFB-I-873

generator. The gas turbine compressor draws ambient air through the air intake silencer and the compressor air discharge flows through an orifice and combines with the turbine exhaust flow prior to exhausting through the silencer.

Material Handling - The unprepared coal, stored in the facility boiler house, will be delivered to the test site by an 8 ton truck to a hopper mounted over a screw feed conveyor, feeding a bucket elevator (Figures 5.23, 5.24 and 5.29). The bucket elevator discharges the coal into a 16 ton capacity unprepared coal silo, fitted with a vibratory bin activator and shut-off valve. A vibrating feed conveyor then transports the coal to a grinding and drying mill system for preparation to a product size of -1/8 inch x 0. Produce size can be changed without shutdown of the mill. After grinding, the coal is pneumatically transported through a velocity separator, allowing the sized particles to continue to a cyclone separator which delivers the product through a rotary air lock valve. Coal drying is accomplished by heating of the inert transport gas by a direct fired heater.

The prepared coal is discharged from the mill cyclone separator into a tubular conveyor for transport to a 16 ton capacity silo, fitted with a vibratory bin activator, rotary air lock valve, and vibratory screener. A second tubular conveyor transports the prepared coal to the two PFB coal injector vessels mounted on load cells, complete with remotely controlled fill valves, discharge flow valves and vent valves. The coal injection system will be operable in manual or automatic mode. The injector vessel discharge is pneumatically conveyed to the PFB with automatic changeover between the two coal injector vessels based upon preset weigh signals from the vessels. The vessels will be filled automatically and sequenced for venting, starting and stopping of the tubular conveyors, and vessels pressurization and injection.

Presized dolomite (-1/8 inch x0) will be delivered by 25 ton enclosed truck and discharged penumatically into a 30 ton storage silo, fitted with a vibratory bin activator, rotary air lock valve and vibrating screener. The dolomite is then transported by tubular conveyor to a surge hopper located over the single dolomite injector vessel. Dolomite will flow into the injector vessel by gravity feed upon opening of automatic valving between the surge hopper and the injector. The injector vessel, complete with remotely controlled fill valve, discharge flow valve and vent valve, and mounted on load cells, is operable in manual or automatic mode. The fill cycle will be sequenced for venting, starting and stopping of the feed from the overhead surge bin, vessel pressurization and injection. The injector vessel discharge is pneumatically conveyed to the PFB vessel. Ash will be stored on-site in a large capacity hopper inside the boiler house prior to off-site disposal.

Controls and Instrumentation - A process control computer system was selected for use during the test and operation of the SGT/PFB test rig and later the PFB pilot plant. The control system will have data logging functions as well as supervisory control functions. Included as specifications for the computer were: process monitoring, alarming, data printing, data storage, calculating, and sequence logic and control. The computer will be capable of handling digital inputs, thermocouple inputs, high level analog inputs, digital and analog outputs and process interrupts.

SMALL GAS TURBINE RIG
SITE PLAN — COAL AND DOLOMITE HANDLING SYSTEM

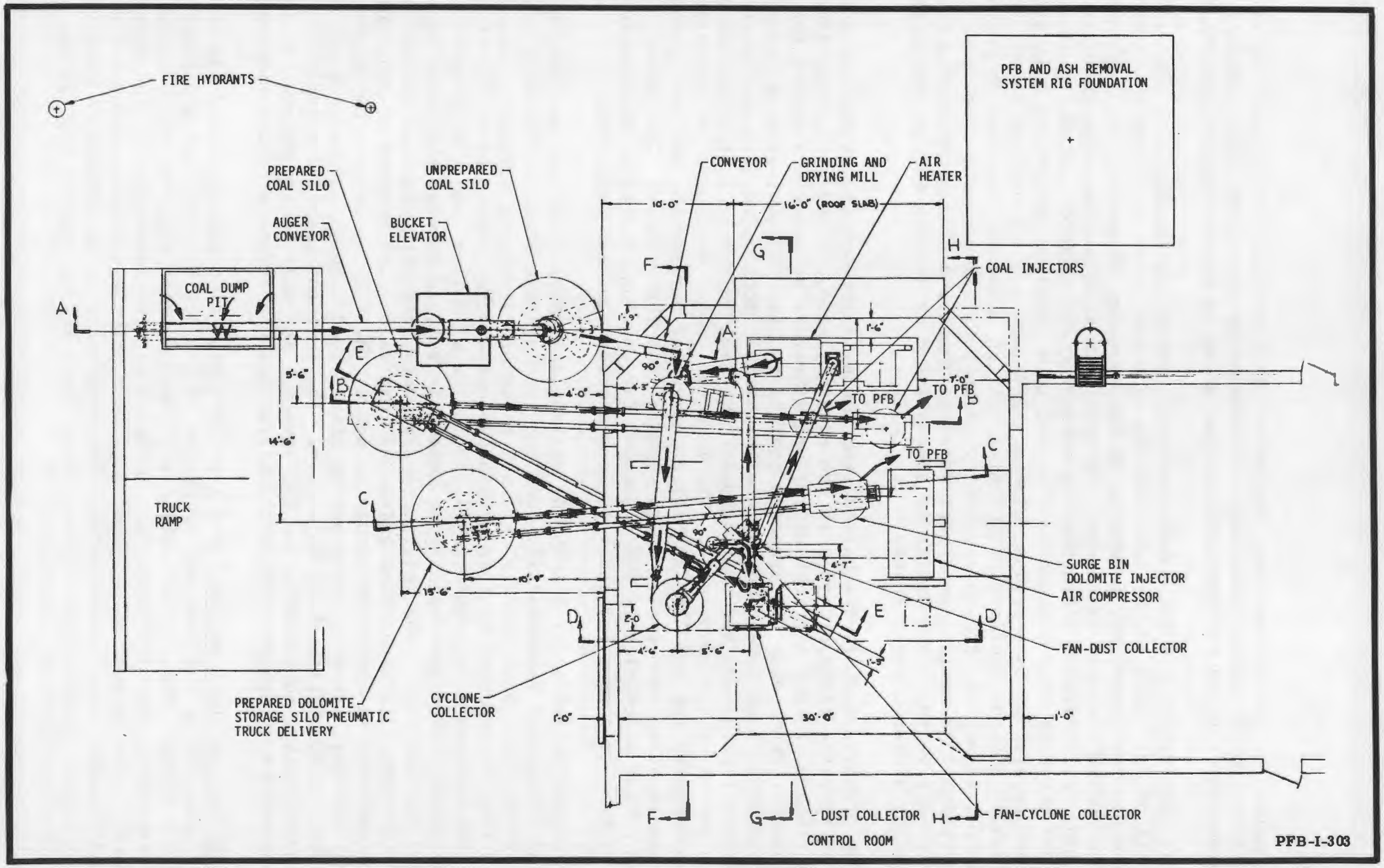


Figure 5.29

An on-line gas analysis system for monitoring SO_2, NO/NO_x, CO_2, CO, and O_2 is provided. The gas parameters selected to be monitored during operation of the SGT/PFB are intended to satisfy Federal and New Jersey State Environmental requirements and provide indication of process performance.

Use of optical and grab sampling methods for the determination of particulates in the gas stream has been studied. Continuous measurements utilizing optical techniques (Laser instrumentation) would be optimum, but units available are prototypes and must be tested, evaluated and qualified before they can be considered prime for measuring on-line particulate loadings and size distribution.

A "grab sampling" method in the exhaust stack is provided as the prime system of particulate measurement. In addition, provisions have been made for future planned evaluations with optical or grab sampling at pressure.

Overall system process and instrumentaiton flow diagrams were prepared. Figure 5.30 is the P&I for the PFB combustor/cyclone and ash cooler. The P&I's contain the complete list of instrumentation and control items required for the operation of the SGT/PFB technology rig. Specifications have been prepared for instrumentation items such as thermocouples, pressure probes, pressure and temperature transmitters, rotameters, pressure safety valves, etc.

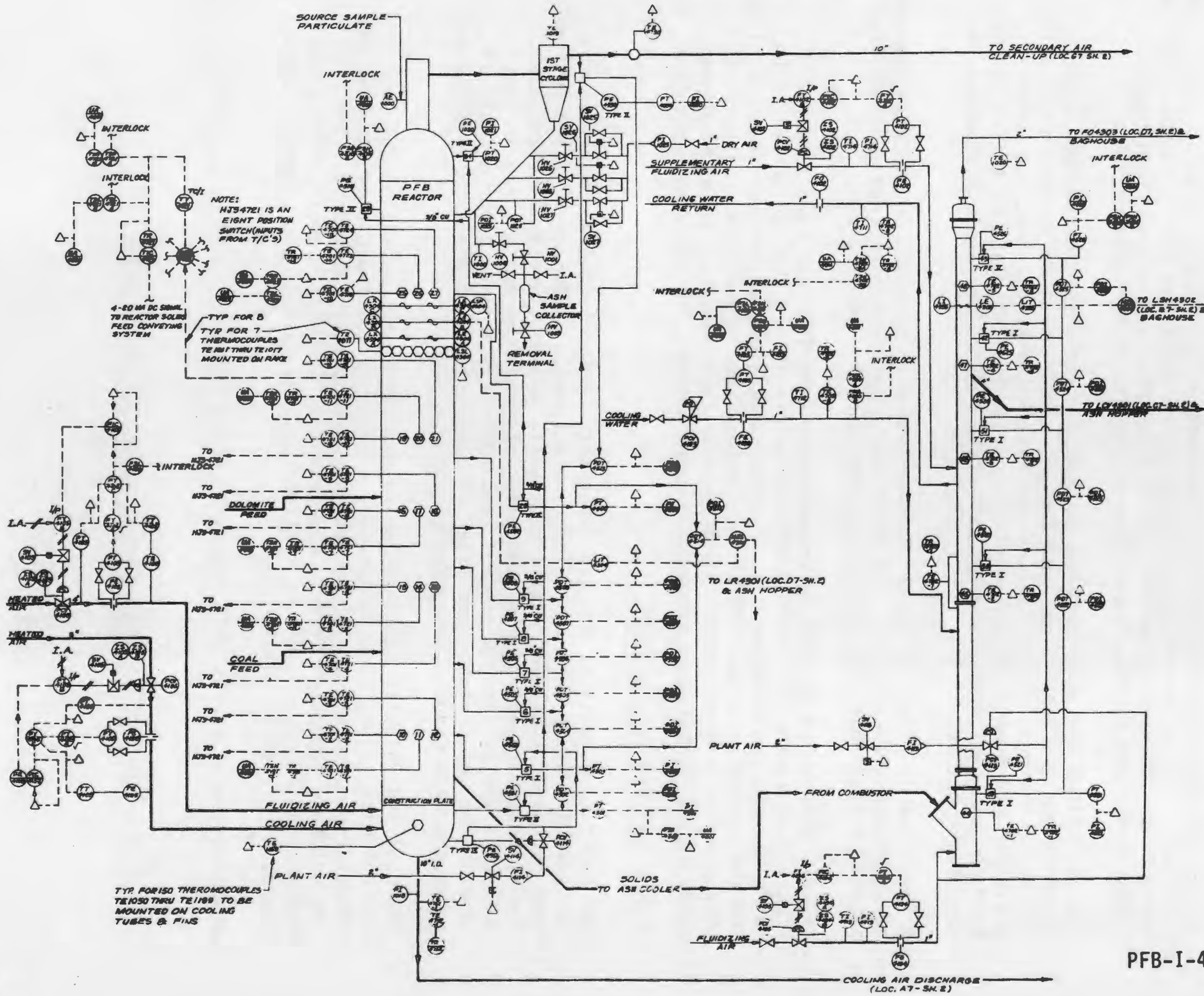
5.4.3 SGT/PFB Test Rig Fabrication

The major components of the PFB combustor, cyclone and ash cooler assembly, as shown in Figure 5.31 are being manufactured. Fabrication of the internal heat exchanger tubes and distributor plate assembly are also progressing. The secondary gas cleanup system materials handling system, gas analysis system, computer process control, and control instrumentation are all on order. The coal grinder and dryer is being installed as are electrical and control system conduit, wireways and panels.

The coal and dolomite receiving and storage system, comprising the coal and dolomite silos, bucket elevator, tubular conveyor systems, screens, bin vibrators and rotary and slide valves, is partially fabricated. The coal and dolomite injection system, consisting of pressure vessels, mixing tee assemblies, transport piping, instrumentation, valving and graphic control board, is partially completed.

Installation of the SGT/PFB rig is expected to be complete by July 1977.

SGT TECHNOLOGY RIG SCHEMATIC
PROCESS AND INSTRUMENTATION - FLOW DIAGRAM



PFB-I-435

Figure 5.30

SMALL GAS TURBINE RIG
TEE - PRIMARY CYCLONE

SGT RIG - BASE VESSEL

Figure 5.31

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