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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

Pilot Plant Facility

Curtiss-Wright Corporation
Power Systems Division
Wood-Ridge, New Jersey 07075

June 1977

Prepared for the United States
Department of Energy

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

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16. Abstracts A promising approach for production of clean cost-competitive electric power generation from coal with improved power cycle efficiency involves the application of a pressurized fluidized bed (PFB) combustor to a combined cycle. Based on a conceptual design of a 500 MW base load power station, a configuration for a pilot electric plant was selected which will use high sulfur (>3%) coal in the presence of a sulfur sorbent (dolomite) material. The gas turbine in this system provides one-third of its compressor airflow to the fluidized bed for coal combustion and the balance of flow to the in-bed heat exchanger. The pilot plant will have the capacity for generating an equivalent of 13 MW. The gas turbine provides over 7 MW of electric power and the steam generated by the waste heat recovery boiler is 58,000 lb/hour. The plant equipment is over 40 percent of the physical size of the commercial plant design. The pilot plant will be a conversion of an existing Total Energy System located at the Wood-Ridge, New Jersey manufacturing facility of Curtiss-Wright. This report describes the plant arrangement, the equipment design configuration, and plant performance.

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Fluidized Bed Processing
Fossil Fuel
Coal
Combustion
Sorbent
Gas Turbine
Combined Cycle

17b. Identifiers/Open-Ended Terms

Fluidized Bed Combustion

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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 of burning 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:

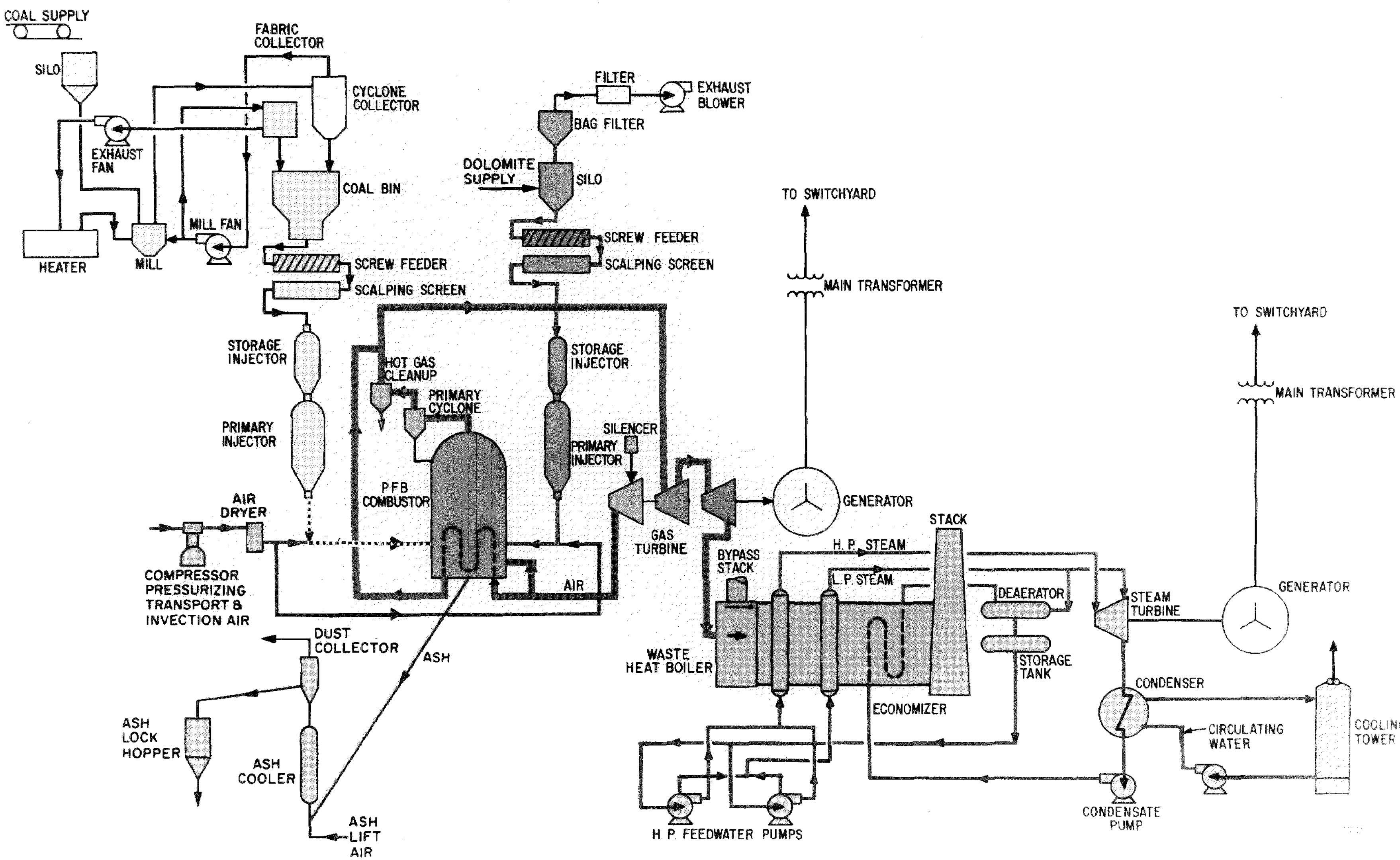
a. Execute a conceptual design for a central station power plant consisting of a PFB combustor with a combined cycle power conversion system.

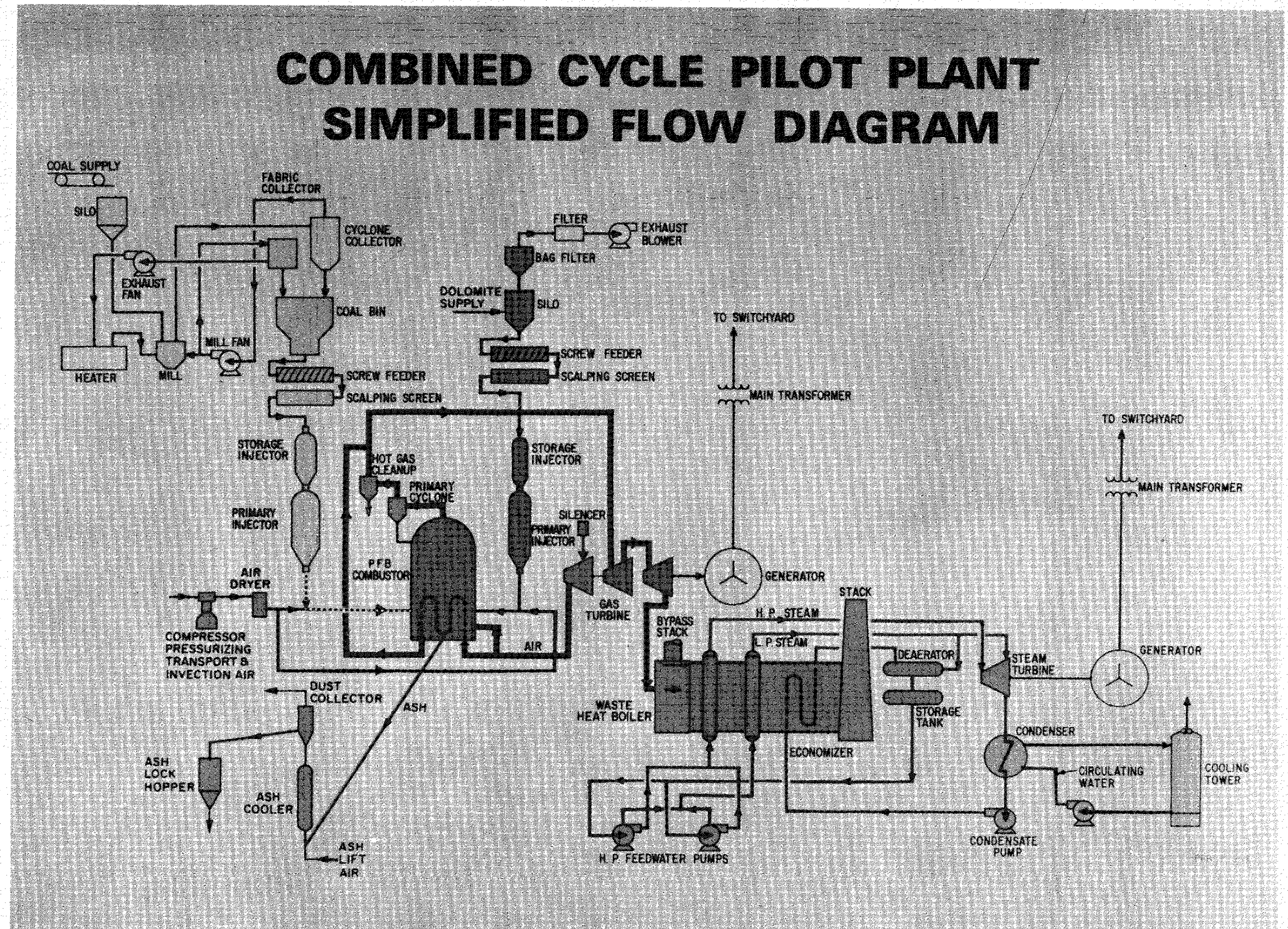
b. Complete a preliminary design of a pilot plant suitable for simulating and evaluating the central station design concept. Supporting experiments to provide technical data for the pilot plant design will be conducted.

c. Design and construct the PFB pilot plant suitable for evaluation of the economic and engineering feasibility of the central station power plant concept.

Fig. 1.1 100%

COMBINED CYCLE PILOT PLANT SIMPLIFIED FLOW DIAGRAM





COMBINED CYCLE PILOT PLANT
SIMPLIFIED FLOW DIAGRAM
COAL SUPPLY
SILO
FABRIC COLLECTOR
CYCLONE COLLECTOR
EXHAUST FAN
COAL BIN
HEATER
MILL
MILL FAN
SCREW FEEDER
SCALPING SCREEN
STORAGE INJECTOR
PRIMARY INJECTOR
FILTER
EXHAUST BLOWER
BAG FILTER
DOLOMITE SUPPLY
SILO
SCREW FEEDER
SCALPING SCREEN
HOT GAS CLEANUP
PRIMARY CYCLONE
STORAGE INJECTOR
PRIMARY INJECTOR
SILENCER
PFB COMBUSTOR
AIR DRYER
COMPRESSOR PRESSURIZING TRANSPORT & INVECTION AIR
AIR
GAS TURBINE
TO SWITCHYARD
MAIN TRANSFORMER
GENERATOR
STACK
H. P. STEAM
L. P. STEAM
BYPASS STACK
WASTE HEAT BOILER
DEAERATOR
STORAGE TANK
ECONOMIZER
TO SWITCHYARD
MAIN TRANSFORMER
GENERATOR
STEAM TURBINE
CONDENSER
CIRCULATING WATER
COOLING TOWER
CONDENSATE PUMP
H. P. FEEDWATER PUMPS
DUST COLLECTOR
ASH
ASH LOCK HOPPER
ASH COOLER
ASH LIFT AIR

Figure 1.1

d. Conduct a test program with the pilot plant to assess the validity of a fullscale 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 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, New Jersey, with major supporting studies being supplied by Dorr-Oliver Corporation, Stamford, Connecticut and Stone and Webster Engineering Corporation, Boston, Massachusetts. Progress during Phase I - Preliminary Engineering is reported herein involving conceptual design, analytical evaluation of commercial and pilot PFB power plants and technology support experiments.

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 (~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 steam 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 drive 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.

The 500 MW PFB commercial plant design is described in an earlier report on Task I - Preliminary Engineering.

A PFB Pilot Plant preliminary design has been completed and is presented in this report. The PFB Pilot Plant will be located at the Curtiss-Wright Wood-Ridge, New Jersey location where an existing 6 MW Gas Turbine Total Energy Power Plant has been in operation since 1970. The PFB Pilot Plant design incorporates the use of this existing power plant with considerable utilization of currently operating equipment.

The pilot plant design is fully representative of the PFB Commercial Power Plant which was conceptually designed earlier in this program. The pilot plant includes a gas turbine powered alternator wherein the gas turbine is approximately 42% of the size (diameter) of the proposed commercial module and a PFB combustor which is 12 ft 4 in. in I.D. compared to a 28 ft I.D. for the proposed commercial unit.

A comparison of the features of each of the two plant designs is shown in Table 1.1.

The pilot plant is designed for ease of maintenance, component servicing and replacement which would be expected in a pilot test program. Area is provided for alternate types of equipment for possible future test programs and includes space for such items as hot gas clean-up systems, sorbent regeneration equipment, etc. The pilot plant is designed for a wide range of operating flexibility to facilitate rapid test evaluation of the PFB combustion concept.

The final design of the pilot plant is expected to be completed in 1978, construction and checkout completed by early 1980, and operational testing will occur largely during 1980 and 1981.

TABLE 1.1

COMMERCIAL PLANT - PILOT PLANT COMPARISON

	Category	Commercial Plant	Pilot Plant
100	Coal Incoming	100 Rail Car Unit Trains 10,000 Ton Live Storage 300 Ton Coal Silo System 300,000 Ton Stock Pile	10 - 12 Rail Car Trains per Week 1700 Ton Live Bunker Storage 10 Ton Surge Hopper 1200 Ton Stock Pile
200	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
300	Limestone Incoming	Rail Car, Bottom Unload Belt Conveyor System 4500 Ton Storage Silo	Rail Car, Pneumatic Unloading and Conveying to 600 Ton Storage Silo
400	Combustor & Process	6 of each: 28' ID PFB Combustor Pneumatic In-Feed and Transport System for Coal and Dolomite Auxiliary Combustor	1 of each: 12' - 4" ID PFB Combustor Pneumatic In-Feed and Transport System for Coal and Dolomite Startup Combustor Auxiliary Combustor
500	Gas Cleanup	3 of each per PFB: Primary Cyclone Secondary-Aerodyne Rotary Split Flow Separator	1 Primary Cyclone 1 Secondary-Aerodyne Rotary Split Flow Separator
600	Combined Cycle	6 Gas Turbines in Three Double Ended Sets 50 MW/Gas Turbine 1 Steam Turbine Plant Complete with Waste Heat Boiler, Condenser, Condenser Cooling Tower, etc 200 MW Steam Turbine	1 Gas Turbine 7 MW/Gas Turbine (42% Scale) 1 Waste Heat Boiler in Parallel with Existing Boilers Steam to Wood-Ridge Plant

TABLE 1.1

COMMERCIAL PLANT - PILOT PLANT COMPARISON (Continued)

Category		Commercial Plant	Pilot Plant
700	Ash Flow	1 for each PFB Combustor, Water and Fluidized Ash Cooler with Lock Hoppers 1 Pneumatic Conveying System 2 2160 Ton Ash Storage Silo	1 Water and Fluidized Ash Cooler with Lock Hoppers 1 Pneumatic Conveying System 1 100 Ton Ash Hopper Storage
800	Control	Analog and Digital Process Control with Auto Data Log Backup Manual Control Boiler and Steam Turbine Controls Backup Computer Multiple PFB Controls	Analog and Digital Process Control with Auto Data Log Backup Manual Control
900	Environmental Monitoring	Opacity Monitoring SO_2 Monitoring CO Monitoring NO_x Monitoring Particulate Monitoring	Opacity Monitoring SO_2 Monitoring CO Monitoring NO_x Monitoring Particulate Monitoring

Section 2.0

PILOT PLANT PRELIMINARY DESIGN AND ANALYSIS

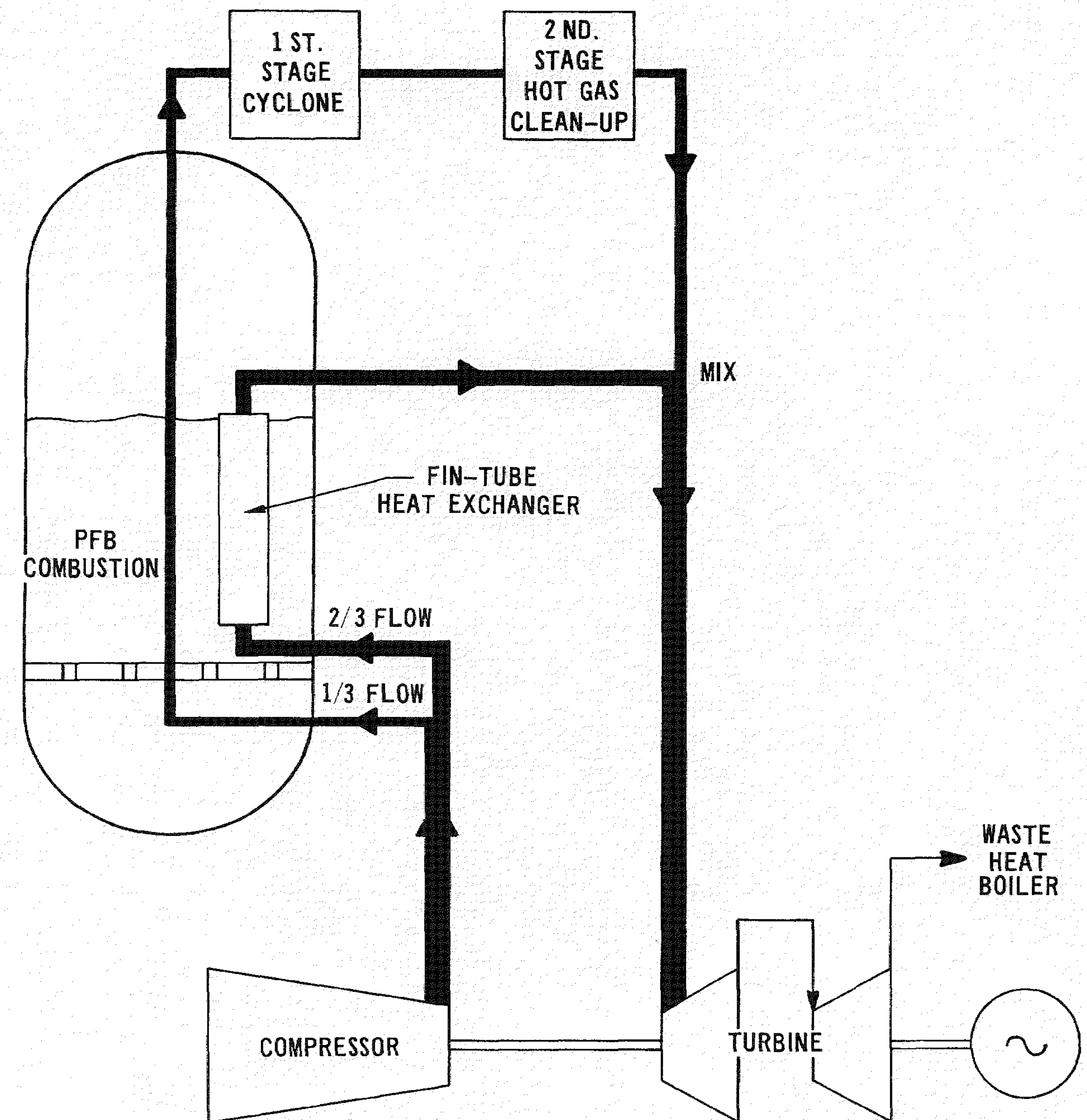
2.1 Cycle Selection and Performance

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 Figures 1.1 and 2.1. 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 2.2 shows the effects of fluidized bed temperature on overall plant thermal efficiency at two levels of PFB pressure for a steam cooled bed system 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. The small difference in heat rate between seven atmospheres and ten atmospheres pressure 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 of 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 heated air to supply the turbines. In this arrangement the levels of corrosive and 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.

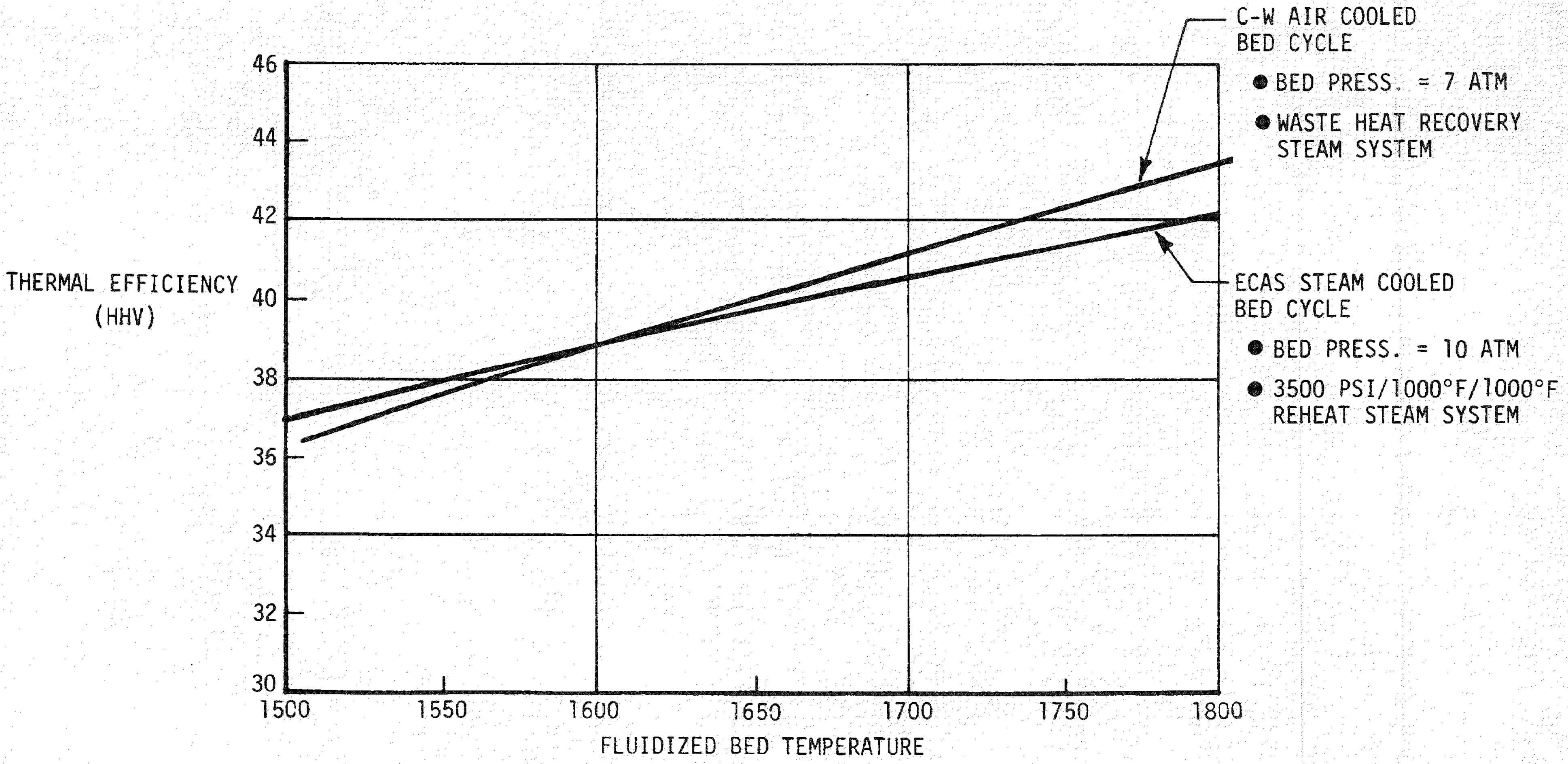
PFB AIR HEATER SYSTEM DESIGN



PFB--I--533

Figure 2.1

PFB COMBINED CYCLE EFFICIENCY
COMPARISON OF COOLING METHODS



5-1-705

Figure 2.2

2.1.1 Pilot Plant to Commercial Plant Relationship

Because the commercial plant design incorporated a scaled-up version of the CW 6515 gas turbine engine as a key component, it was decided that a cost-effective approach to provide a pilot plant is to convert the existing MOD POD 8 Total Energy Power Generating System at the Curtiss-Wright Wood-Ridge Facility (Figure 2.3). The MOD POD 8 system combines an industrialized J65 type gas turbine engine, the CW 6515, with an industrial power turbine driving an alternator, and a waste heat recovery boiler. The system was designed to produce 8 MW of electrical power and 60,000 pph of saturated steam at 175 psig for plant heating and process use. The electrical system, which is used to supply plant load on normal working days, is connected to and synchronized with the local utility, Public Service Electric and Gas Company of New Jersey, so that the system is operated as a utility unit although under local plant control. Currently the utility does not purchase the excess electrical power produced, if any, but arrangements have been made by which they can absorb the excess produced during the Phase IV long time operation of the pilot plant.

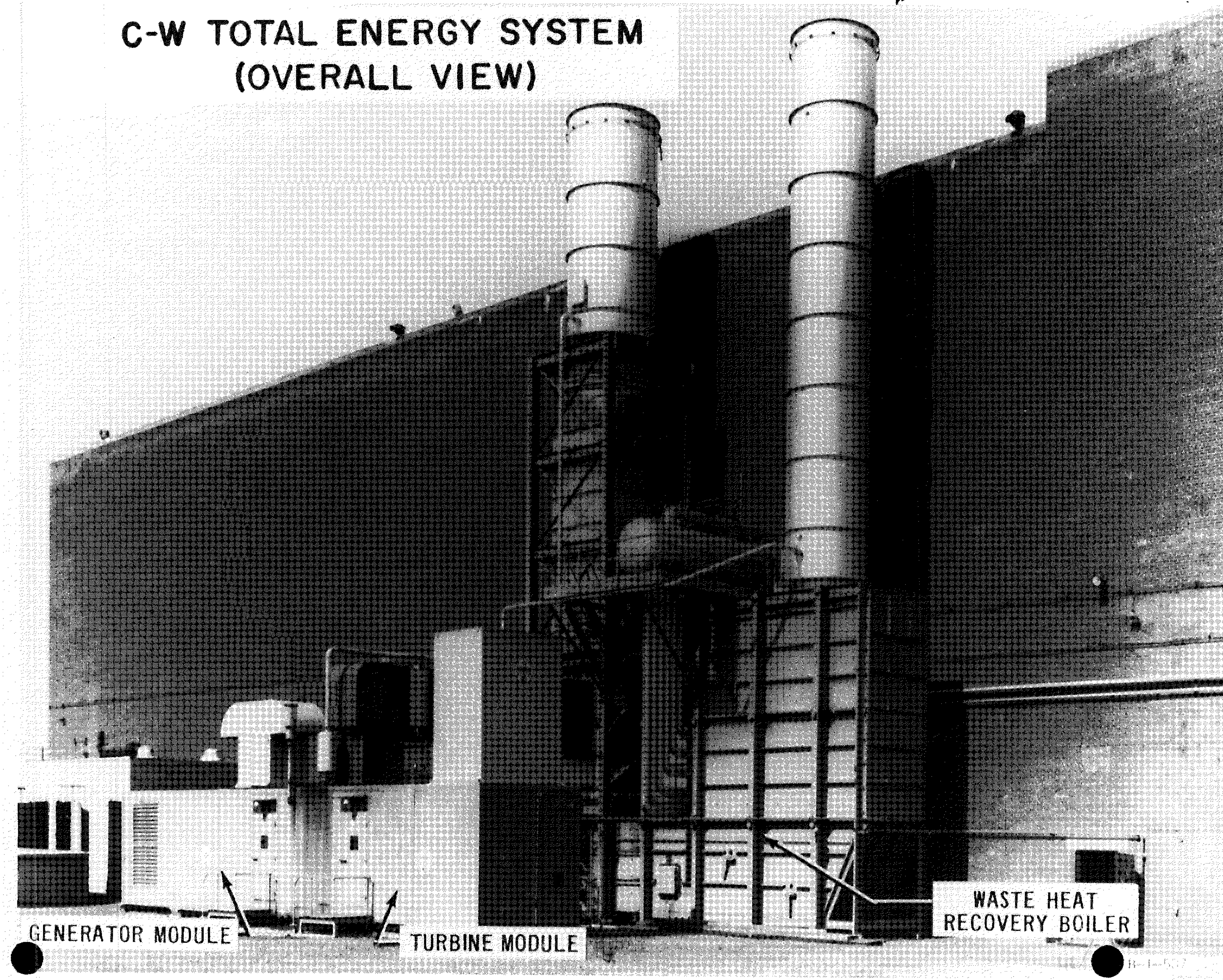
Conversion of this plant by removal of the present oil or gas combustor and installation of the pressurized fluidized bed combustor and associated coal handling, processing and feed equipment will produce an exact simulation of the commercial plant cycle with regard to pressure ratio and compressor efficiency and exact duplication of the PFB operation in one-fifth airflow scale, i.e. one fifth bed cross section area or 45 percent bed diameter. Thermal efficiency will be lower because no electrical power will be produced from the steam system and also because some of the other components used were not designed to current baseload plant standards.

2.1.2 Current Versus Optimized Pilot Plant Performance

The existing MOD POD 8 power system 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 gearbox 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 2.1. The equivalent power

C-W TOTAL ENERGY SYSTEM (OVERALL VIEW)



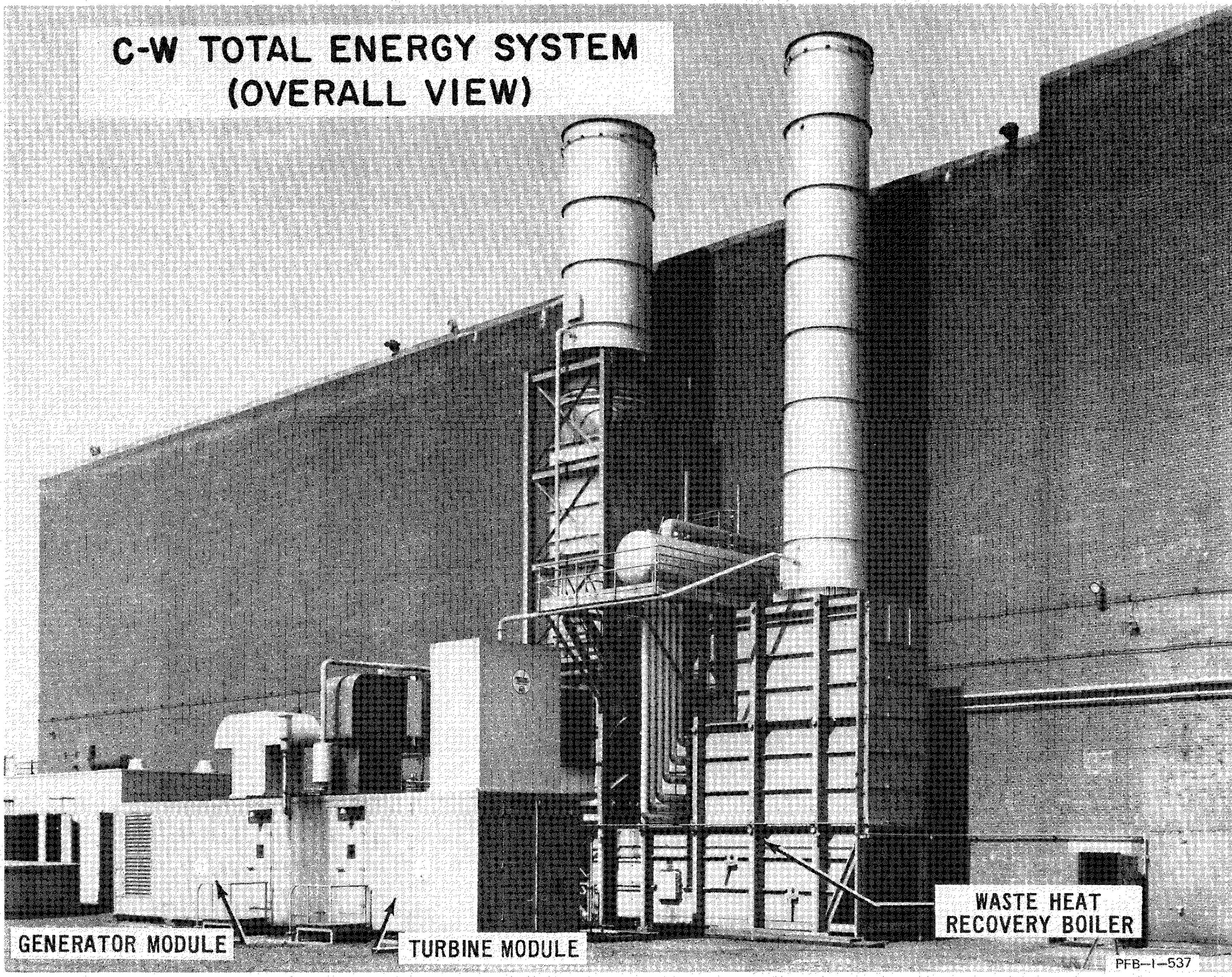

C-W TOTAL ENERGY SYSTEM
(OVERALL VIEW)
GENERATOR MODULE
TURBINE MODULE
WASTE HEAT
RECOVERY BOILER
PFB—1—537

Figure 2.3

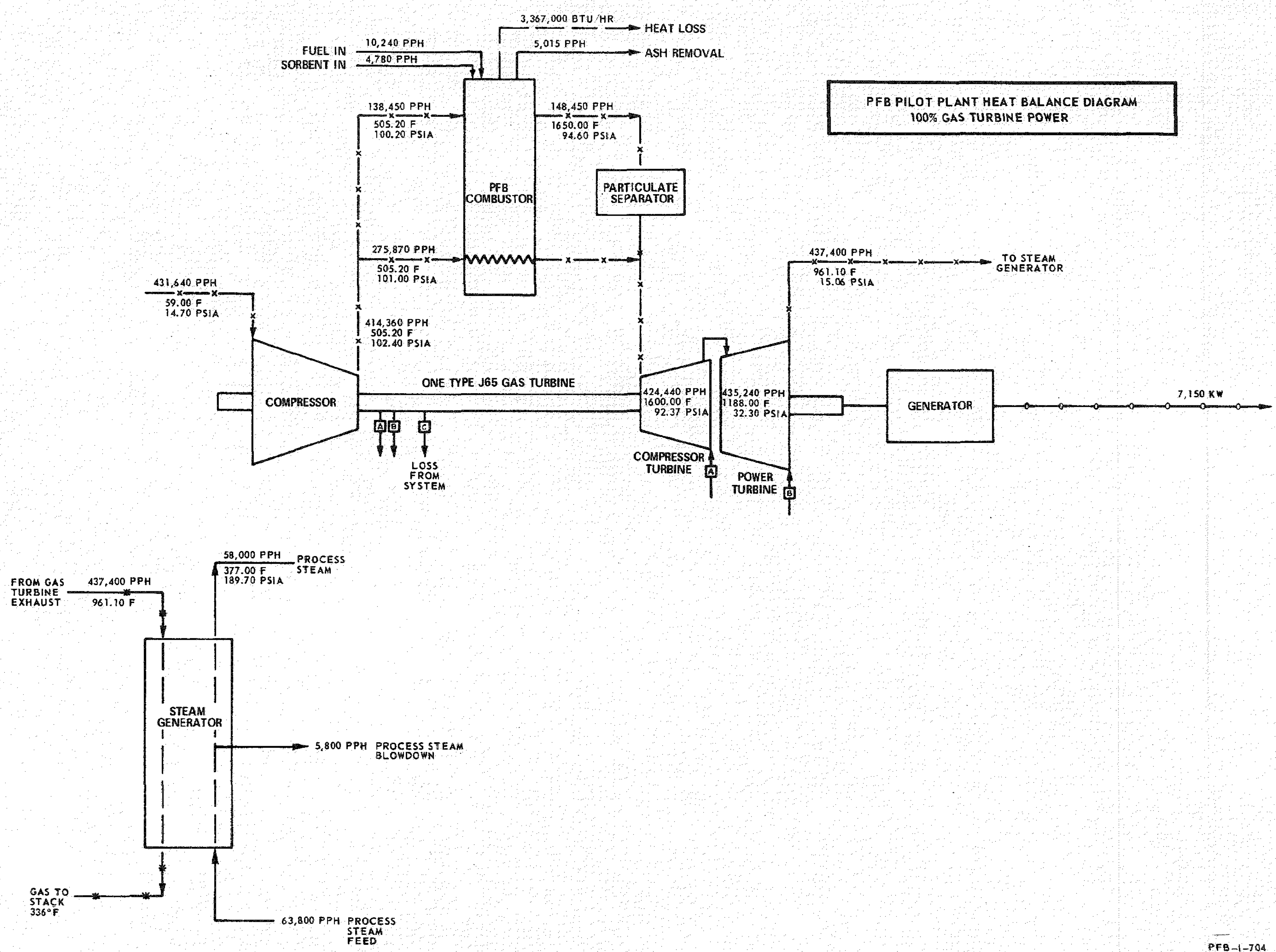
TABLE 2.1

SELECTED DESIGN POINT DATA

		Current Equipment	Optimized Pilot Plant	Commercial Plant	
				Per Unit	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	–	–	–

estimated for the pilot plant equipped with modern base load type turbine and electrical generator and with a steam turbogenerator of commercial plant type added is shown. The equivalent heat rate of the optimized pilot plant is somewhat higher than that of the commercial plant because electrical generators under 40 MW in size are not hydrogen cooled and therefore, not as high in efficiency and also because the pilot plant PFB will have a higher dolomite to coal ratio in order to meet the New Jersey requirement on emission of sulfur oxides, which is more restrictive than the Federal EPA regulation.

Material and energy balance diagrams and tables for the Pilot Plant, current and optimized are shown on Figures 2.4 and 2.5, and Tables 2.2 and 2.3 respectively. These balances, in percentage of total feed are compared to the full scale commercial plant values in Table 2.4.



PFB PILOT PLANT HEAT BALANCE DIAGRAM
100% GAS TURBINE POWER
3,367,000 BTU/HR
HEAT LOSS
5,015 PPH
ASH REMOVAL
FUEL IN
10,240 PPH
SORBENT IN
4,780 PPH
138,450 PPH
505.20 F
100.20 PSIA
PFB COMBUSTOR
148,450 PPH
1650.00 F
94.60 PSIA
PARTICULATE SEPARATOR
275,870 PPH
505.20 F
101.00 PSIA
431,640 PPH
59.00 F
14.70 PSIA
414,360 PPH
505.20 F
102.40 PSIA
COMPRESSOR
ONE TYPE J65 GAS TURBINE
A
B
C
LOSS FROM SYSTEM
424,440 PPH
1600.00 F
92.37 PSIA
COMPRESSOR TURBINE
435,240 PPH
1188.00 F
32.30 PSIA
POWER TURBINE
437,400 PPH
961.10 F
15.06 PSIA
TO STEAM GENERATOR
GENERATOR
7,150 KW
FROM GAS TURBINE EXHAUST
437,400 PPH
961.10 F
58,000 PPH
377.00 F
189.70 PSIA
PROCESS STEAM
STEAM GENERATOR
5,800 PPH
PROCESS STEAM BLOWDOWN
GAS TO STACK
336°F
63,800 PPH
PROCESS STEAM FEED
PFB-1-704

Figure 2.4

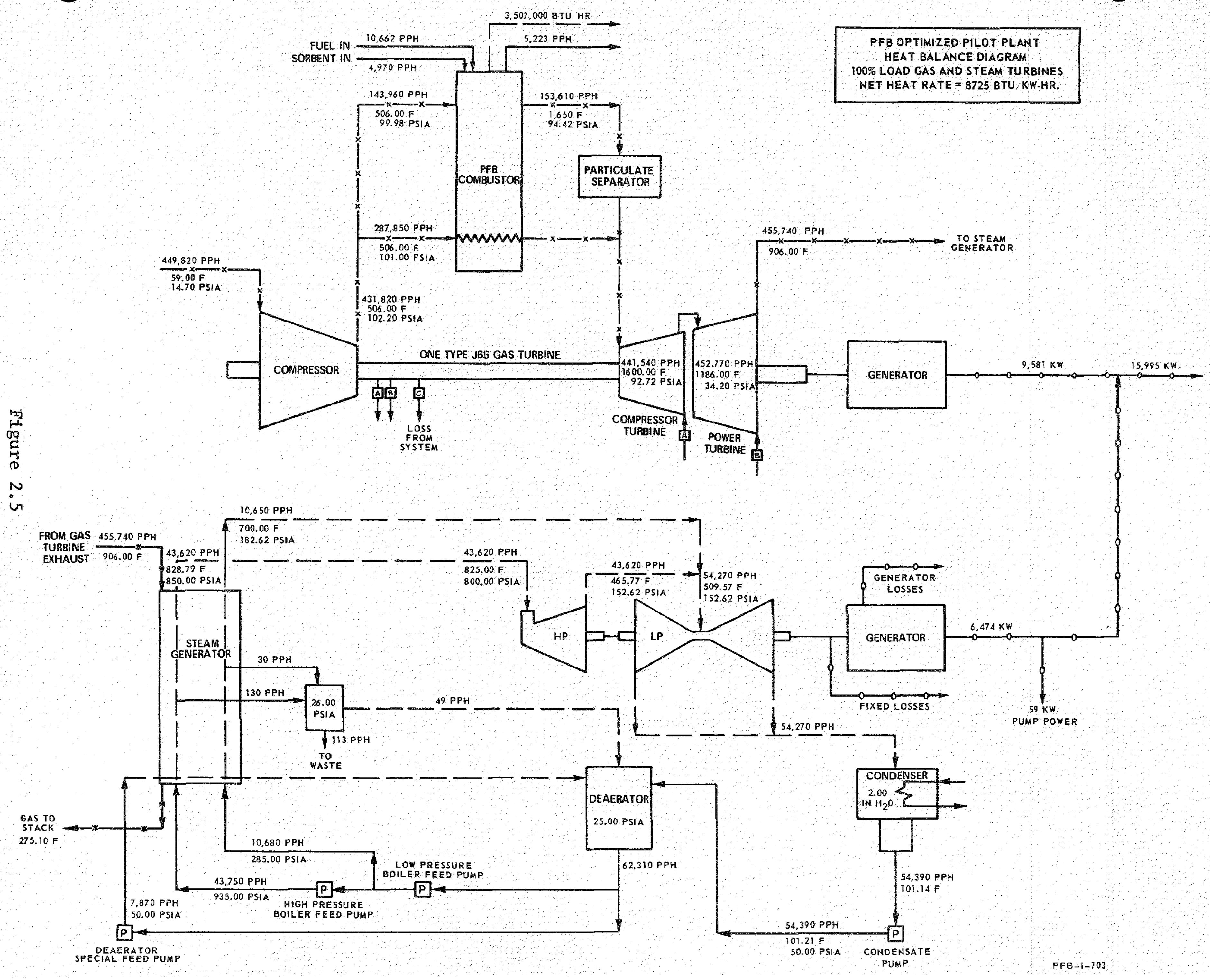

PFB OPTIMIZED PILOT PLANT
HEAT BALANCE DIAGRAM
100% LOAD GAS AND STEAM TURBINES
NET HEAT RATE = 8725 BTU/KW-HR.
3,507,000 BTU/HR
5,223 PPH
FUEL IN
10,662 PPH
SORBENT IN
4,970 PPH
143,960 PPH
506.00 F
99.98 PSIA
PFB COMBUSTOR
153,610 PPH
1,650 F
94.42 PSIA
PARTICULATE SEPARATOR
287,850 PPH
506.00 F
101.00 PSIA
449,820 PPH
59.00 F
14.70 PSIA
431,820 PPH
506.00 F
102.20 PSIA
455,740 PPH
906.00 F
TO STEAM GENERATOR
COMPRESSOR
ONE TYPE J65 GAS TURBINE
441,540 PPH
1600.00 F
92.72 PSIA
452,770 PPH
1186.00 F
34.20 PSIA
GENERATOR
9,581 KW
15,995 KW
A
B
C
LOSS FROM SYSTEM
COMPRESSOR TURBINE
POWER TURBINE
FROM GAS TURBINE EXHAUST
455,740 PPH
906.00 F
43,620 PPH
828.79 F
850.00 PSIA
10,650 PPH
700.00 F
182.62 PSIA
43,620 PPH
825.00 F
800.00 PSIA
43,620 PPH
465.77 F
152.62 PSIA
54,270 PPH
509.57 F
152.62 PSIA
GENERATOR LOSSES
HP
LP
GENERATOR
6,474 KW
STEAM GENERATOR
30 PPH
130 PPH
26.00 PSIA
49 PPH
113 PPH
TO WASTE
FIXED LOSSES
59 KW
PUMP POWER
54,270 PPH
CONDENSER
2.00 IN H_2O
DEAERATOR
25.00 PSIA
GAS TO STACK
275.10 F
10,680 PPH
285.00 PSIA
LOW PRESSURE BOILER FEED PUMP
62,310 PPH
43,750 PPH
935.00 PSIA
HIGH PRESSURE BOILER FEED PUMP
7,870 PPH
50.00 PSIA
54,390 PPH
101.14 F
54,390 PPH
101.21 F
50.00 PSIA
DEAERATOR SPECIAL FEED PUMP
CONDENSATE PUMP
P
PFB-1-703

Figure 2.5

TABLE 2.2

PFB PILOT PLANT - MATERIAL AND ENERGY BALANCE

Base Load - 100% Gas Turbine Power

	Material Lb/Hr	Energy MM Btu/Hr	Percent	MW
Feeds				
Coal	10,242	+134.068		
Air	431,640	0.0		
Sorbent	4,781	-0.696		
Feeds Subtotal	446,663	+133.372	+100	
Products				
Ash	5,015	-2.075		
Process Steam	-	-67.802		
Stack Gas at 336°F	437,400	-34.327		
Products Subtotal	442,415	-104.204	-78.130	
Work				
Gas Turbine Gross Work		-24.406		7.150
Work Subtotal		-24.406	-18.299	7.150
Losses				
Gas Turbine Alternator		-1.787		
Gas Turbine Loss	4,316	-0.467		
PFB Heat Loss		-1.292		
Heat Loss in Process Steam Generator		-1.216		
Losses Subtotal	4,316	-4.762	-3.571	

TABLE 2.3

OPTIMIZED PFB PILOT PLANT

WITH STEAM PLANT SIMILAR TO COMMERCIAL POWER PLANT

Base Load - P.T. Exit Temperature 906°F; Stack Exit Temperature 275°F

	Materials Lb/Hr	Energy MM Btu/Hr	Percent	MW
Feeds				
Coal	10,662	+139.566		
Air	449,820			
Sorbent	4,970	-0.725		
Feeds Subtotal	465,452	+138.841	+100	
Products				
Stack Gas at 275°F	455,735	-27.545		
Ash	5,223	-2.161		
Products Subtotal	460,958	-29.706	-21.396	
Cooling Duties				
Steam Turbine Condenser		-49.844	-35.900	
Work				
Gas Turbine Gross Work		-32.700		+9.581
Steam Turbine Gross Work		-22.098		6.474
Auxiliary Power		+0.200		-.059
Work Subtotal		-54.598	-39.324	15.997
Losses				
Gas Turbine Alternator Loss		-0.838		
Steam Turbine Alternator Loss		-0.566		
G.T. Loss	4,494	-0.487		
PFB Heat Loss		-1.346		
Heat Loss Steam Generator		-1.456		
Losses Subtotal		-4.693	-3.380	
Thermal Efficiency (Based on HHV of Coal)			39.12	

TABLE 2.4

PILOT PLANT/COMMERCIAL PLANT COMPARISON

	Commercial Plant		Pilot Plant		Improved Pilot Plant with Equiv. Electric Power from Steam	
	Material %	Energy %	Material %	Energy %	Material %	Energy %
Feed						
Coal	2.262	99.645	2.293	100.522	2.291	100.522
Air	96.946	0.0	96.637	0.0	96.640	0.0
Sorbent	0.792	0.352	1.070	− 0.522	1.069	− 0.522
Subtotal	+100.000	+100.000	+100.000	+100.000	+100.000	+100.000
Products						
Stack Gas	98.064	19.952	97.911	25.738	97.911	19.839
Ash	0.966	1.111	1.123	1.556	1.123	1.556
Subtotal	− 99.030	− 21.063	− 99.034	− 27.294	− 99.034	− 21.395
Process Steam				− 50.537		
Cooling Duties						
Steam Turbine Condenser		− 36.130				− 35.900
Work						
Gas Turbine Gross Work		− 23.898		− 18.299		− 23.552
Steam Turbine Gross Work		− 16.125		−		− 15.916
Auxiliary Power		+ 0.145		−		+ 0.144
Subtotal		− 39.878		− 18.299		− 39.324
Losses						
Gas Turbine Alternator		− 0.364		1.340		− 0.604
Steam Turbine Alternator		− 0.304		−		− 0.408
Gas Turbine Losses	− 0.970	− 0.353	− 0.966	− 0.350	− 0.966	− 0.351
PFB Heat Loss		− 0.970		0.969		− 0.969
Steam Generator Heat Loss		− 0.938		0.911		− 1.049
Subtotal		− 2.929		− 3.570		− 3.381
Thermal Efficiency		40.01				39.12

2.2 Pilot Plant Overall Arrangement

The PFB Pilot Plant is a total energy system consisting of 7.15 megawatts generated by a CW 6515 gas turbine powered alternator and 58,000 pph of steam generated by a waste heat boiler. Figure 2.6 is a simplified flow diagram of the pilot plant.

Figure 2.7 is an artist's conception of the pilot plant. Figures 2.8, 2.9 and 2.10 are plot plan and plant elevations. The plant area, including existing bunker coal storage area, is approximately 2 acres with an additional 1.5 acres available for a coal pile on the north side of the boiler house.

Complete coal and dolomite unloading and storage facilities are provided. Coal will be received from 10 - 12 rail car shipments per week and transportation into the existing boiler house 1700 ton storage bunkers. Additional coal storage, up to 1200 tons, is available from the reserve stockpile. Dolomite is received by rail, unloaded pneumatically, and stored in a 600 ton domed storage silo. Conveyors transport coal and dolomite from the storage facilities to the pressurized lock hoppers, for injection into the pressurized fluidized bed combustor.

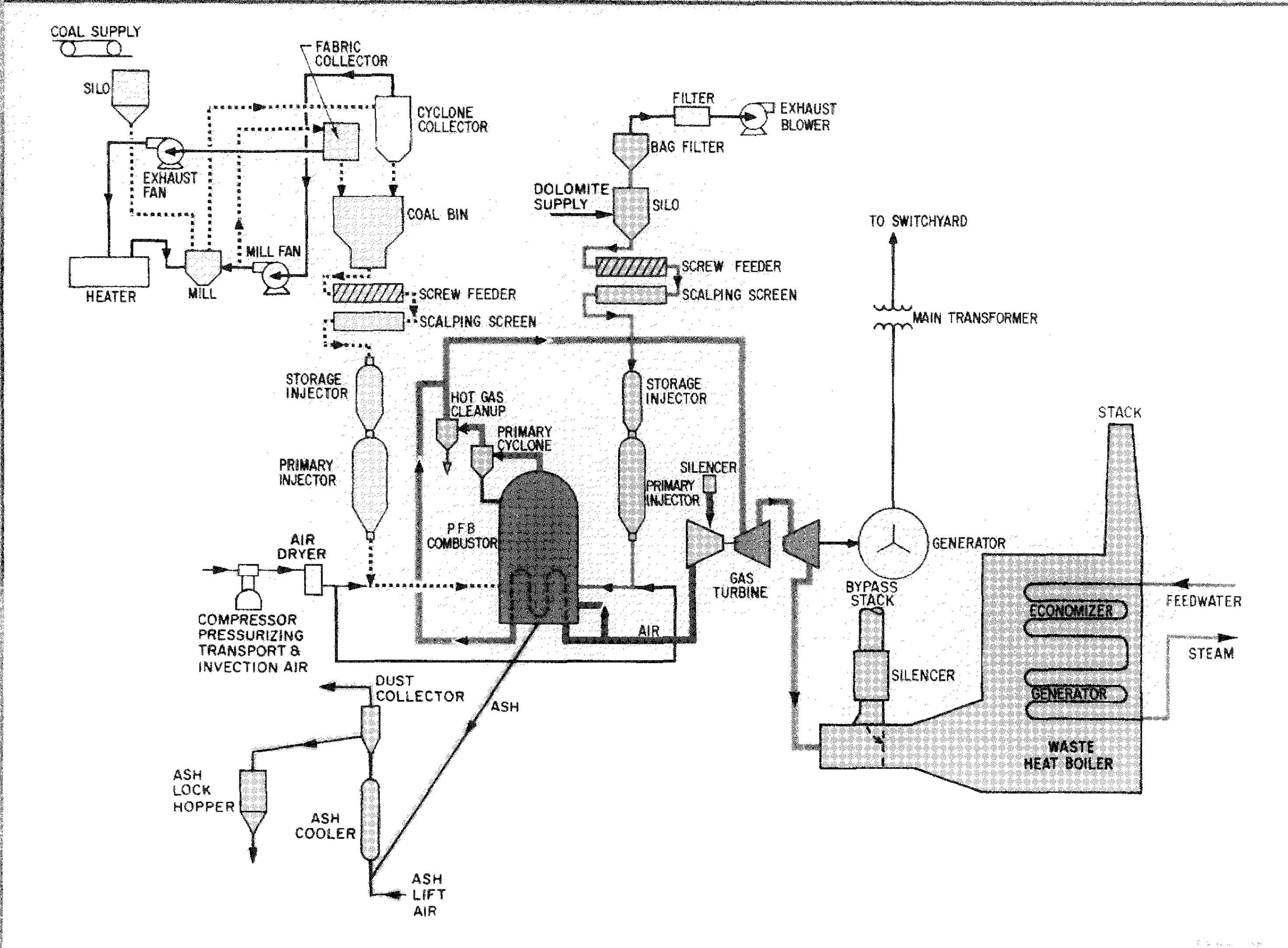
Ash flows out of the PFB and is fluidized by 100 psig air in a vertical column. As ash is lifted up the column, surrounding water jackets cool it until it is finally drawn off through a lock hopper system and pneumatically conveyed to a 100 ton silo storage system where it is retained until removed from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

The existing gas turbine power train will be modified by removal of the oil fired combustor which will be replaced with a volute arrangement for routing compressor air from the gas turbine to the PFB combustor and hot gas from the PFB to combustor back to the turbine. The gas turbine shaft length and bearing support system will be maintained so changes to the gas turbine are minimized. Compressor air is divided between two flow inputs to the PFB combustor.

One third of the compressor airflow enters the bed through tuyeres for combustion and is subsequently rendered free of erosive particulate matter by a primary cyclone followed by a secondary gas cleanup system. The remaining two thirds of compressor air is utilized to cool the bed by flowing through a number of vertically oriented heat exchanger tubes immersed within the bed. The flows are rejoined to drive the compressor turbine, and the free power turbine driving the alternator. Finally, the flow passes through the waste heat boiler, generating steam for plant process purposes. Table 2.5 shows in turn, Pilot Plant Design Characteristics, Design Guidelines, Environmental Performance and Operating and Design Parameters.

Fig. 2.6 100%

COMBINED CYCLE PILOT PLANT SIMPLIFIED FLOW DIAGRAM



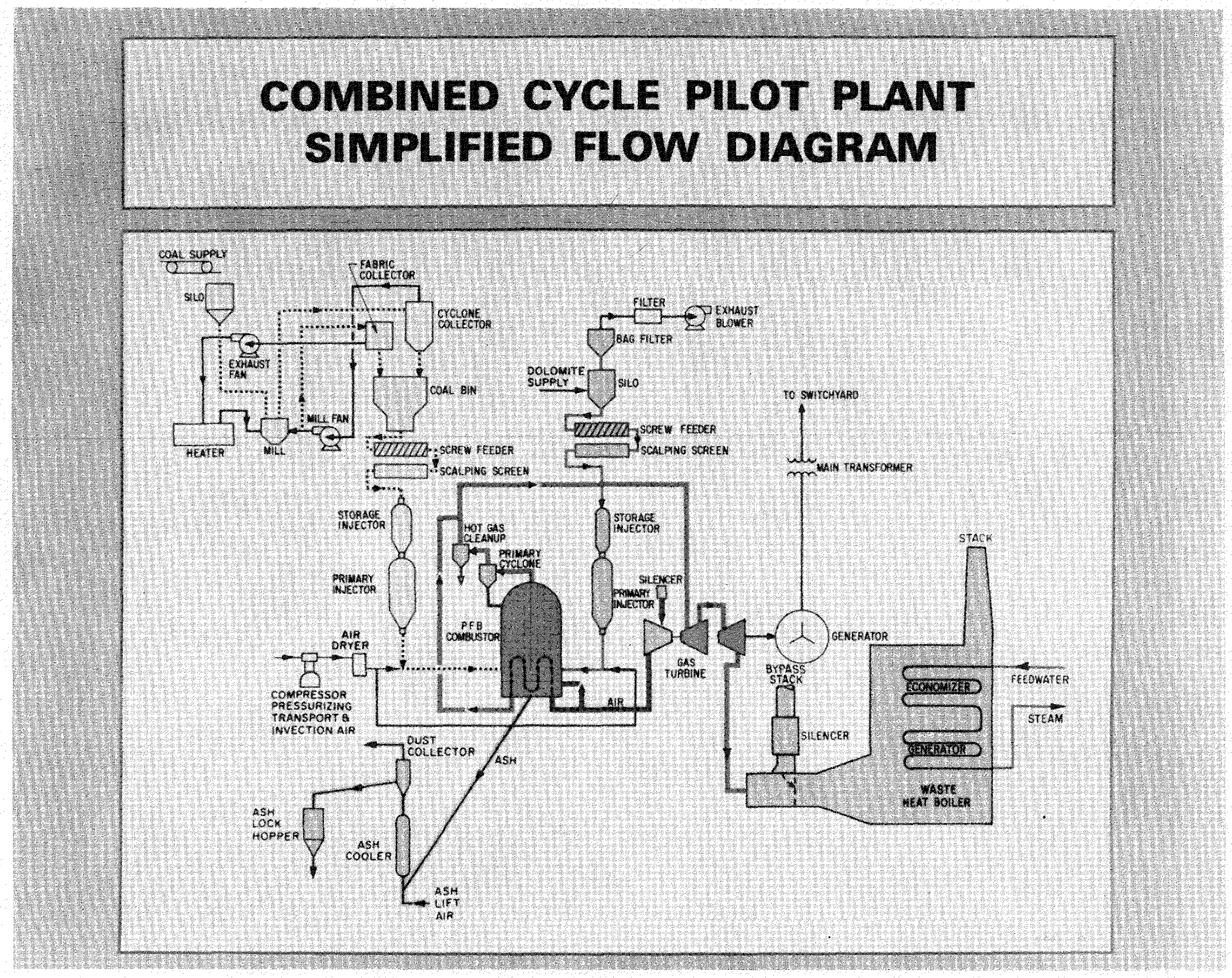
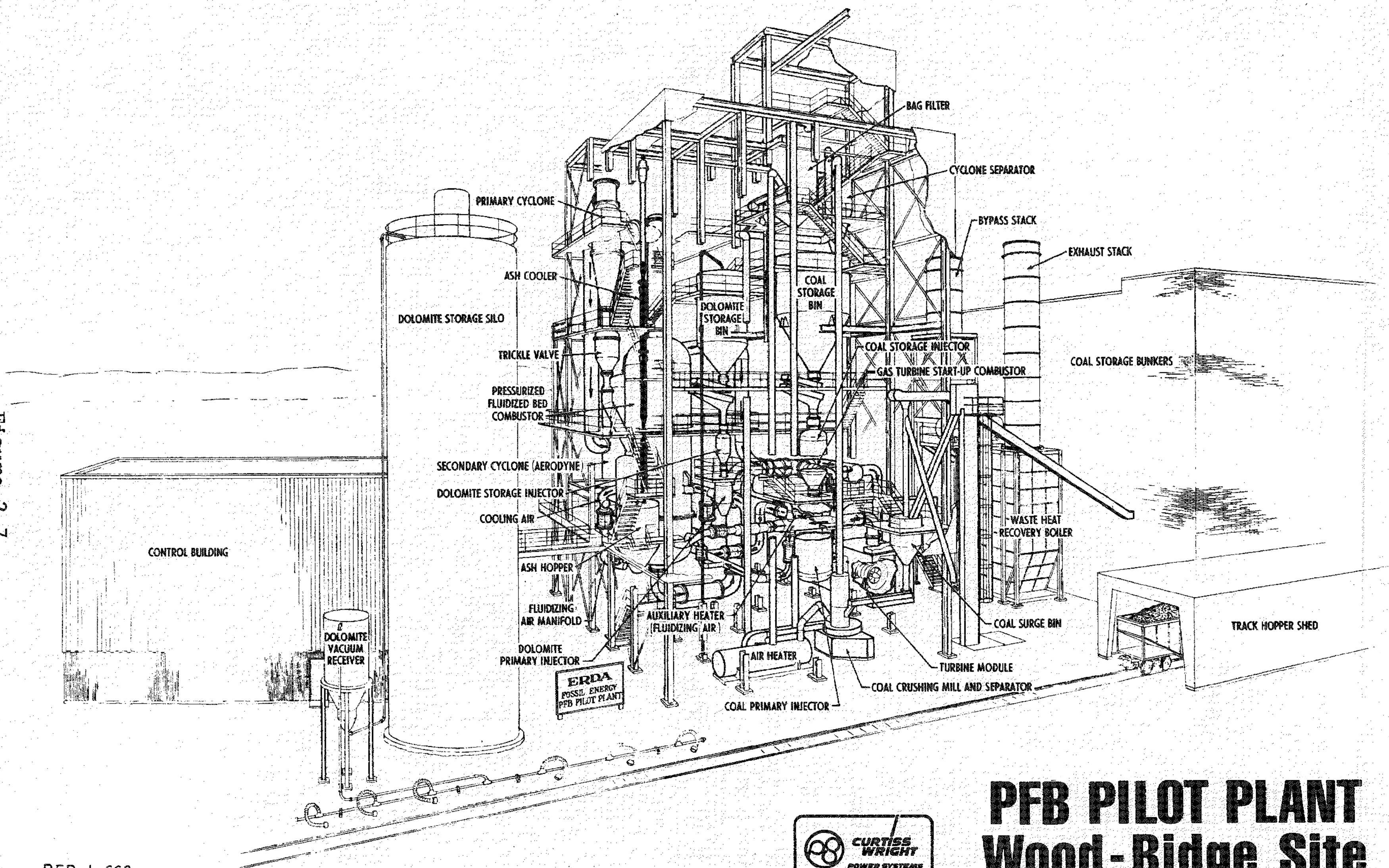

COMBINED CYCLE PILOT PLANT
SIMPLIFIED FLOW DIAGRAM
COAL SUPPLY
SILO
FABRIC COLLECTOR
CYCLONE COLLECTOR
EXHAUST FAN
COAL BIN
MILL FAN
HEATER
MILL
SCREW FEEDER
SCALPING SCREEN
FILTER
EXHAUST BLOWER
BAG FILTER
DOLOMITE SUPPLY
SILO
SCREW FEEDER
SCALPING SCREEN
TO SWITCHYARD
MAIN TRANSFORMER
STORAGE INJECTOR
HOT GAS CLEANUP
PRIMARY CYCLONE
STORAGE INJECTOR
STACK
PRIMARY INJECTOR
SILENCER
PRIMARY INJECTOR
PFB COMBUSTOR
GENERATOR
AIR DRYER
GAS TURBINE
BYPASS STACK
FEEDWATER
ECONOMIZER
COMPRESSOR PRESSURIZING TRANSPORT & INVECTION AIR
AIR
STEAM
SILENCER
GENERATOR
DUST COLLECTOR
ASH
WASTE HEAT BOILER
ASH LOCK HOPPER
ASH COOLER
ASH LIFT AIR

Figure 2.6

21



CURTISS WRIGHT POWER SYSTEMS

PFB PILOT PLANT
Wood-Ridge Site

PFB-1-662

Figure 2.7

PFB PILOT PLANT – GENERAL ARRANGEMENT

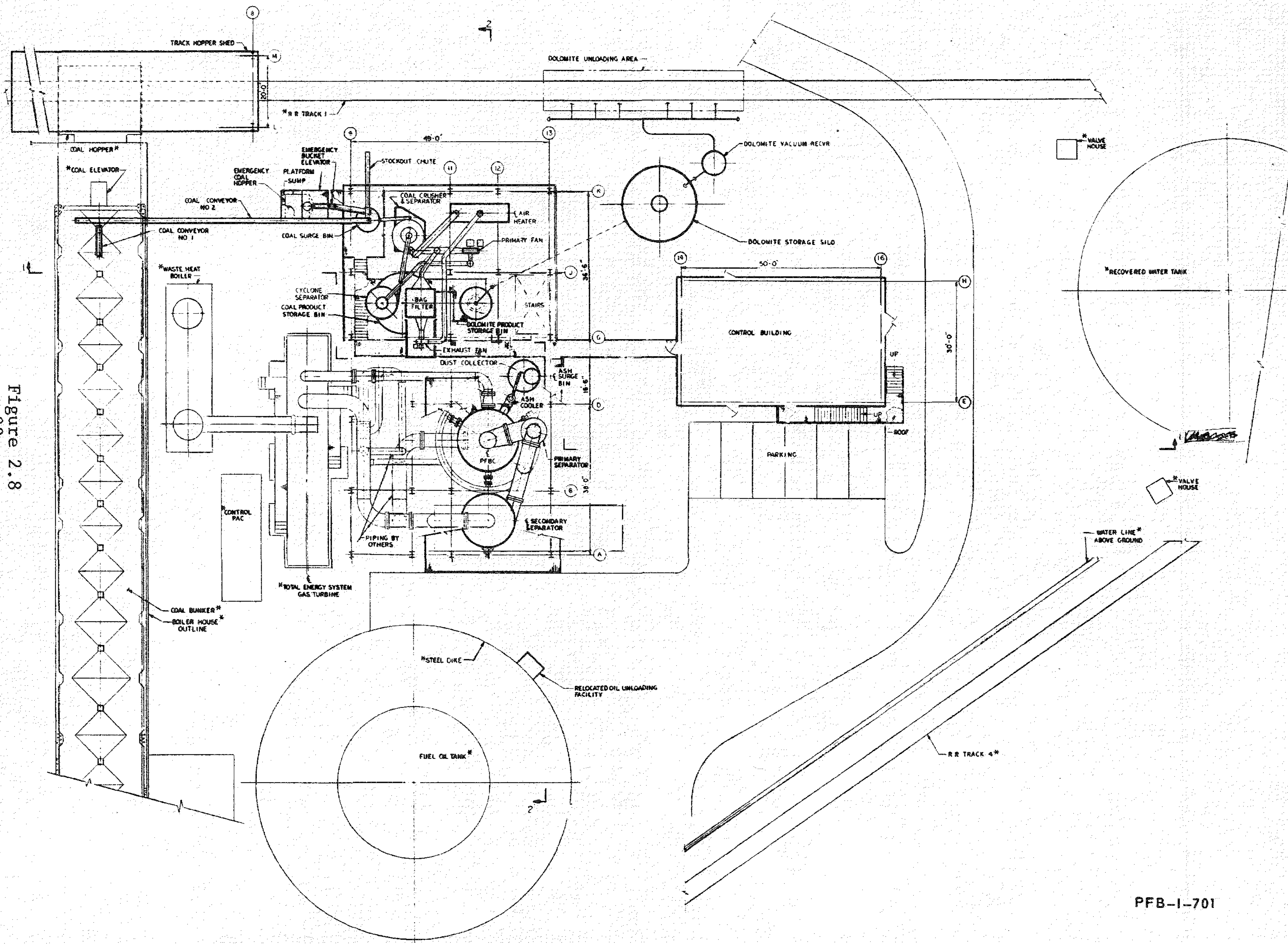
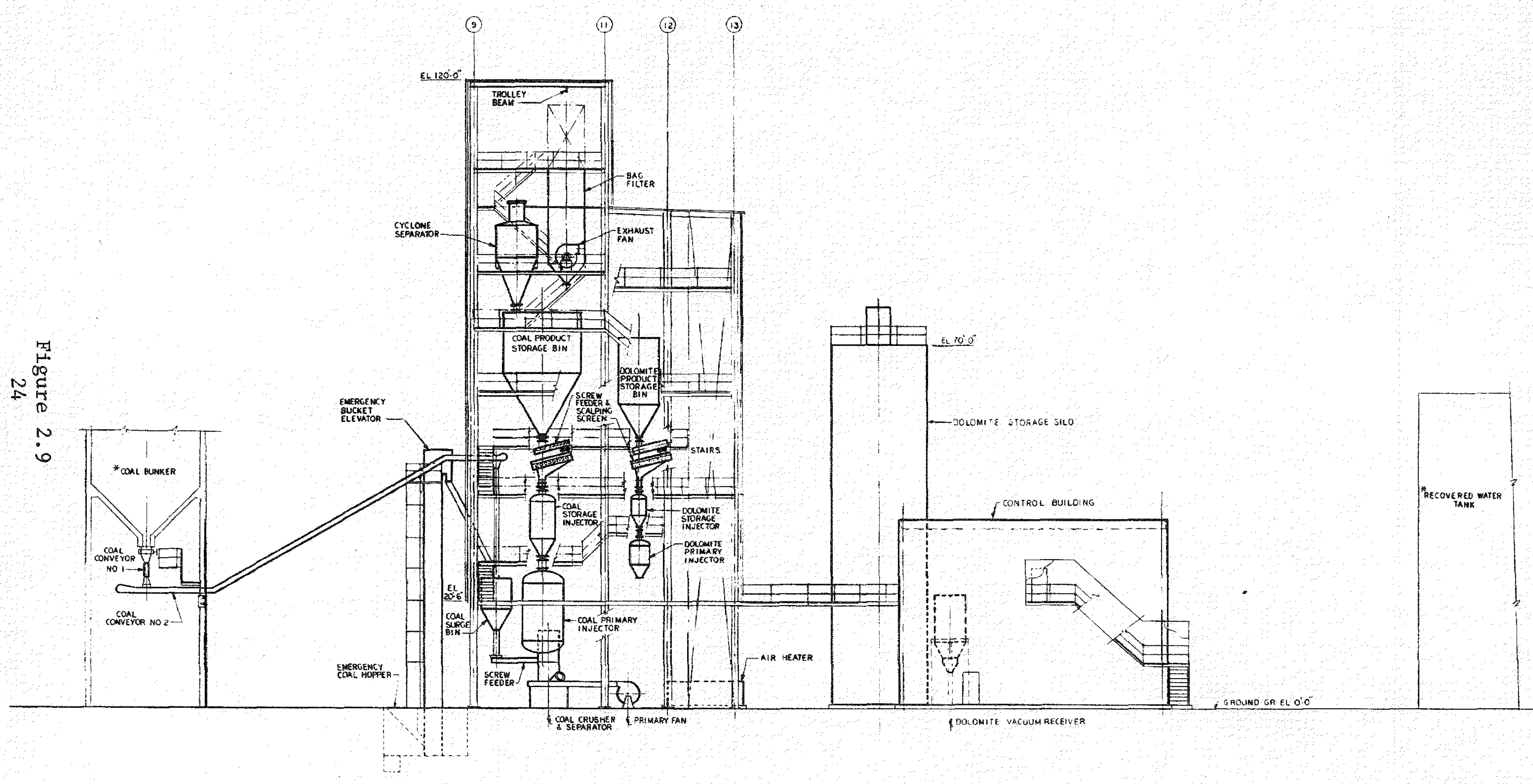


Figure 2.8

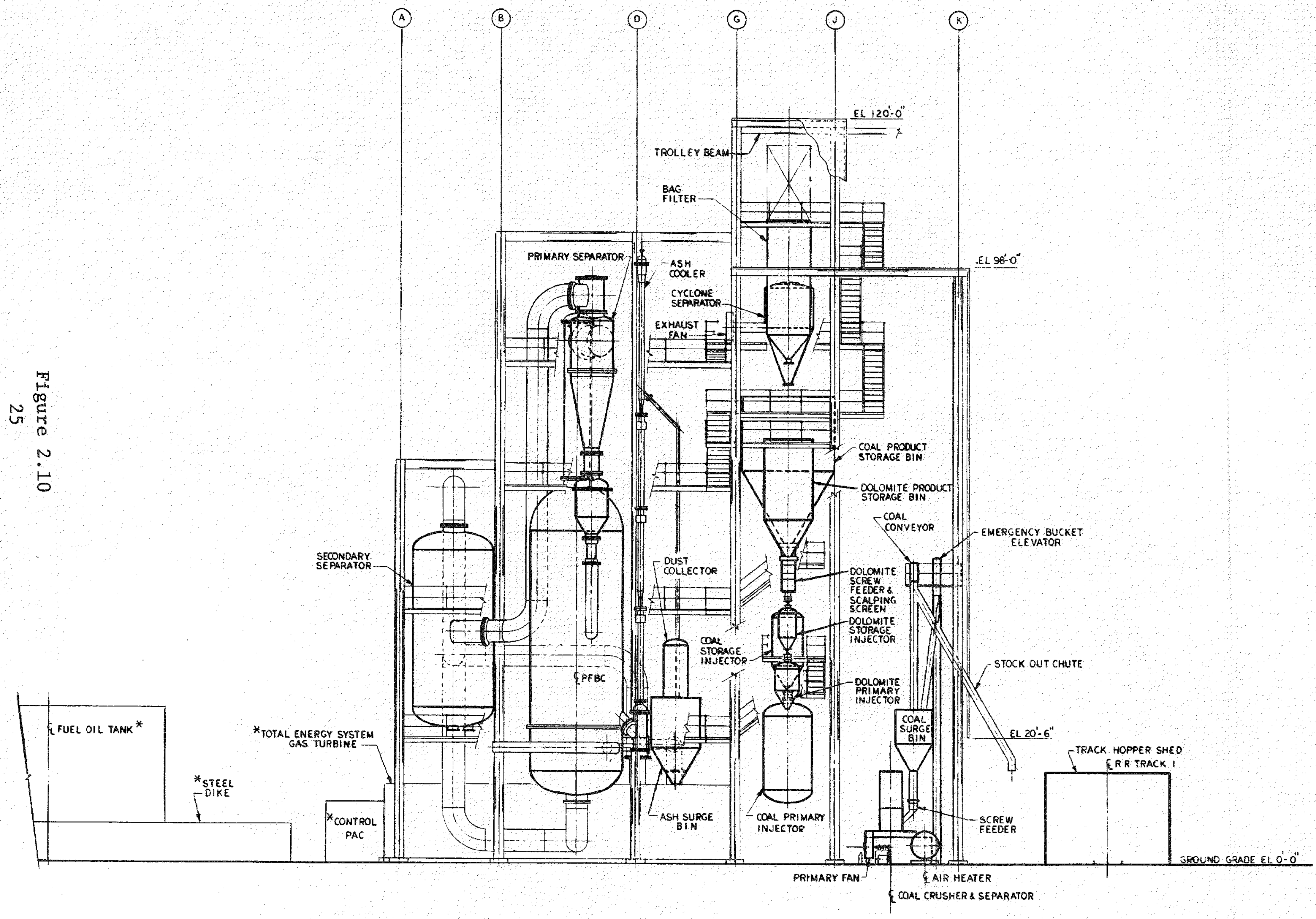
Figure 2.9
24

PFB PILOT PLANT - FRONT ELEVATION



PFB-1-700

PFB PILOT PLANT – END ELEVATION



PFB-1-699

Figure 2.10

TABLE 2.5

PILOT PLANT DESIGN CHARACTERISTICS, GUIDELINES AND PARAMETERS

Pilot Plant Design Characteristics

Actual Plant Rating (Gas Turbine)	7.15 MW
Optimized Plant Rating (Gas Turbine and Steam Turbine)	16 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	Double Flow Cyclone

Plant Design Guidelines

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%

Environment

Noise Design Standard	NEMA D at 400 ft
Air Pollutants Allowable	
SO_2 (New Jersey)	0.3 lb per Million Btu
NO_x	0.7 lb per Million Btu
Particulate	0.1 lb per Million Btu

Principle Plant Operating and Design Parameters

Gas Turbine Generator Performance

Total Power Output	7.15 MW
Gas Turbine Inlet Airflow (6 Turbines)	120 pps
GT Inlet ΔP	3" H_2O
GT Compressor Pressure Ratio	7:1
Exhaust Pressure ΔP	10" H_2O
Exhaust Temperature	961 °F
Alternator Speed	7500 rpm

Pressurized Fluidized Bed Combustor

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

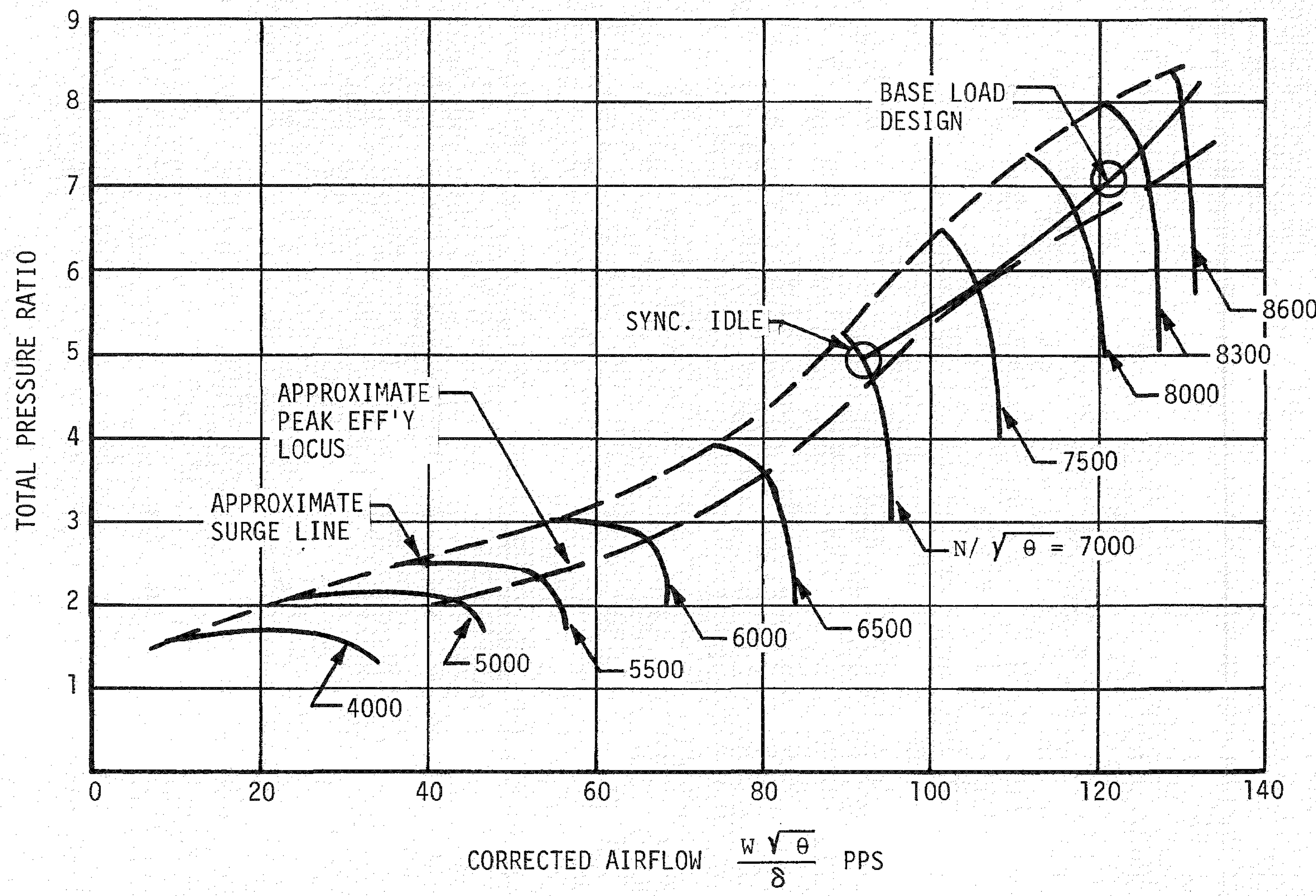
2.3 Pilot Plant Component Performance and Operating Conditions

The MOD POD 8 Total Energy System at the Curtiss-Wright Wood-Ridge Facility will be converted to the Pressurized Fluidized Bed Pilot Plant by removing the present gas or oil fired combustor and replacing it with a compressor discharge diffuser and scroll and a turbine inlet scroll connected to the pressurized fluidized bed combustor. The oil fired combustor will be used as the start-up combustor for the system by installing it in an appropriate housing in a PFB bypass loop. Because of the higher pressure drop in the PFB combustor system and associated piping, it is necessary to change the flow capacities of both the compressor drive turbine and the power turbine. For the compressor drive turbine a larger area stator is available, from another model of the J65 engine, which will increase turbine capacity by 6.7 percent. For the power turbine the required capacity increase of 8.8 percent will require rework of the existing stator vanes. Three possible reworks are under consideration, namely: (a) restagger to more open angle, (b) removal of vanes and resetting by spacers, and (c) cutback of vane trailing edges. During the final design of the pilot plant the details of this rework will be completed.

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 2.0 to assure at least 96 percent sulfur retention which, for the selected 4.1 percent sulfur coal, will result in less than 0.3 lbs/million Btu of sulfur dioxide in the plant exhaust as required by the State of New Jersey Environmental Protection regulations. 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 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 of air of 31 percent. The bed depth is 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. 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. With the exception of the higher calcium to sulfur ratio required by local regulations, the PFB operating conditions are identical to those at the commercial plant design.

In order to confirm 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 2.11 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 compressor air bleed or variable geometry. Tables 2.6, 2.7 and 2.8 show significant component performance data for three power levels on a standard day and the base load rating on hot and cold days. In accordance with common practice in gas turbine power systems, the heat release rate

PFB PILOT PLANT COMPRESSOR PERFORMANCE



PFB-I-692A

Figure 2.11

TABLE 2.6

COMPONENT OPERATING CONDITIONS - TURBOMACHINERY

Ambient Temperature	°F	59	59	59	59	100	0
Percent Base Load Power . .	%	100	80	60	Sync Idle	100	100
A. COMPRESSOR							
Inlet Pressure	psia	14.55	14.55	14.55	14.55	14.55	14.55
Outlet Pressure . . .	psia	102.4	93.7	84.0	67.6	91.1	118.0
Outlet Temperature . . .	°F	505	478	448	391	540	450
Airflow.	pps	119.9	112.6	103.4	92.4	105.9	139.2
Speed.	rpm	8155	7845	7400	7000	8028	8220
B. COMPRESSOR DRIVE TURBINE							
Inlet Pressure	psia	92.9	84.5	75.2	59.5	81.9	137.0
Inlet Temperature. . . .	°F	1600	1483	1374	995	1600	1600
Outlet Pressure. . . .	psia	32.5	29.6	26.7	19.3	28.8	37.8
Outlet Temperature . . .	°F	1204	1106	1019	677	1207	1203
Gas Flow	pps	117.9	110.5	109.2	89.8	104.0	137.0
C. POWER TURBINE AND ALTERNATOR							
Inlet Pressure	psia	32.3	29.4	26.5	19.1	28.6	37.5
Inlet Temperature. . . .	°F	1187.6	1091.3	1006.2	669.5	1192.2	1185.7
Outlet Pressure. . . .	psia	16.25	16.0	15.8	15.4	16.0	16.65
Outlet Temperature . . .	°F	961	896	844	640	993	926
Gas Flow	pps	120.9	113.3	103.8	70.8	106.7	140.5
Power.	MW	7150	5720	4290	500	5490	9585

TABLE 2.7

COMPONENT OPERATING CONDITIONS - PRESSURE VESSELS

Ambient Temperature	°F	59	59	59	59	100	0
Percent Baseload Power	%	100	80	60	Sync Idle	100	100
A. PRESSURIZED FLUIDIZED BED							
Inlet Pressure	psia	101.2	92.6	83.0	66.7	90.0	116.7
Inlet Temperature	°F	505	478	448	391	541	450
Tuyere Airflow	pps	38.5	35.0	31.2	24.6	33.9	44.7
Cooling Airflow	pps	76.6	73.1	68.1	64.1	67.7	88.9
Outlet Pressure	psia	94.6	86.1	76.6	60.5	83.5	110.0
Bed Temperature	°F	1650	1650	1650	1650	1650	1650
Cooling Air Outlet Temp.	°F	1573	1393	1232	710	1573	1573
Coal Feed	pps	2.845	2.422	2.024	1.136	2.432	3.466
Dolomite Feed	pps	1.328	1.130	0.945	0.530	1.135	1.618
Bed Material Offtake	pps	1.393	1.187	0.991	0.555	1.191	1.698
Outlet Gas Flow	pps	41.2	37.4	33.1	25.7	36.3	48.1
Excess Air	%	31.4	40.4	50.4	110.0	35.5	25.3
B. PARTICULATE SEPARATORS							
Inlet Presssure	psia	94.6	86.1	76.6	60.5	83.5	110.0
Outlet Pressure	psia	93.4	85.0	75.7	59.8	82.5	108.5
Temperature	°F	1650	1650	1650	1650	1650	1650
Gas Flow	pps	41.2	37.4	33.1	25.7	36.3	48.1

TABLE 2.8

COMPONENT OPERATING CONDITIONS - WASTE HEAT RECOVERY BOILER

Ambient Temperature.	°F	59	59	59	59	100	0
Percent Base Load Power. . .	%	100	80	60	Sync Idle	100	100
WASTE HEAT BOILER							
Gas Flow	lb/sec	121.5	113.8	104.3	92.6	107.2	141.2
Inlet Temperature.	°F	961	896	844	633	993	926
Pressure Drop.	in. H_2O	10	10	10	NA	10	10
Steam Flow	lb/hr	58,000	50,600	43,600	NA	52,500	64,800
Stack Temperature.	°F	336	343	350	633	353	325

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:

Fuel Heating Values Used in Analysis

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. Change in Calorific Value for Bed Sulfation Reaction (Btu/lb Coal). . . . . +276

d. Change to Calorific Value for Bed Calcination Reaction (Btu/lb Coal). . . . . -333

Base load rating for the gas turbine is defined by turbine inlet temperature of 1600°F. Figure 2.12 shows the variation of power and fuel flow with ambient temperature at base load and at 80 percent and 60 percent ratings which are defined by constant temperatures of 1483°F and 1374°F respectively.

Figures 2.13 - 2.16 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. The gas turbine with fluidized bed combustor is capable of power reduction to synchronous idle, approximately 500 KW power, without variable geometry or air bleed for surge control. At a corrected speed of 7000 rpm the power reduction to synchronous idle is obtained by opening the power turbine bypass valve while holding gas generator speed constant. This procedure has the advantage of maintaining the PFB operating pressure above 65 psia which simplifies the coal and dolomite feed systems by reducing the range of feed pressure required.

PFB PILOT PLANT
ESTIMATED SEA LEVEL PERFORMANCE
POWER OUTPUT - COAL FLOW RATE

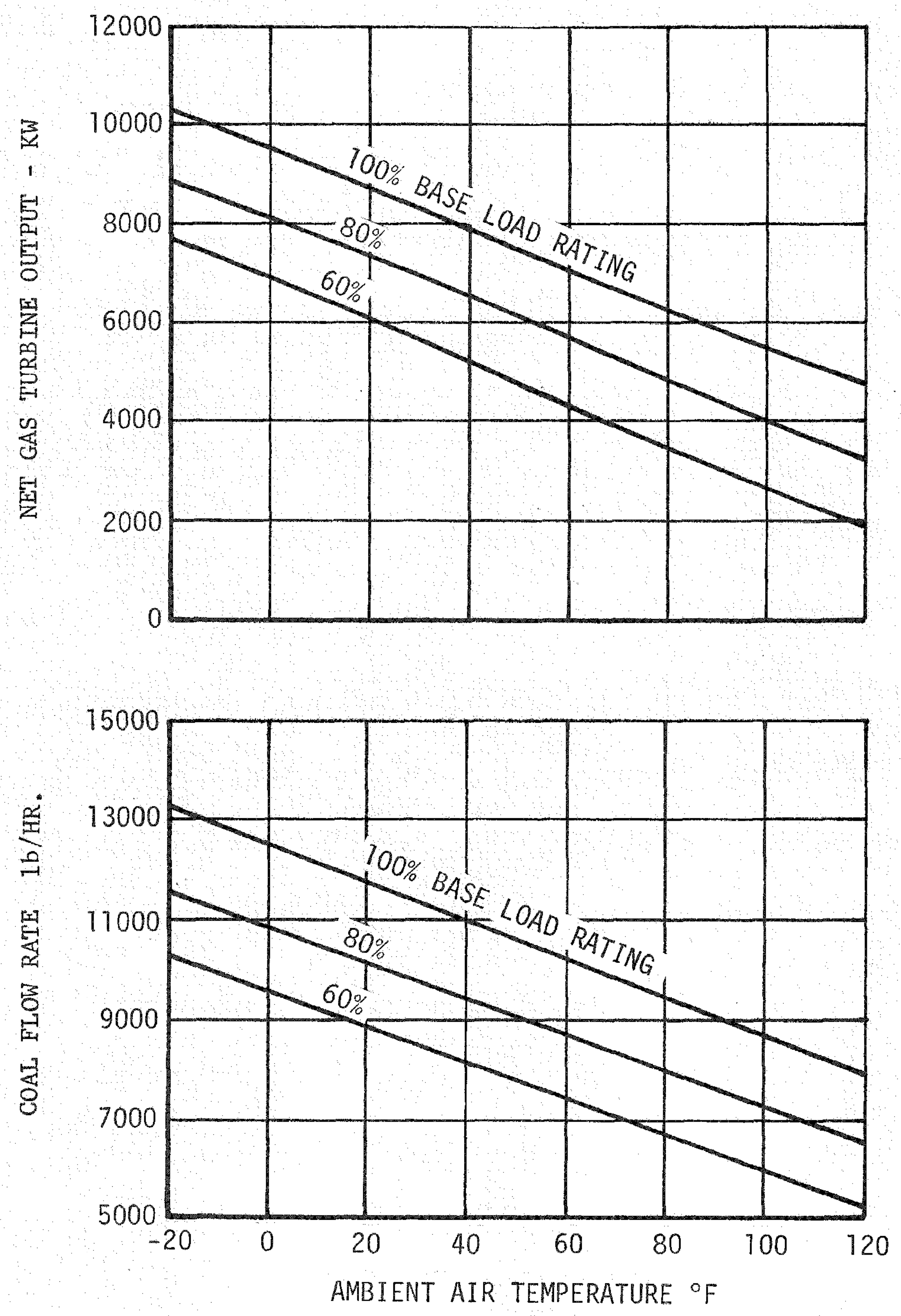


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Figure 2.12

PFB PILOT PLANT
ESTIMATED SEA LEVEL PERFORMANCE
GAS GENERATOR TURBINE INLET TEMP. VS NET OUTPUT

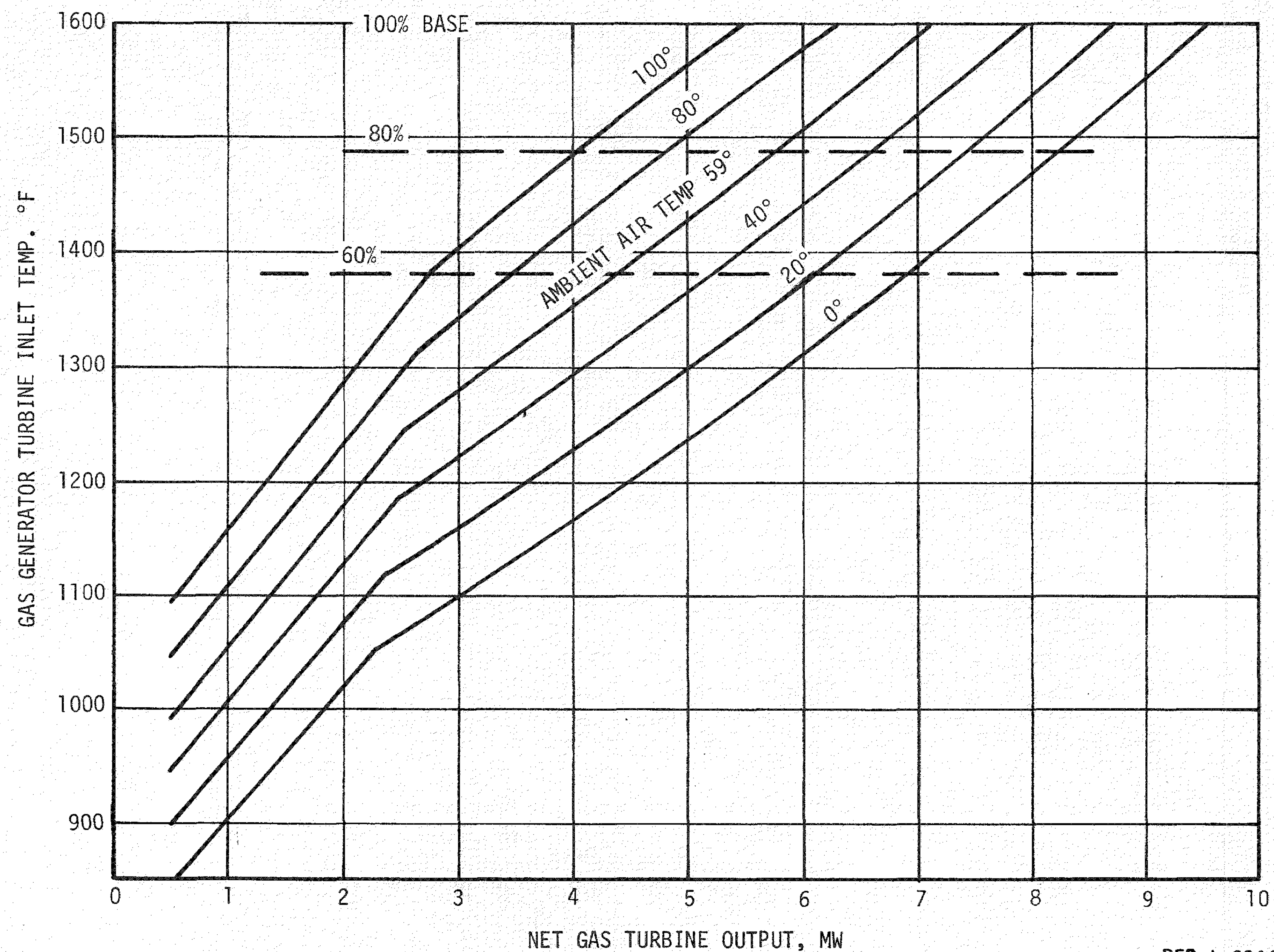

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Figure 2.13

PFB PILOT PLANT
ESTIMATED SEA LEVEL PERFORMANCE
EXHAUST TEMPERATURE VS NET OUTPUT

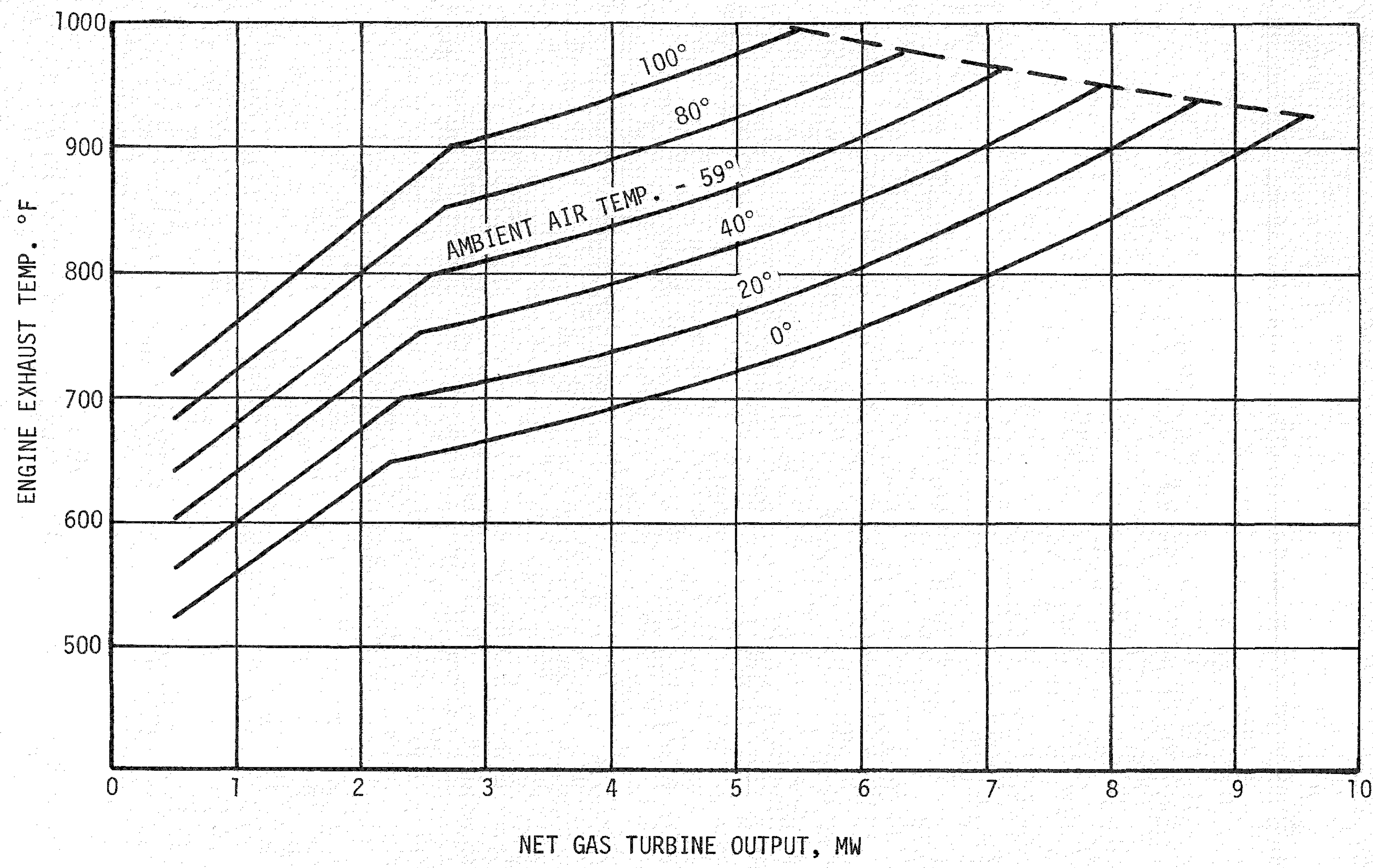

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Figure 2.14

PFB PILOT PLANT
ESTIMATED SEA LEVEL PERFORMANCE
EXHAUST FLOW RATE VS NET OUTPUT

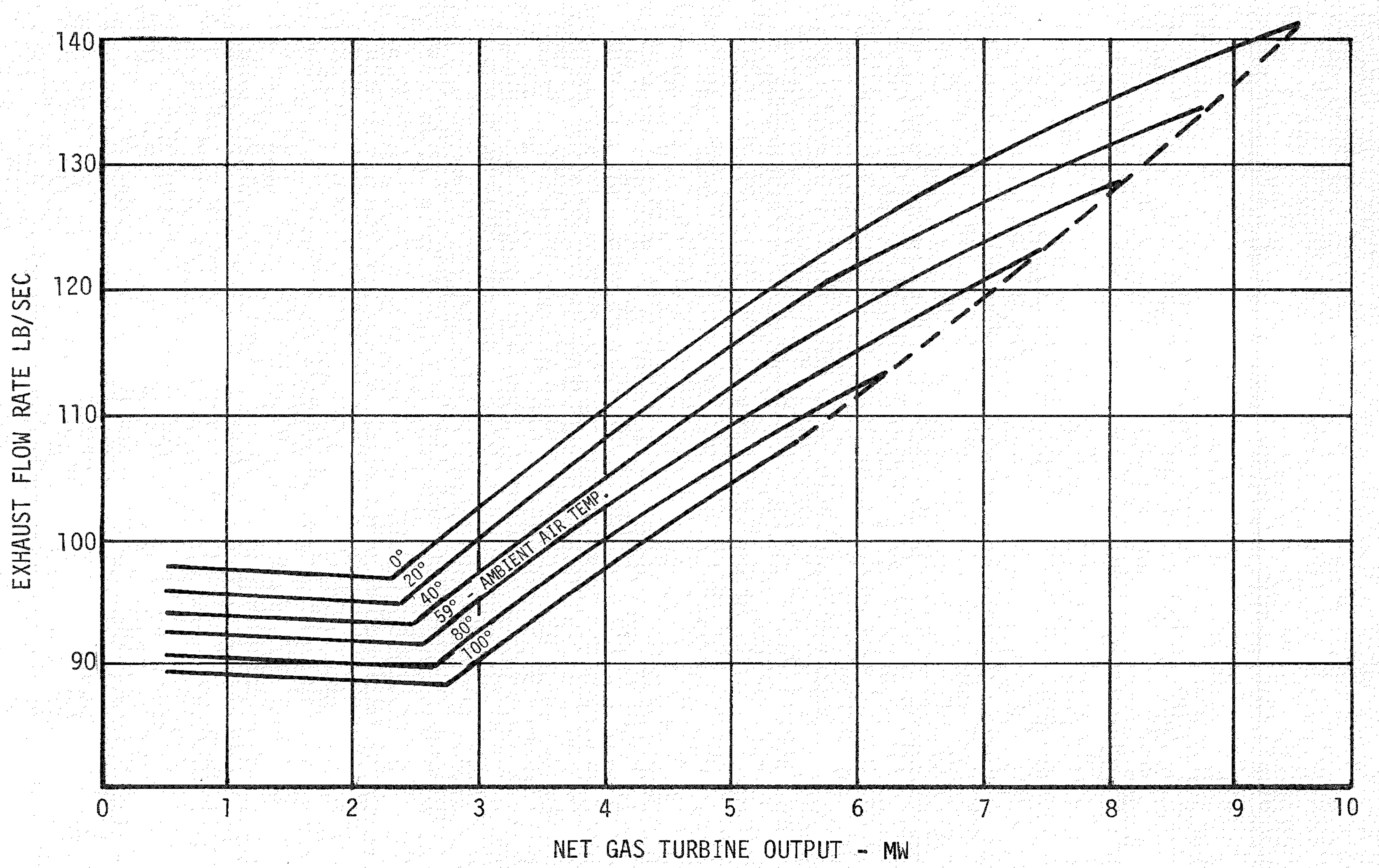

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Figure 2.15

PFB PILOT PLANT
ESTIMATED SEA LEVEL PERFORMANCE
COAL FLOW RATE VS. NET OUTPUT

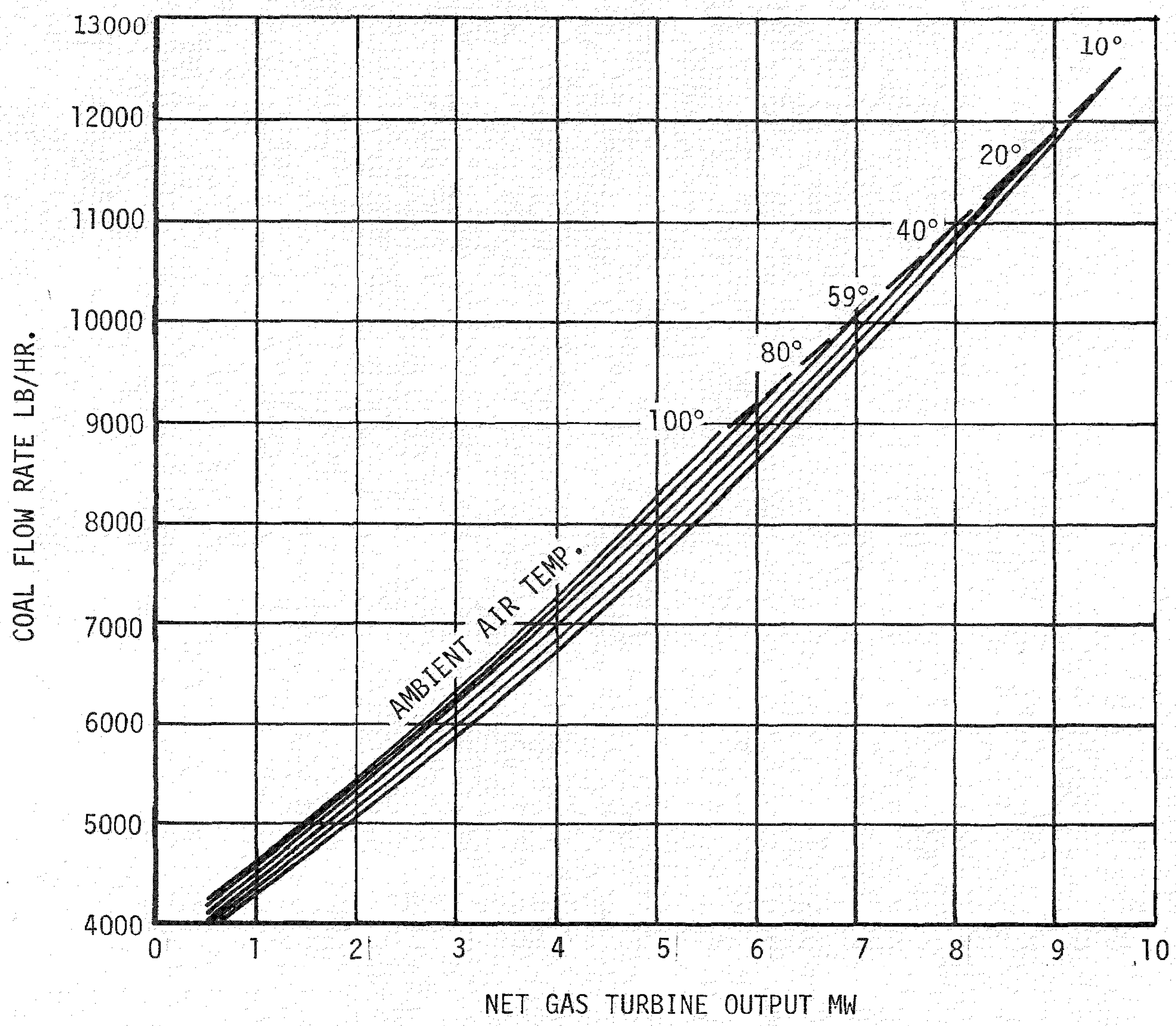

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Figure 2.16

2.4 Component Preliminary Design and Analysis

2.4.1 Pressurized Fluidized Bed Combustor and Heat Exchanger

The design concept for the PFB combustor is a single wall pressure vessel lined with refractory insulation with bayonet type (concentric flow) heat exchanger tubes in the active bed region. The general arrangement of the selected PFB combustor is shown in Figure 2.17.

Pressure Vessel - The PFB combustor consists of two sections, the upper section which includes the bed and freeboard and the lower section which is removable bottom head of the vessel. The upper section, shown in Figure 2.18 is a flanged cylindrical vessel 15 ft outside diameter with a hemispherical dome. The overall length of the upper section is 43-1/2 ft. The cylindrical section of the vessel is constructed of one inch thick plate carbon steel except at the vessel mounting pads and the lower portion of the cylindrical vessel where the shell thickness was increased to two inches. The hemispherical dome is one inch thick. Located 3 ft 9 in. from the pressure vessel flange is a reinforced cylindrical shelf for mounting the refractory lining.

The technical basis for the design of the PFB pressure vessel shell is the ASME Boiler and Pressure Vessel Code, Section VIII - Division 2. This document is applied as well to the design of the penetrations, reinforcement of the shell and shell support structure.

The material of construction is 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.

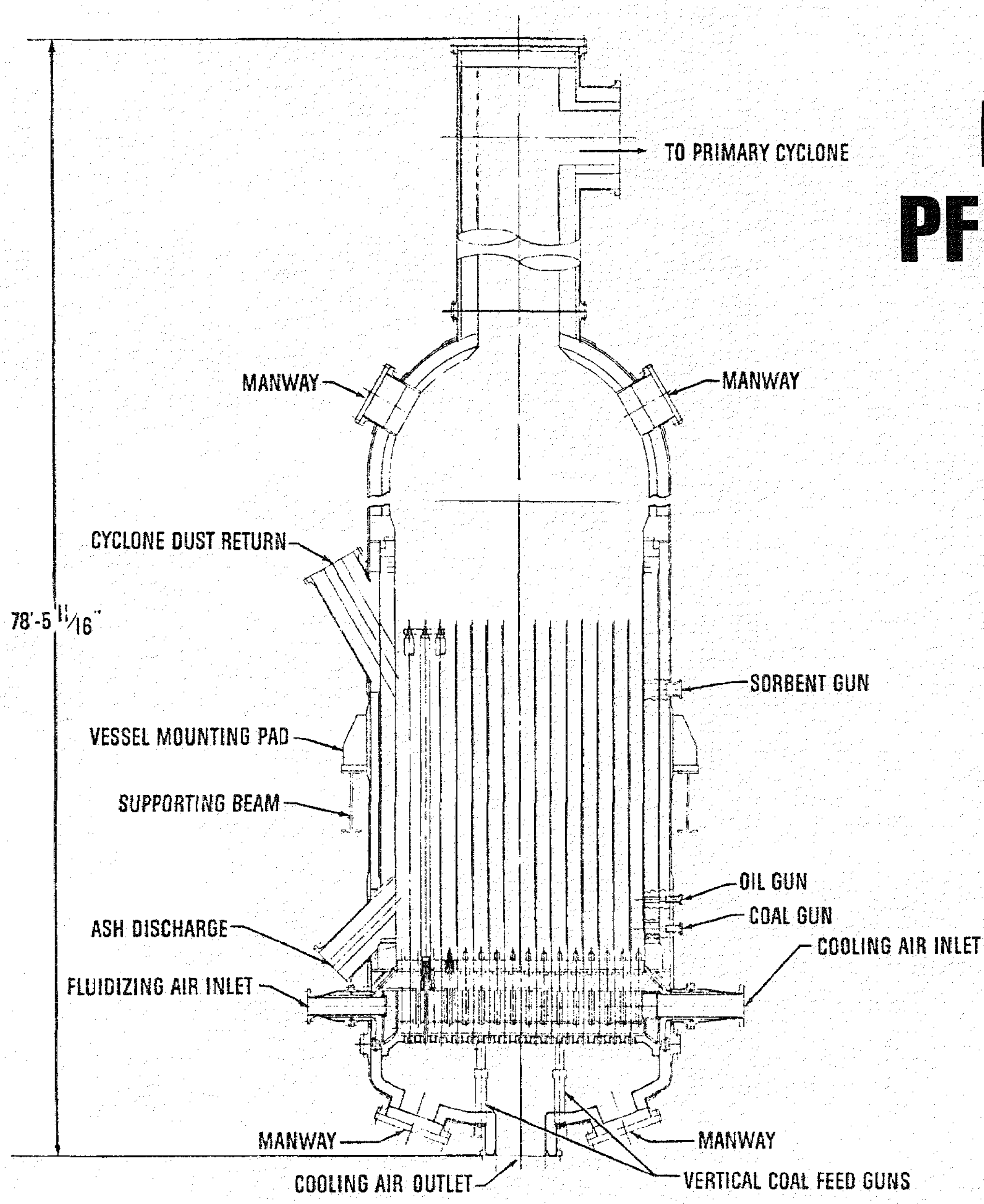
The refractory insulation design shown in Figure 2.19 for the active bed region and a portion of the freeboard includes a heavy liner of refractory brick backed with a layer of castable to maintain a temperature of 226°F at the outer shell wall in the region of the active bed on a 100°F day with no wind.

The Ufala brick, unlike ordinary 60 percent alumina brick is characterized by high purity and density, and low porosity. At operating temperatures, these qualities make Ufala highly resistant to penetration and reaction by contaminants, including the mineral matter associated with various coals. Its low iron content and high firing temperature during manufacture result in a high degree of resistance to carbon monoxide attack.

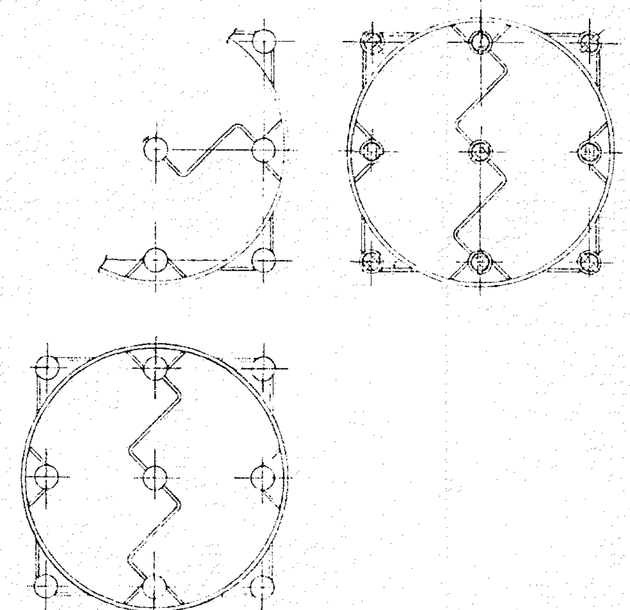
The backup castable is a medium density castable refractory (83 lb/cu ft) with a low thermal conductivity (2.5 to 3.5 Btu/sq ft/hr/°F/in.). The backup material has performed successfully as a backup liner on coal gasification applications.

Immediately adjacent to the brick and backup castable in the freeboard section is a transition refractory lined configuration. The thickness varies from 15 in. to 12 in. in the 15 in. length. This transition section is located in the freeboard area and redesigned to maintain a temperature of 288°F at the outer

PILOT PLANT PFB COMBUSTOR



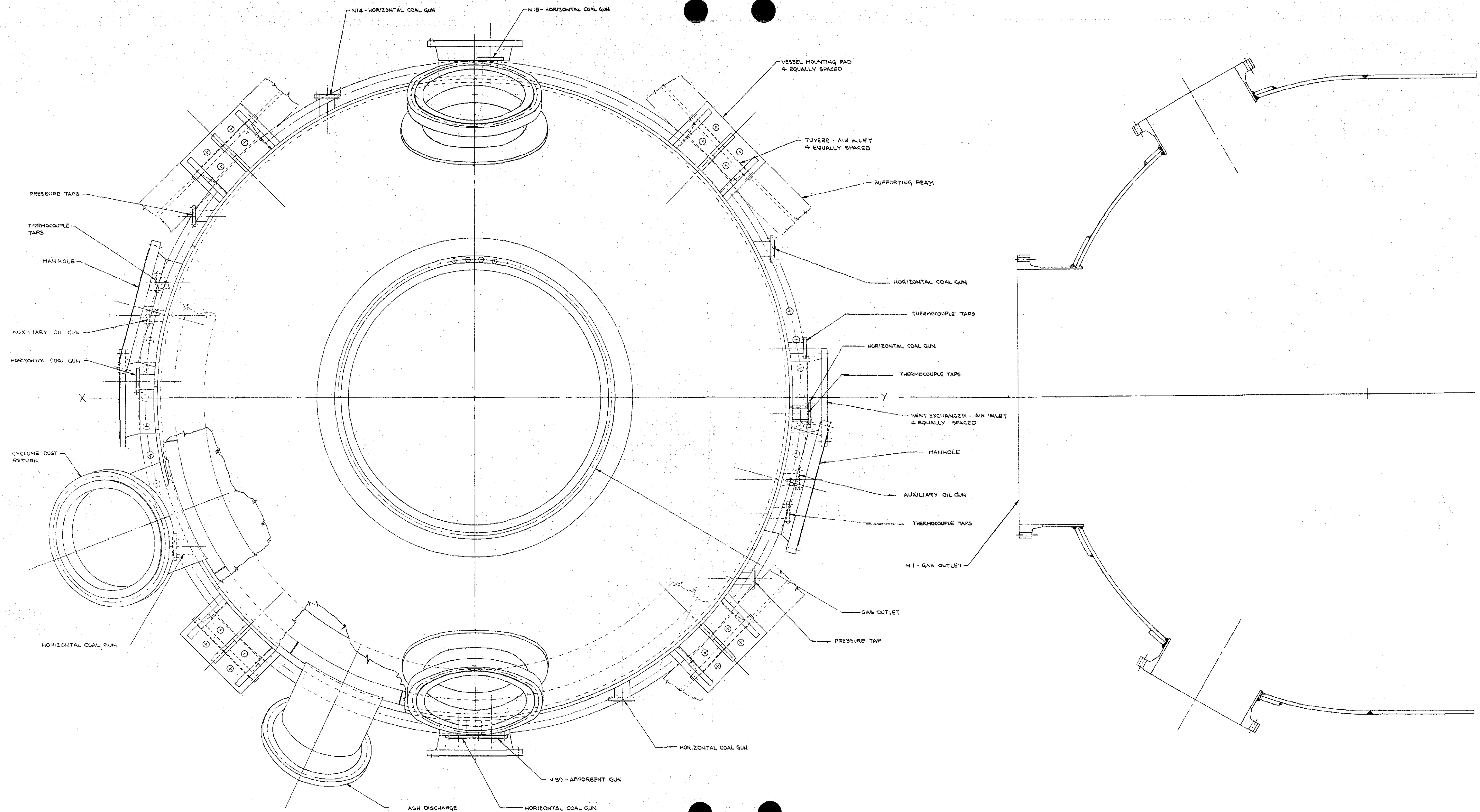
PLAN VIEW
HEAT EXCHANGER TUBE CLUSTER



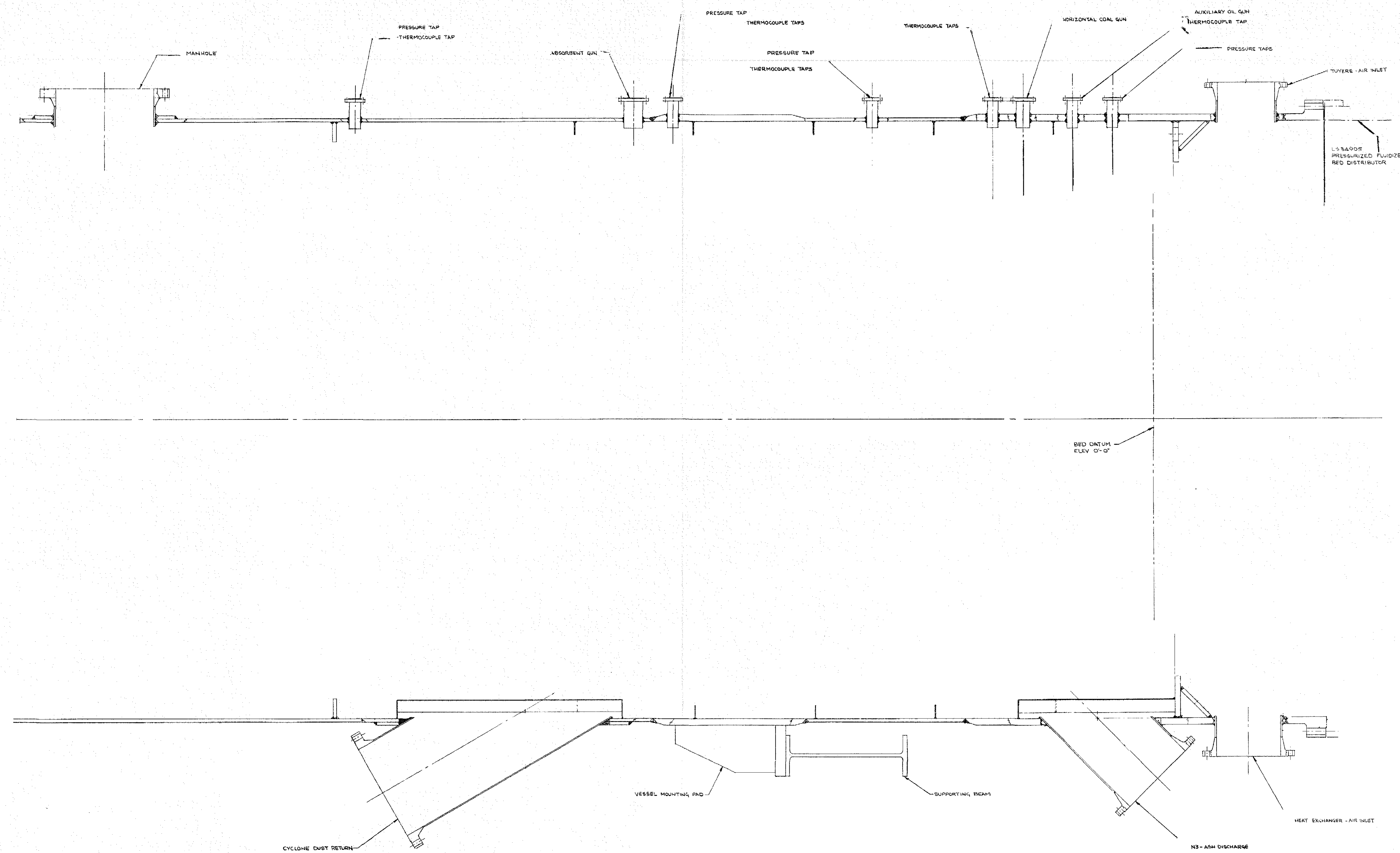
PFB-I-654

Figure 2.17

PFB COMBUSTOR VESSEL



PFB COMBUSTOR VESSEL



PFB-I-629

Figure 2.18

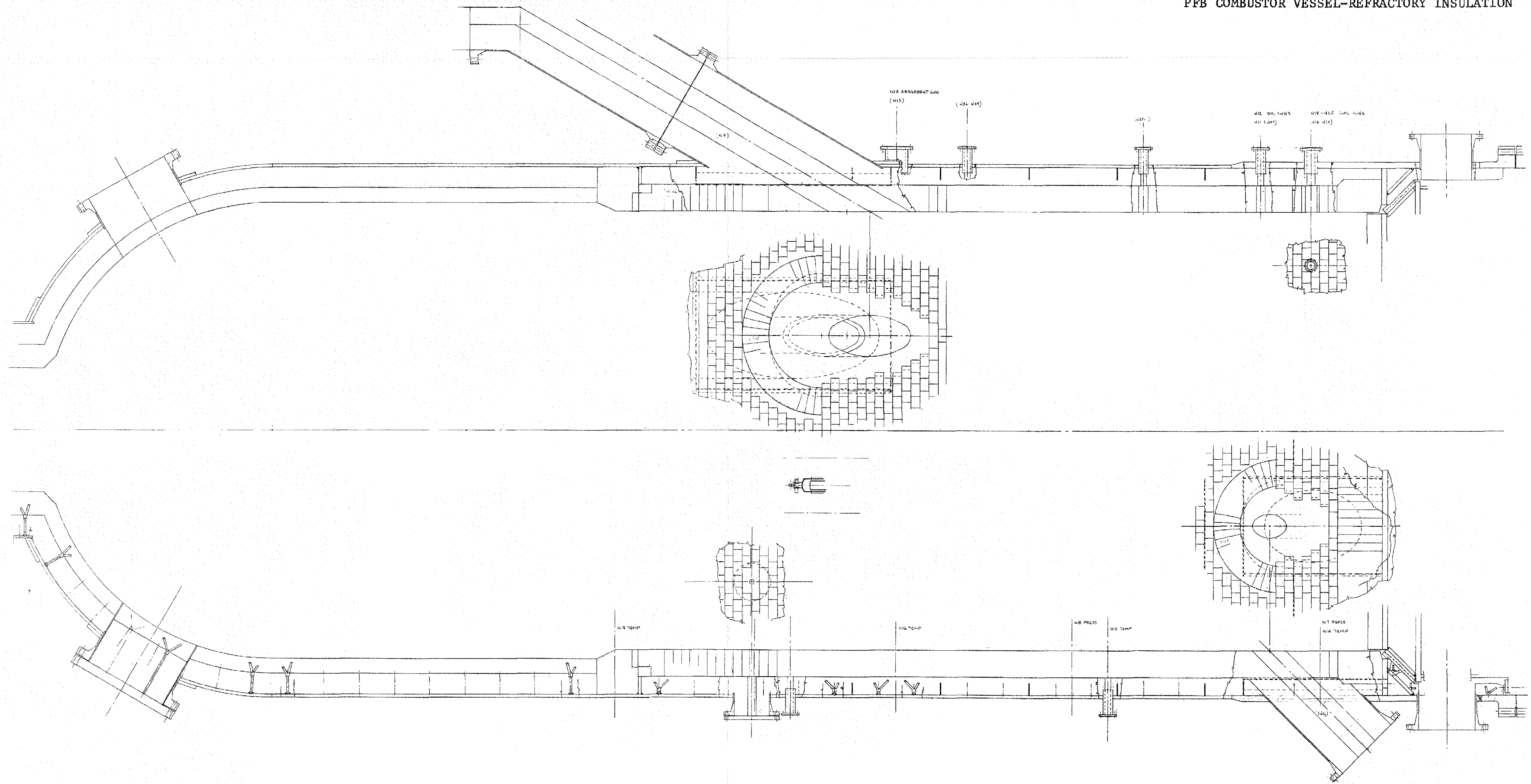

N13 ABSORBENT GUN
(N13)
N12 OIL GUNS
N16 TEMP
N8 PRESS
N15 TEMP
N7 PRESS
N14 TEMP

Figure 2.19

shell wall on a 100°F day with no wind. The material is an abrasion and erosion resistant low iron castable which should provide good protection against particulate laden gas and CO.

The remainder of the freeboard and top hemispherical head are lined with a two-component castable, gun applied. The outer shell wall in the freeboard and top hemispherical head is maintained at 254°f on a 100°F day with no wind.

The lower section is a flanged ASME code flanged and dished head (torispherical), 15 ft outside diameter and an overall length of 5-1/2 ft. Within this section the windbox-heat exchanger assembly is mounted with a radial centering joint which permits differential radial thermal growth without inducing thermal stresses. The plenum below the windbox-heat exchanger assembly which receives the 1600°F heated air is insulated and lined so that the external shell of the lower section is maintained at 250°F on a 100°F day with no wind.

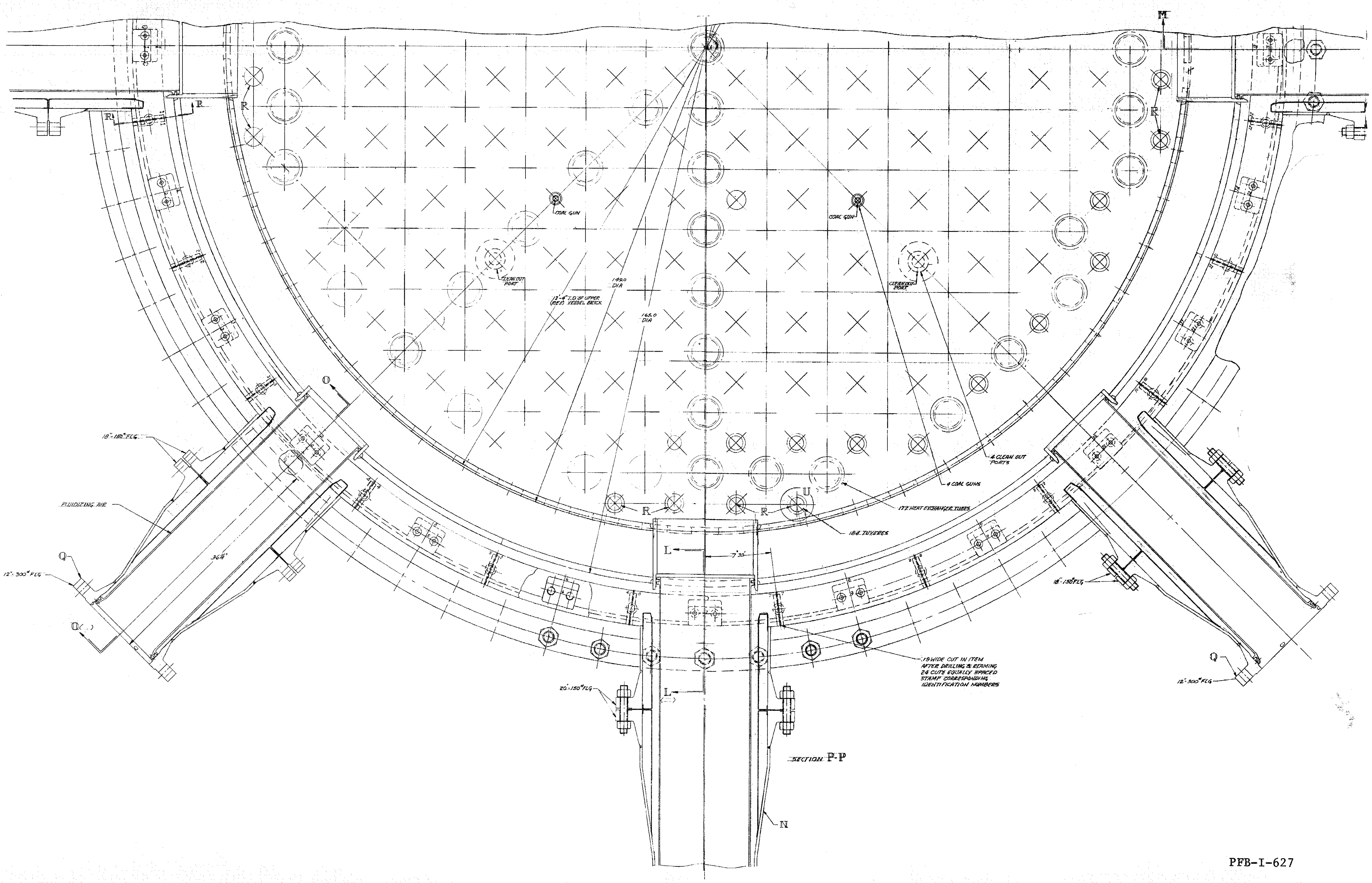
Heat Exchanger and Distributor Assembly - The heat exchanger and distributor assembly is shown in Figures 2.20, 2.21 and 2.22. This assembly consists of the following:

a. Heat Exchanger Tubes
b. Tuyeres
c. Cooling and Fluidizing Air Inlets
d. Windbox and Lower Section
e. Coal Supply Guns

Heat Exchanger Tubes - The heat exchanger tubes are mounted in the windbox and lower section as shown in Figure 2.20. These tubes consist of an outer pipe with O.D. and I.D. fins and an inner insulated pipe. Cooling air flows up through the annulus between the outer pipe and inner pipe and down through the inside of the inner pipe into the heat exchanger plenum as shown in Figure 2.21. The length of the heat exchanger tube is over 20 ft. The outer pipe with fins extends 16 ft above the castable cover on the windbox distributor plate. The pipe and fins are constructed from Inconel 600. This assembly is fabricated in two lengths, welded together with the fins on each length aligned. There are 19 fins brazed on the O.D. of the pipe. Nineteen convoluted fins are brazed to the inside of this pipe. This provides 38 radial legs (fins). The apex of each convolution of the inner fins is aligned with every fin on the O.D. An Inconel 600 pipe cap is welded to the upper end of the outer pipe. A trunnion is welded to this end cap which provides a means for supporting the upper ends of the tubes and contains a mounting hole for a shackle for lifting the tube assembly.

The lower end of the outer tube is welded to an adapter that supports the outer tube in the windbox. The adapter provides several functions. It has a step that supports the outer pipe in the windbox connecting tube. It has an internal ring that captures the inner insulated tube so that they may be handled as an assembly. Adequate clearance is provided for thermal growth and for tube assembly into the distributor plate. The lower end of the adapter is mechanically rolled radially outward into two shallow grooves to provide a seal. Tooling can be designed for "on site" assembly so that tubes may be replaced during the life of the PFB.

PFB COMBUSTOR LOWER HEAD AND HEAT EXCHANGER ASSEMBLY



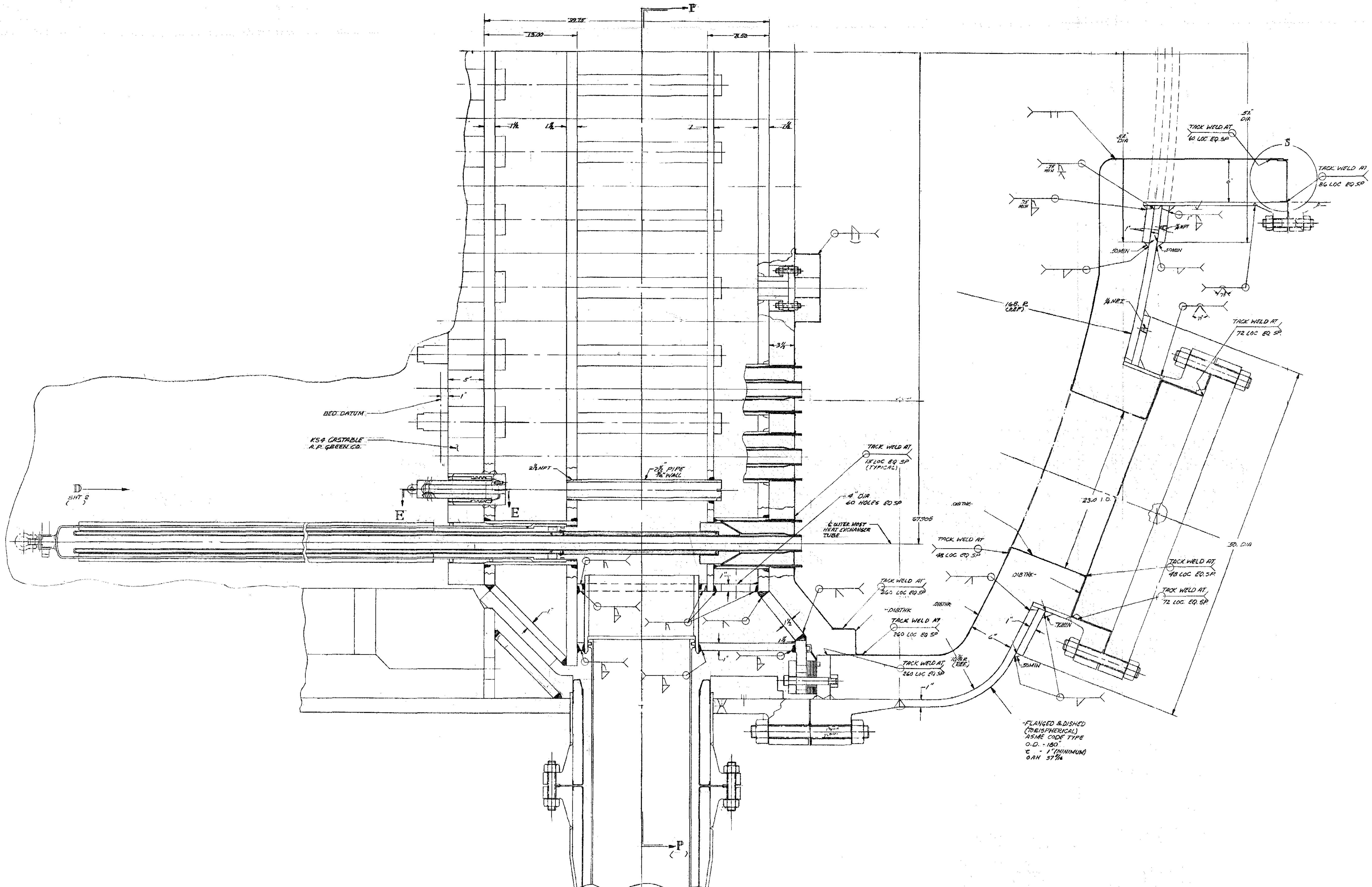
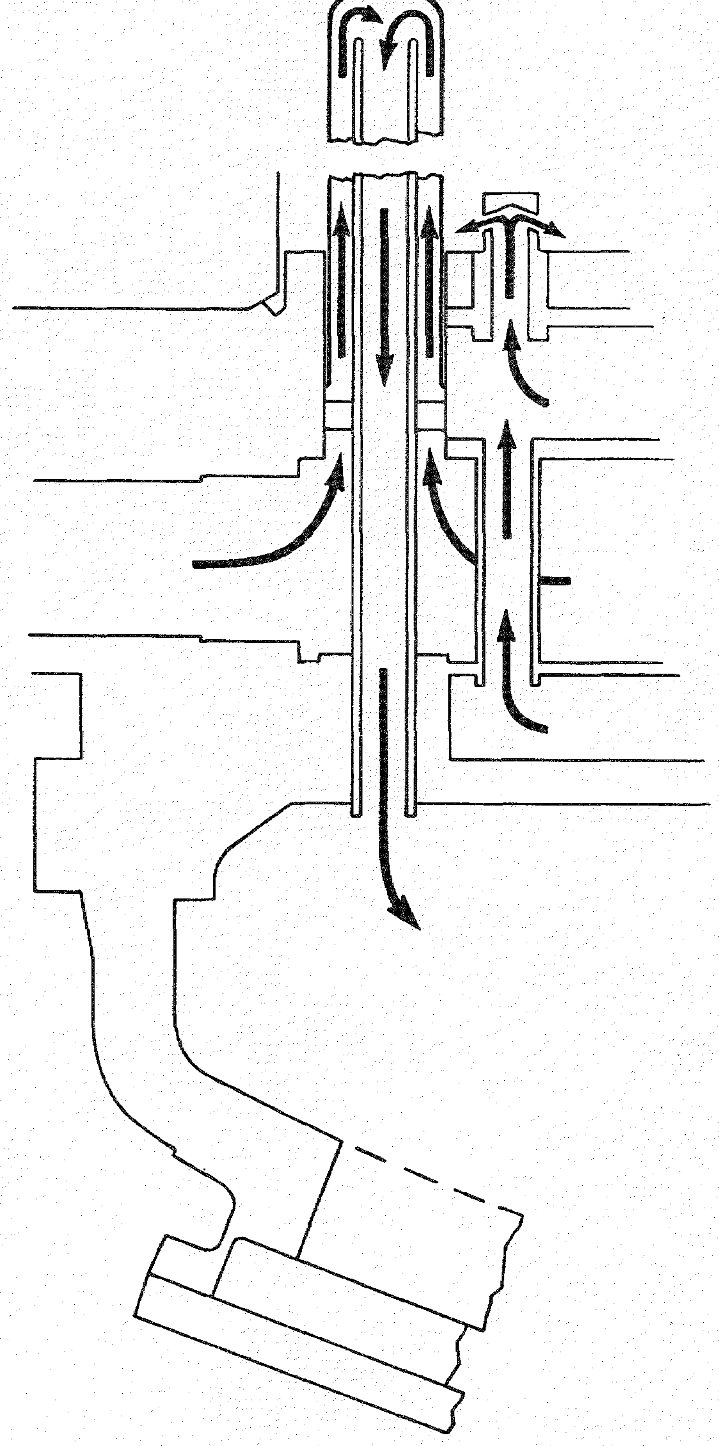

BED DATUM
KS4 CASTABLE A.P. GREEN CO.
TACK WELD AT 15 LOC EQ SP (TYPICAL)
4" DIA 60 HOLES EQ SP
℄ OUTER MOST HEAT EXCHANGER TUBE
TACK WELD AT 48 LOC EQ SP
TACK WELD AT 260 LOC EQ SP
TACK WELD AT 72 LOC EQ SP
TACK WELD AT 60 LOC EQ SP
TACK WELD AT 86 LOC EQ SP
FLANGED & DISHED (TORISPHERICAL) ASME CODE TYPE O.D. - 180" t - 1" (MINIMUM) OAH 37 9/16
30. DIA
23.0 I.D.
168. R (REF)

Figure 2.20

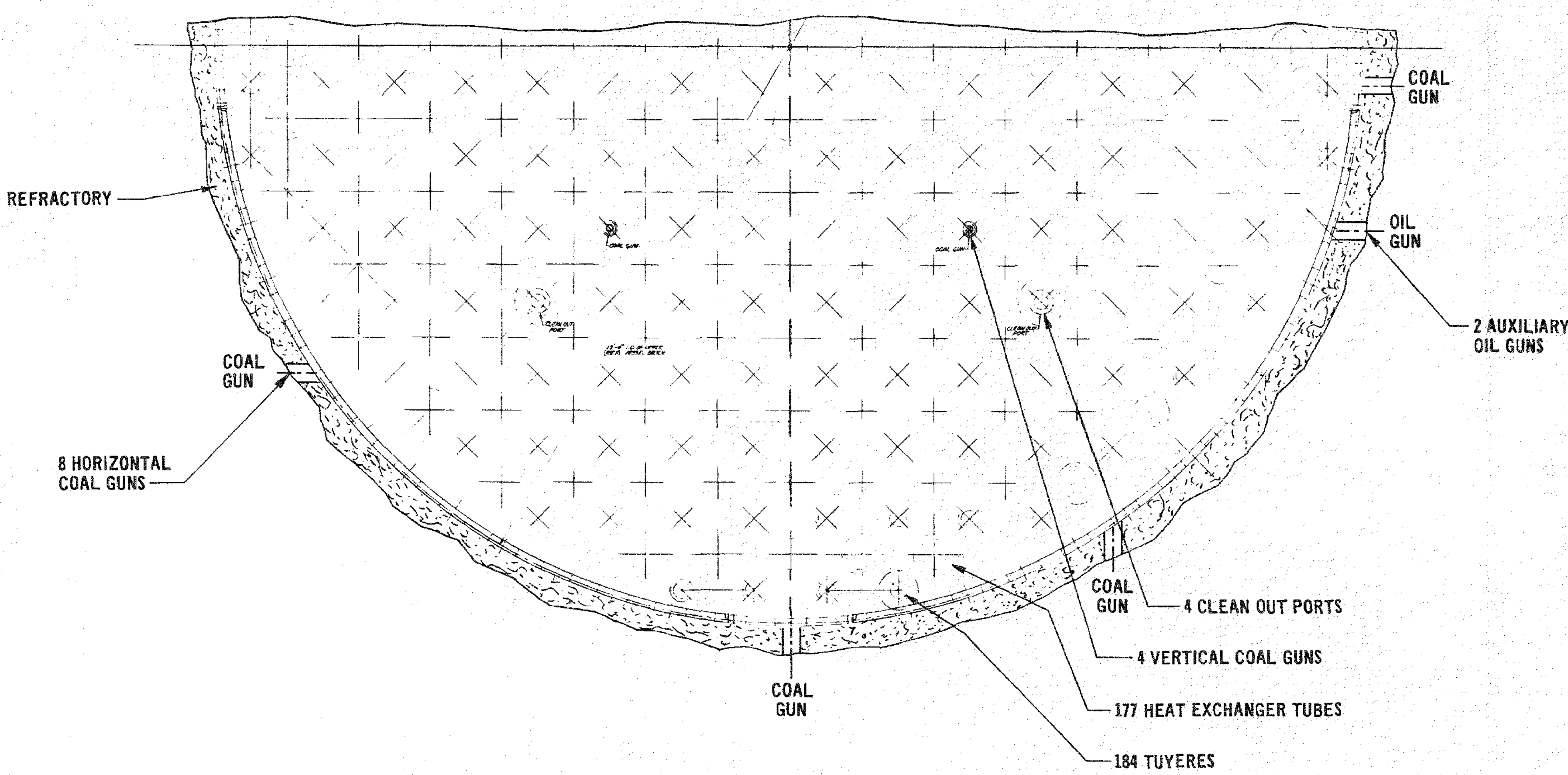
DETAIL OF ANNULAR HEAT EXCHANGE TUBES AND TUYERE



PFB-1-673

Figure 2.21

COMBUSTOR FUEL/AIR DISTRIBUTION
PFB PILOT PLANT



PFB-I-702

Figure 2.22

The insulated inner tube assembly is constructed to AISI 310-S stainless steel. This assembly consists of an outer tube 3.0 in. O.D. and inner tube 2.0 in O.D. They are joined at the upper end by a machined cap that is welded to each tube. Inspaper insulation is provided between the 3 in. and 2 in. tubes to prevent cooling air heat loss to the incoming cooling air. The lower end of the inner tube assembly is supported with a conical section (Figure 2.20) to provide a gradual change in the thermal stresses.

The support for the upper ends of the heat exchanger tubes is shown in Figure 2.17. Circular ring assemblies are used to support clusters of nine tubes. A segment of a circular ring assembly is used for clusters of 7 tubes located on the outer perimeter. These support configurations provide flexibility when the windbox grows thermally. The ring assemblies are constructed of Inconel 600. The circular ring passes within equal distance of the eight outer tubes. Hubs are supported from this ring and fit on the trunnions of the heat exchanger tubes. A pin passes through a hole in the trunnion above the hub to secure the ring assembly to the tubes. The pin is locked in place by a weld to the trunnion.

Tuyeres - The tuyeres are mounted to the upper plate of the windbox. Figure 2.20 shows a cross section of one of these tuyeres. The tuyere is constructed of Inconel 600. There are 16 holes in sets of 4 located 90 degrees from each other. The holes are angled down at 20 degrees to prevent ash from entering the tuyeres on shutdown. The lower end of the tuyere contains a truncated sphere which fits into a conical surface of the socket. A pin pressed into the bottom of the tuyere mates with a hole in the socket and orients the tuyere holes so that they are in line with the space between heat exchanger tubes. Tuyeres located adjacent to the vessel inner liner have 3 sets of 4 holes oriented so that the fluidizing air will not impinge on the liner. The socket is constructed of AISI 409 corrosion resistance steel and is welded to the upper plate of the windbox. It contains a 30 degree conical seat and a 3-1/2 2 Acme Class 2G thread. The gland nut is constructed of AISI 410 corrosion resistant steel. This nut engages the socket Acme threads and drives the tuyere spherical end into the conical seat of the socket to provide a tight seal. The Acme threads are coated with graphite red lead per MIL-L-24479 to prevent the threads from seizing. The class 2G Acme threads are free running which will also help prevent seizing. After torquing, the upper thin section of the socket is formed into one of the tightening slots on the gland nut for locking purposes. A lug is welded to the upper end of the tuyere so that a shackle may be attached to pull the tuyere from the socket.

Cooling and Fluidizing Air Inlets - There are four (4) inlets to the PFB combustor supplying fluidizing air and four (4) inlets supplying cooling air as shown in Figure 2.20.

Each cooling air inlet includes a reducer section which joins the cooling air inlet flange with the vessel nozzle. The reducer provides a gradual change in the thermal stresses between the 500°F inlet pipe and the 250°F vessel nozzle. Thermal insulation lines the inside of the reducer and vessel nozzle. The insulation is supported and enclosed by a AISI 304-L stainless steel shell that is welded to the inlet and vessel nozzle as shown. A thickness of 1.5 in. of insulation is thermally adequate.

A thermal sleeve conveys cooling air between the inlet flange and the heat exchanger and distributor assembly. The sleeve is a weldment constructed from AISI 304-L stainless steel material. A single piston ring, made from Inconel X750 is mounted at each end to seal the sleeve. End clearance is provided so that the sleeve may grow thermally. At the 16 in. flange, three equally spaced internal tabs retain the thermal sleeve.

Each fluidizing air inlet includes a reducer section which joins the fluidizing air inlet flange with the vessel nozzle. The reducer provides for a gradual change in the thermal stresses between the 1000°F inlet pipe and the 250°F vessel nozzle. Thermal insulation lines the inside of the reducer and vessel nozzle. This insulation is supported and enclosed by a shell of AISI 304-L stainless steel that is welded to the inlet and vessel nozzle as shown. A thickness of 2.0 in. of insulation is thermally adequate. The thermal sleeve and piston rings are similar in construction and materials to the sleeve and piston rings used for the cooling air inlet.

Windbox and Lower Section - The windbox and lower section shown in Figure 2.20 is welded structure that is mounted on the lower vessel with a radial centering joint that is thermally insulated from the shell. This assembly consists of an upper section or windbox that forms the bed plate and a lower section that encloses the heat exchanger plenum. These two sections are connected by two concentric shells and pipes for conveying fluidizing air between sections. Fluidizing air from the four (4) inlets flows between the concentric shells and down into the lower section through sixty (60) 4 in. holes. The air flows throughout the lower section, then up into the windbox through the connecting pipes, then into the tuyeres. During the start-up cycle, 1000°F air circulating in this manner, uniformally heats up the windbox and lower section to minimize thermal stresses. This structure also provides adequate heat paths between sections so that thermal stresses are minimized during bed soakback after shutdown.

The windbox and lower section assembly are constructed of 2-1/4 percent CR - 1 percent Mo steel. The windbox consists of a top plate and a bottom plate 1-1/2 in. thick, spaced 10 in. apart. These two plates are connected by tubes that provide the mounts for the heat exchanger pipes. These connecting tubes are spaced from each other in a square pattern. This spacing results in a 4 in. wide corridor between tube rows. At the center of all squares and partial tuyeres are located except for those squares that contain the four (4) vertical coal guns. The top surface of the upper plate is thermally insulated with 5 in. of refractory.

A 1 in. thick outer shell 13 ft 9 in. in diameter and a 1 in. thick inner shell 12 ft 5 in. in diameter join the windbox with the lower section. Four (4) 16 in. pipes pierce the two concentric shells and are aligned with the cooling air inlets. Four 12 in. pipes are located between these pipes for the fluidizing air.

A support plate containing the radial centering mounting joint is welded to the bottom plate of the lower section. The flange of the support plate has 24 equally spaced rectangular slots machined in the outer perimeter. Twenty-four positioning lugs fit into these slots. The positioning lug/slot arrangement maintains the position of the assembly during thermal growth. In order to minimize the thermal stresses in the lower support plate a thermal barrier is provided to isolate the hot support plate from the relatively cool vessel support.

Coal Supply Guns - There are 4 vertical and 8 horizontal coal supply guns located as shown in Figure 2.22. A section through one of the vertical guns is shown in Figure 2.23. The coal gun consists of two concentric pipes. Coal flows through the 3/4 in. Sch. 80 inner pipe while cooling air flows between the inner pipe and the 1-1/2 in. Sch. 80 outer pipe. The vertical pipes extend from the head of the lower vessel, through the heat exchanger plenum up through the heat exchanger and distributor assembly to a point above the castables on the windbox. The outer pipe is constructed of three pipe sections made from ASTM A-312 TP 316 stainless steel and is insulated where it passes through the heat exchanger plenum.

The inner pipe is also made from ASTM A-312 Gr. TP 316 stainless steel and can be withdrawn for replacement or service.

2.4.2 Gas Turbine Power Train

The CW 6515 Gas Generator used for the pilot plant will be the total energy unit with minimum modifications necessary to be used with the PFB combustor. The major change to the engine is the replacement of the engine combustion chamber and outer housing with a compressor exit diffuser discharge manifold, turbine inlet manifold, and a new turbine entry passage. The existing gas generator and power turbine are shown in Figure 2.24.

There will be two gas generator turbine configurations. The first installed gas generator will be with the existing 1st and 2nd stage turbine rotor blades and the existing 2nd stage stator vanes. The first stage stator vanes will be replaced by those from another CW J65 engine to provide a better match for the PFB flow conditions and to provide increased surge margin for the gas generator compressor.

The second installed configuration will have the same flow areas as the first installed engine, however, the 1st stage stator vane and the 1st stage rotor blade will be transpiration air protected configurations.

Existing Gas Generator - The gas generator (CW 6515) which is an industrial version of the J65 turbojet engine, is an axial flow machine with a thirteen stage compressor, an annular combustion chamber containing 36 fuel vaporizer tubes and a two stage turbine. Conversion to the CW 6515 industrial gas generator for the total energy installation which is designed for a life of 10,000 hours, required the following changes:

a. Incorporation of tandem front main bearing
b. Increased diameter thrust equalizer
c. Modification of the combustion chamber to permit operation on either liquid or gaseous fuels
d. Addition of an exhaust transition duct.

The engine materials of construction are shown in Figure 2.25.

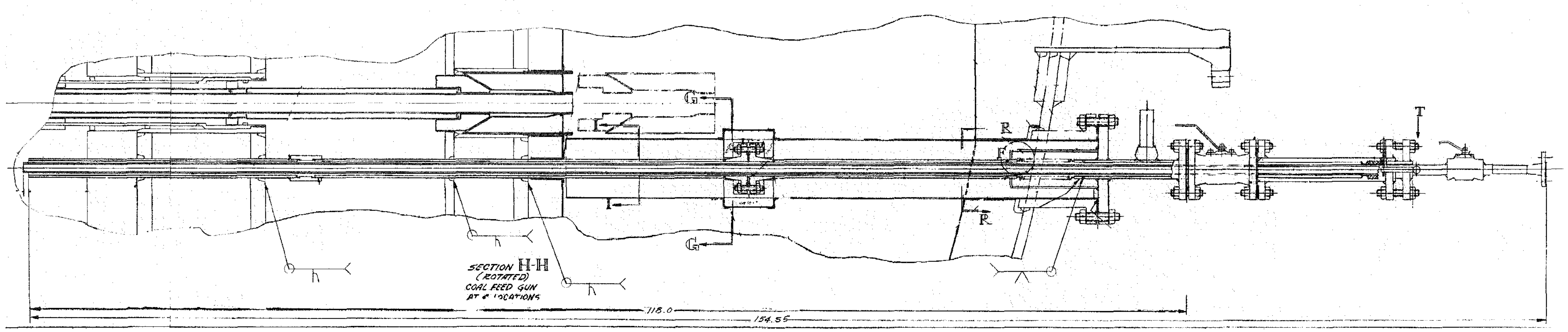


Figure 2.23

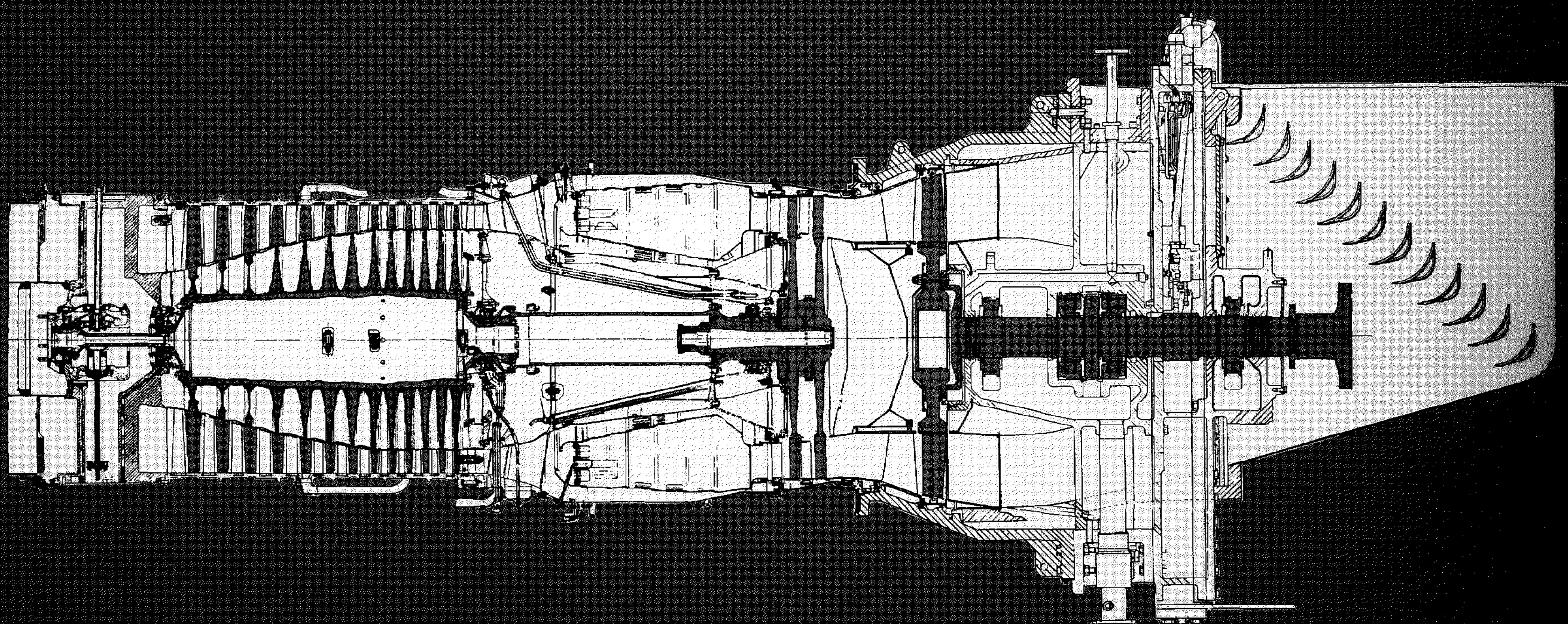
Fig 2.24

100%

CURTISS WRIGHT

POWER SYSTEMS

CW 65 Industrial Gas Turbine



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CURTISS WRIGHT
POWER SYSTEMS

CW 65 Industrial Gas Turbine

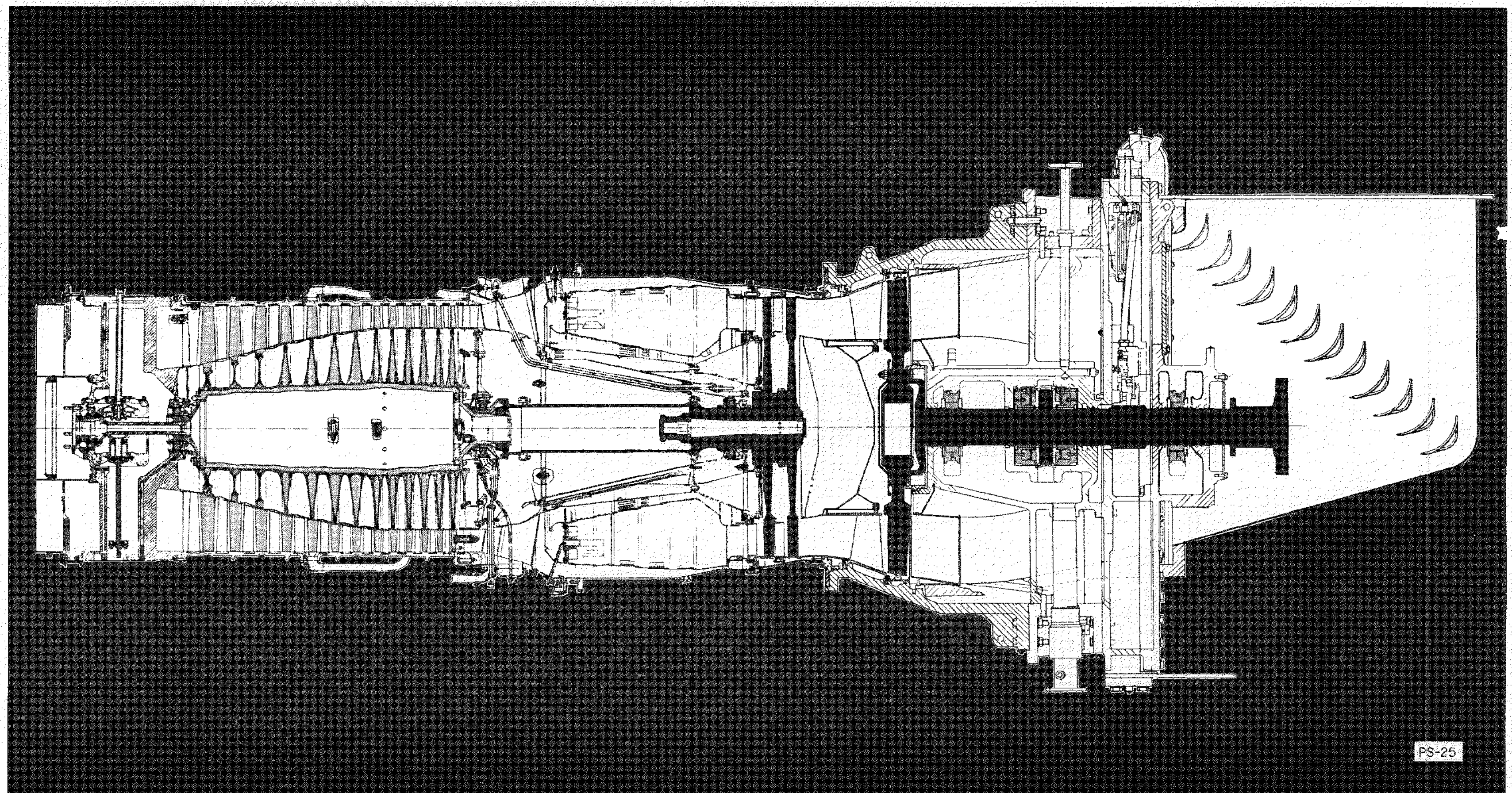
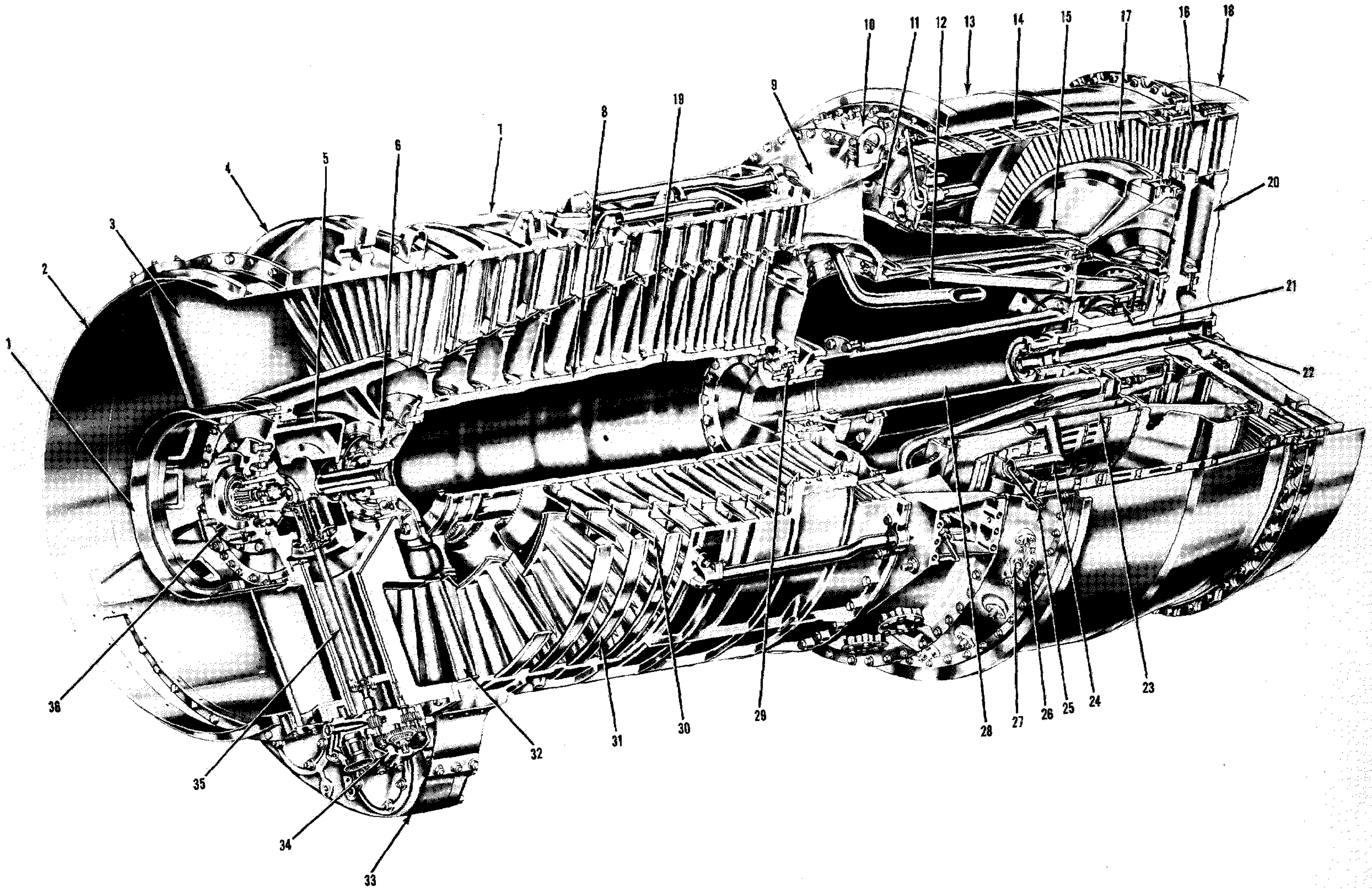


Figure 2.24

CW657D GAS GENERATOR MATERIALS



1. Air adapter, inner - 321 Stainless
2. Air adapter, outer - Aluminum
3. Strut fairing - Magnesium
4. Front main bearing support - Magnesium
5. Internal accessory drive housing - Steel
6. Front main bearing - SAE 52100
7. Compressor housing - Cast Aluminum
8. Compressor rotor shaft - Steel
9. Center main bearing support - Nodular Cast Iron
10. Combustor inlet housing - Timken Alloy
11. Burner support plate - 321 Stainless
12. Internal bearing cooling air tube - Low Carbon Steel
13. Combustion chamber housing - Timken 17-22
14. Combustion chamber outer liner Hastelloy X
15. Combustion chamber inner liner Hastelloy X
16. Turbine rotor blade Inco 700 (Both Stages)
17. Turbine stator blade - Nimonic 80
18. Exhaust housing - 321 Stainless
19. Compressor rotor disc - Low Alloy Steel
20. Turbine rotor disc - 7823 Alloy Steel
21. Rear main bearing - M-10 Tool Steel
22. Turbine rotor shaft - Timken Alloy
23. Combustion chamber heat shield - 321 Stainless
24. Primary air-fuel vaporizer Hastelloy X
25. Internal fuel tube - 321 Stainless
26. Fuel primer - 321 Stainless
27. Igniter housing - 321 Stainless
28. Turbine rotor front shaft - AMS 6412
29. Center main bearing - M-10 Tool Steel
30. Compressor rotor blade - Stage 1-3, 410 Stainless
    4-7, Aluminum Alloy
    8-13, 410 Stainless
31. Compressor stator blades - 410 Stainless
32. Compressor inlet guide vanes - 410 Stainless
33. Accessory gear box housing - Magnesium
34. Oil pump housing - Aluminum
35. Oil pump drive internal shaft - Low Alloy Steel
36. Starter adapter - Cast Aluminum

Figure 2.25

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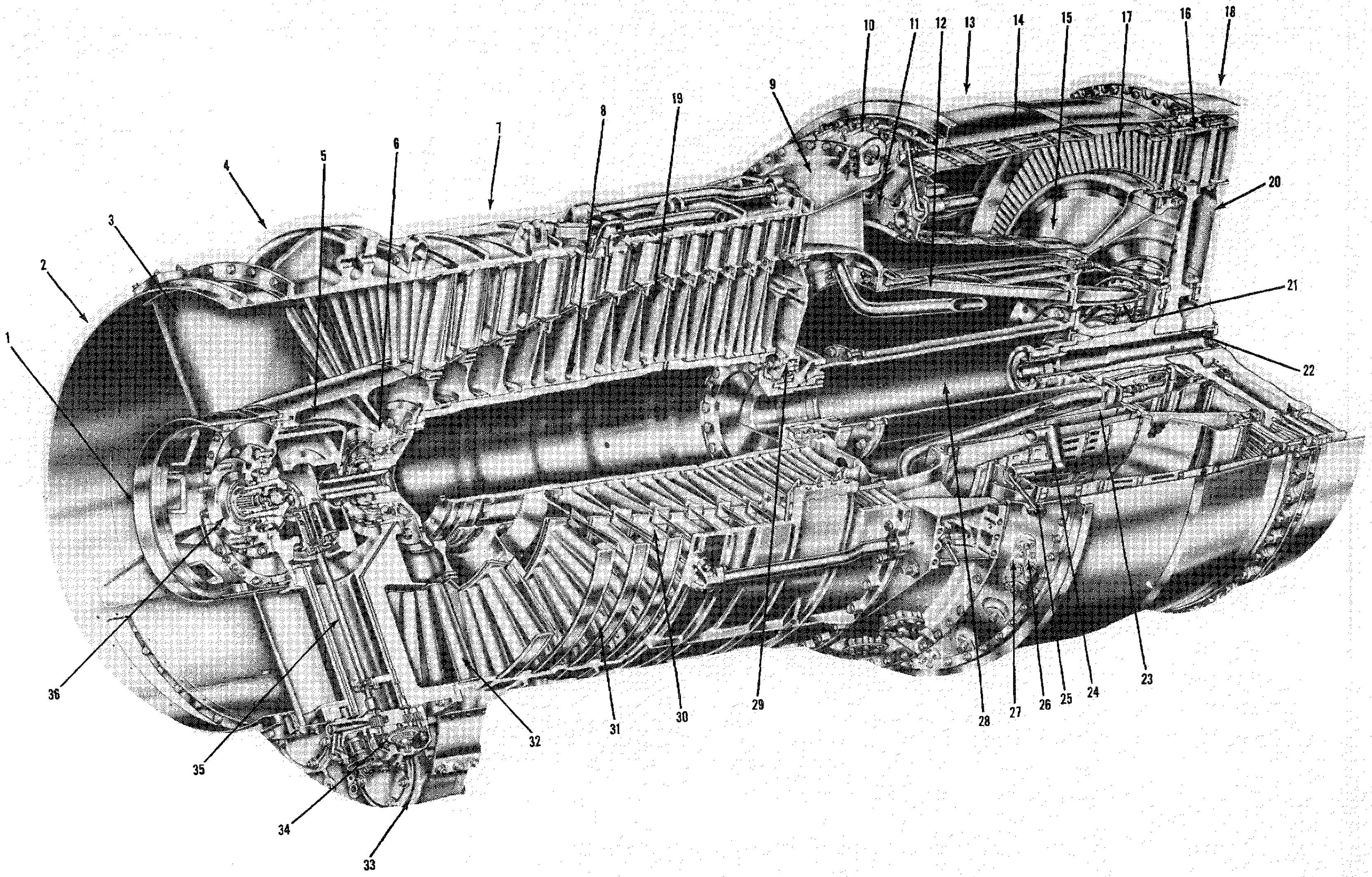
CW657D GAS GENERATOR MATERIALS



1. Air adapter, inner - 321 Stainless
2. Air adapter, outer - Aluminum
3. Strut fairing - Magnesium
4. Front main bearing support - Magnesium
5. Internal accessory drive housing - Steel
6. Front main bearing - SAE 52100
7. Compressor housing - Cast Aluminum
8. Compressor rotor shaft - Steel
9. Center main bearing support - Nodular Cast Iron
10. Combustor inlet housing - Timken Alloy
11. Burner support plate - 321 Stainless
12. Internal bearing cooling air tube - Low Carbon Steel
13. Combustion chamber housing - Timken 17-22
14. Combustion chamber outer liner Hastelloy X
15. Combustion chamber inner liner Hastelloy X
16. Turbine rotor blade Inco 700 (Both Stages)
17. Turbine stator blade - Nimonic 80
18. Exhaust housing - 321 Stainless
19. Compressor rotor disc - Low Alloy Steel
20. Turbine rotor disc - 7823 Alloy Steel
21. Rear main bearing - M-10 Tool Steel
22. Turbine rotor shaft - Timken Alloy
23. Combustion chamber heat shield - 321 Stainless
24. Primary air-fuel vaporizer Hastelloy X
25. Internal fuel tube - 321 Stainless
26. Fuel primer - 321 Stainless
27. Igniter housing - 321 Stainless
28. Turbine rotor front shaft - AMS 6412
29. Center main bearing - M-10 Tool Steel
30. Compressor rotor blade - Stage 1-3, 410 Stainless
    4-7, Aluminum Alloy
    8-13, 410 Stainless
31. Compressor stator blades - 410 Stainless
32. Compressor inlet guide vanes - 410 Stainless
33. Accessory gear box housing - Magnesium
34. Oil pump housing - Aluminum
35. Oil pump drive internal shaft - Low Alloy Steel
36. Starter adapter - Cast Aluminum

Gas Generator Design Initial Turbine - The gas generator will be moved forward, just upstream of the power turbine to provide space for a power turbine bypass bleed manifold and 24 variable geometry vanes downstream of the bleed manifold and upstream of the power turbine inlet vanes (Figure 2.26). Power turbine vleed will be used for synchronizing the gas generator on line during startup. Upon loss of electrical power an emergency shutdown will require closing the 24 variable geometry vanes and modulation of the two bleed valves to prevent the power turbine and alternator from overspeeding.

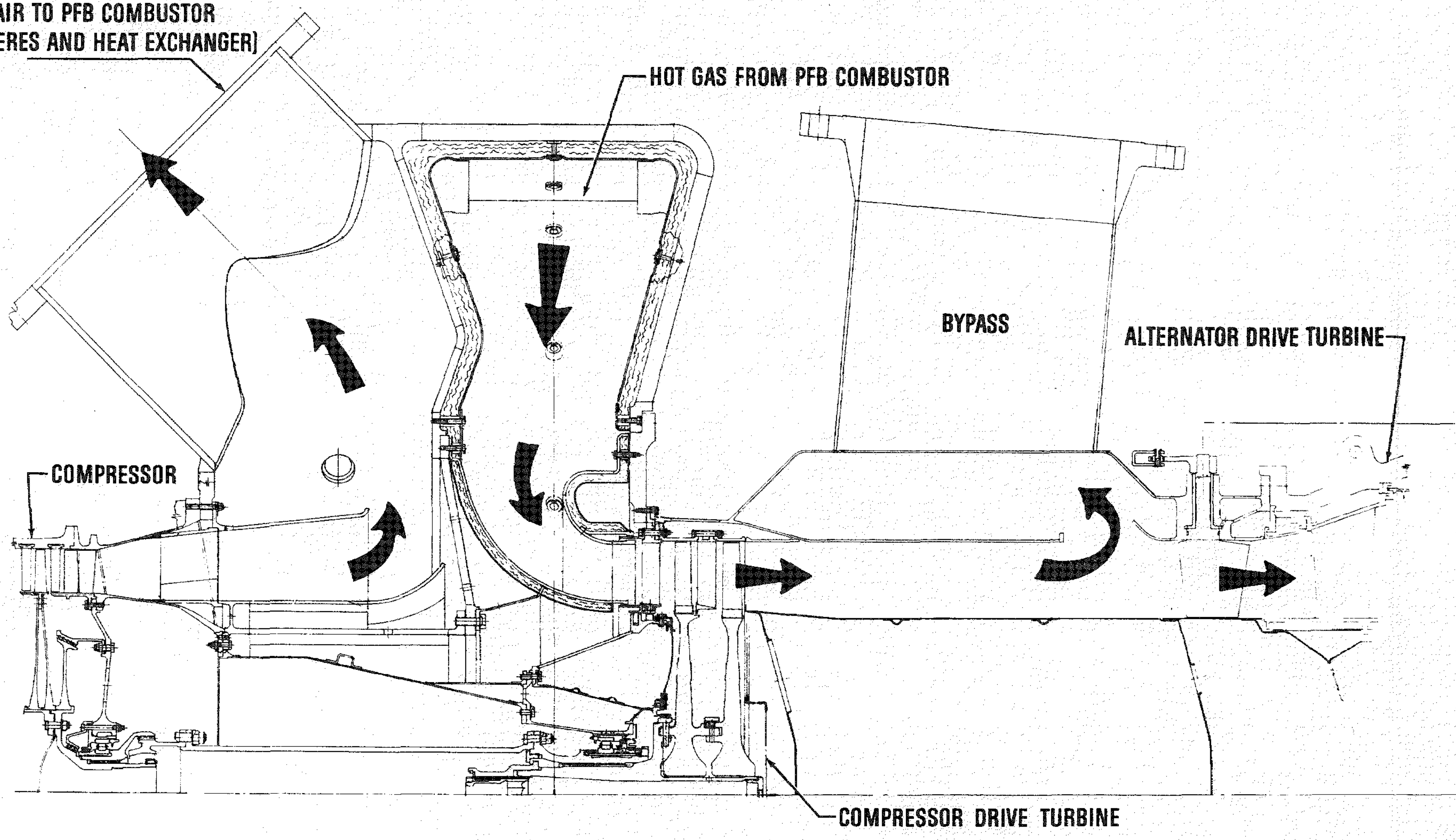
The gas generator will remain unchanged forward of the thrust balance disc. The thrust balance disc diameter may be changed if thrust balance calculations indicate this requirement. Aft of the thrust balance disc, the combustor is removed and a diffuser is provided at the compressor discharge to recover the velocity head before entering the compressor discharge manifold. The existing center main bearing support passage area has been modified (reduced) starting at strut midspan aft for optimum diffusion. This is accomplished by welding new inner and outer duct walls to the struts and existing walls. The aft end of the diffuser is bolted to the center-main bearing support and extends into the discharge manifold where it makes a turn and discharges into the manifold.

The compressor discharge manifold is annular in shape with a cylindrical inner and outer wall parallel to the engine axis. The side walls are composed primarily of conical sections for increased strength and stiffness. An elliptical discharge port located at the top of the manifold provides the exit passage for the air to the PFB system. Bleed holes are located on the inner and aft walls of the manifold for cooling of the inner hot sections of the engine. Cooling of the outer hot section of the engine is accomplished by cooling air bleed lines tapped into the outer wall of the compressor bleed manifold.

The hot gas returns from the pressurized fluidized bed combustor and heat exchanger to the engine turbine inlet manifold through two transition ducts located 180 degrees apart on the horizontal centerline. The turbine inlet manifold and the compressor discharge manifold have a common axial wall for strength and space considerations. By utilizing this feature the critical rotating elements of the engine remain unchanged viz engine rotor shaft, bearings, etc. The two inlet ducts and the discharge manifold are internally lined with refractory fiber insulation to maintain compressor discharge temperatures on the pressure carrying outer walls. The insulation in turn is lined with steel sheet attached to the outer wall with bolts and welding studs. This inner liner is used to prevent the insulation from entering the airstream and contaminating the clean air entering the turbine.

The inner hot liner is composed of many segments which are attached to the colder outer walls with slip joints for differential thermal expansion and also for assembly consideration. A small quantity of compressor discharge air is used for cooling the outer hot section of the engine at the turbine. The gas generator turbine is the same as that used for many years on the total energy system except the first stage stator assembly will be replaced with one of comparable materials and design but with increased throat for matching PFB flow conditions.

CW6515 GAS GENERATOR MODIFIED FOR PFB COMBUSTOR



PFB-1652

Figure 2.26

The variable geometry vanes have a NACA 63-009 airfoil shape for minimum drag. The vane shafts are supported on bearings located in the outer wall. The vane actuation system consists of two piston actuators which rotate a 360 degree unison ring. The unison ring is connected to the vane shafts by 24 links. The circumferential rotation of the unison ring is translated to vane rotation by the links. The link is connected to the unison ring via a spherical bearing and bolt. A square drive is incorporated between the link and louver shaft to translate link motion to shaft rotation. Two balanced pistons located 180 degrees apart prevent any radial loads on the unison ring and links due to piston rod loads.

Due to the increased overall length of the gas generator with the power turbine bypass bleed system new mounts will be provided to support the increased weight of the assembly. A new lateral stop on the forward end of the compressor discharge manifold will be installed for the increased length and additional external piping loads. The existing lateral stop at the aft end of the power turbine will remain, but with increased clearance.

Gas Generator Design (Transpiration Air Protected 1st Stage Stator Vane and 1st Stage Rotor Blade) - The transpiration air protected turbine will have the same number of vanes and blades and the same aerodynamic blade shapes and flow areas as the solid blade turbine.

In transpiration air protection, air is passed through a porous wall to establish a complete and continuous protective blanket of air on the outer airfoil surface of buckets and vanes. The presence of this continuous air blanket surrounding the airfoil will offset the aggressive environment produced by the PFB combustor in the following ways:

a. Prevent impingement erosion of the airfoil by deflecting low micron, hard, abrasive particles in the gas stream.

b. Prevent condensation of alkali-metal salts on the airfoil which can cause hot-corrosion.

c. Serve to keep the airfoil skin temperatures below the hot-corrosion "threshold" temperature for the airfoil material.

d. Permit the use of airfoil skin materials inherently very resistant to both oxidation and hot-corrosion, and permit flexibility in selecting skin materials, since the airfoil skins are essentially non-load-carrying members.

e. Utilize a wide variety of high-strength superalloys for the load-carrying strut, since strut temperatures are kept very low and are fully protected from the aggressive gases.

The 1st stage stator vane is mounted on the outer diameter with no change from that of the solid 1st stage stator vane. The inner diameter is mounted in a 360 degree box section air manifold which supplies the stator vane air radially outward (Figure 2.27).

CW6515 COMPRESSOR DRIVE TURBINE WITH TRANSPIRATION COOLED 1ST STAGE

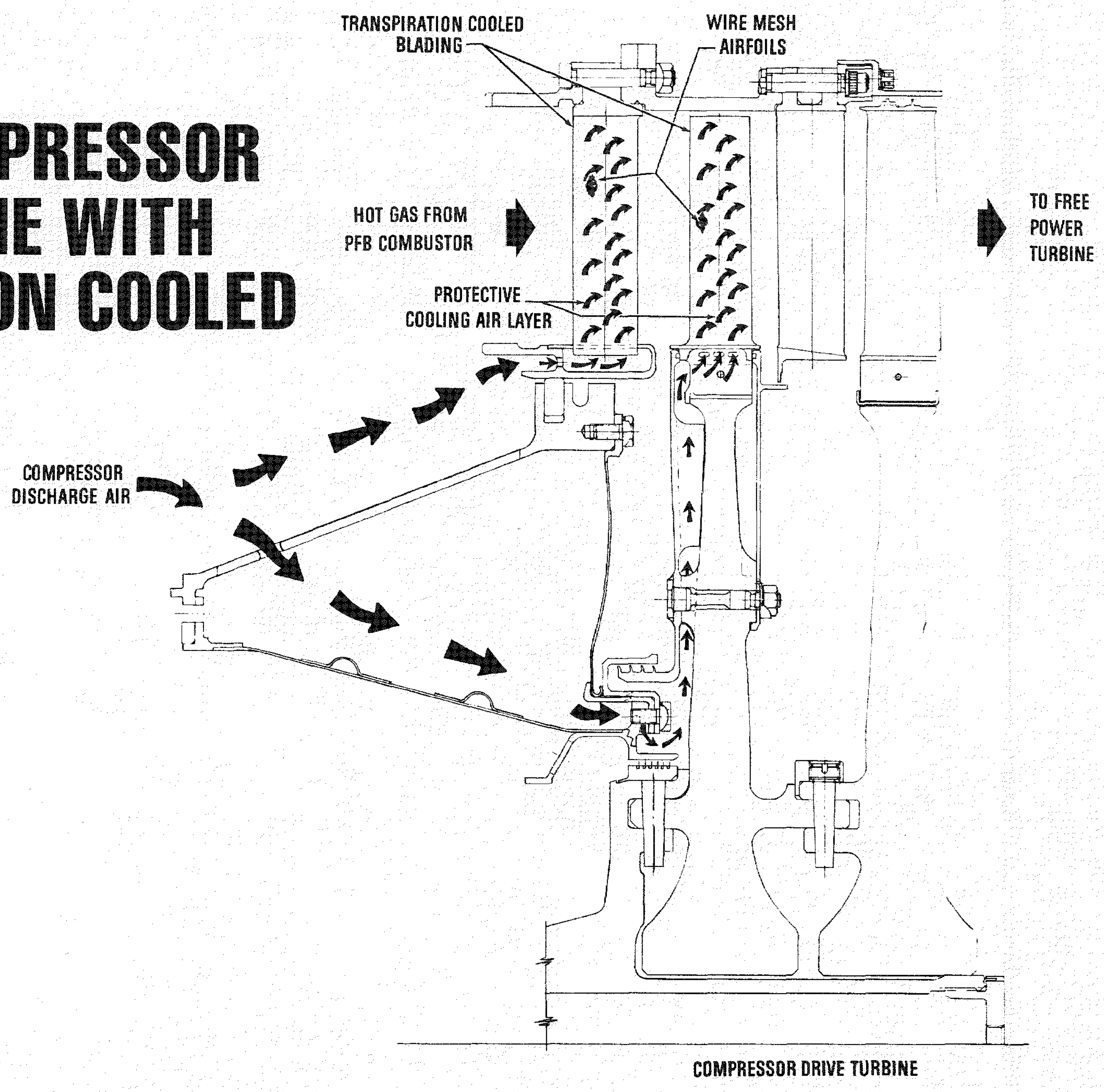


Figure 2.27

The vane consists of a structural spar with spanwise radial channels to which a porous metal is electron-beam welded (Figures 2.28 and 2.29 show the rotor blade, which is similar). The air is fed through holes at the base of the vane to each of the individual channels and then out the porous metal skin.

The rotor blade consists of a structural spar with spanwise radial channels to which a porous metal skin is electron-beam welded (Figures 2.28 and 2.29). Cooling air is directed radially outward between the annular space formed by the forward face of the turbine disc and the aft face of the turbine forward diaphragm. Adequate provisions exist for sealing at the outer rim. At the disc rim, the air is fed through holes in the blade attachment butt to each of the individual channels and then out the porous metal skin. A rear cover plate is attached at the rear of the disc to contain the cooling air. A boundary of protective cooling air is thus formed around the blade and the temperature of the spar is kept at a reasonable level to insure meeting the blade design life requirements. The transpiration skin is conservatively considered as dead weight or non-load carrying insofar as structural analysis of the rotor blade is concerned. The transpiration skin is nickel base Nichrome V Cb.

Power Turbine - The existing power turbine (Orenda Model OT-F-3, CW Modification) which will be used is a single stage assembly with shrouded turbine rotor blades (Figures 2.24 and 2.30). A bi-furcated exhaust elbow containing fixed turning vanes direct the gases through a right angle turn, discharging vertically upward.

Machined castings make up the two matched halves of the casing assembly which contains the bearing housings, fixed stator vanes, and overspeed trip mechanism. Differential expansion between the turbine and driven equipment is compensated for by using the lubricating oil to maintain the four vertical support legs of the housing at constant temperature.

The short rigid shaft assembly is carried in two tilting pad bearings with end thrust absorbed by a central Kingsbury type thrust bearing. The turbine stator vanes are cast of high temperature X-40 Stellite, while the rotor blades are cast of Udimet 500. Fir tree attachments hold the blades to the H-46 alloy steel disc.

The gas generator with its turbine bypass system is mounted to the power turbine. Turbine cooling is accomplished by ducting a small quantity of gas generator compressor air to the turbine. A heat exchanger reduces air temperatures to desirable levels. Basic turbine characteristics are shown in Table 2.9.

Electric Alternator and Reduction Gas Drive - The existing alternator is a three phase, four pole, "wye" connected alternator manufactured by the Brown Boveri Corporation of Zurich, Switzerland with a rated output of 6000 KW at 13,800 volts, 60 Hertz. During peaking operation, 7000 KW are provided. The design incorporates brushless excitation. The laternator is attached to the skid by means of soleplates. Sleeve type journal bearings, lubricated from the main oil supply system support the rotor. Forced ventilation air cooling is provided. Table 2.10 lists alternator design characteristics.

TRANSPIRATION AIR PROTECTED TURBINE BLADE CONCEPT

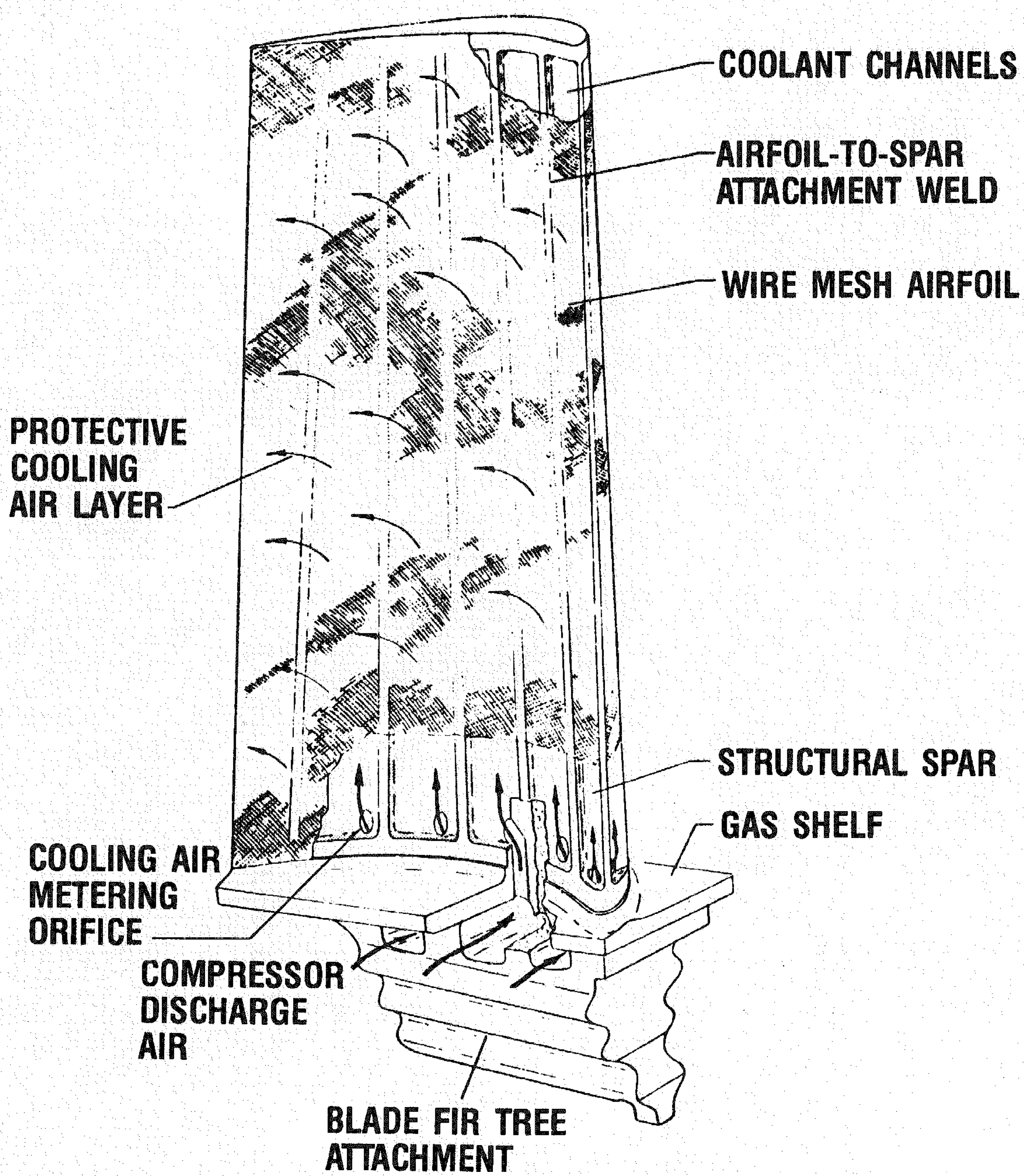
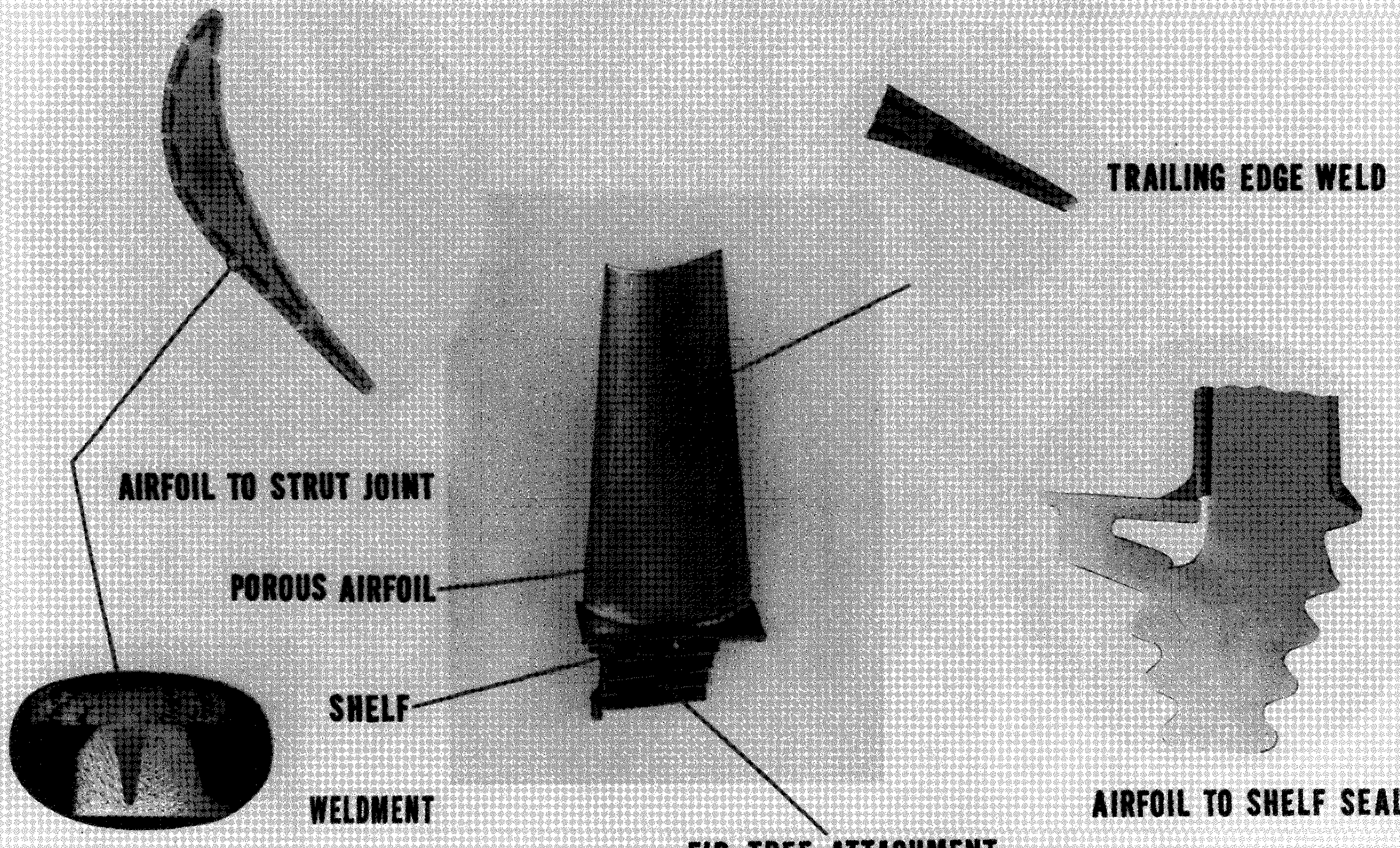


Figure 2.28

Figure 2.24 100%

Fabrication Summary

COOLED ROTOR BLADE



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Fabrication Summary

COOLED ROTOR BLADE

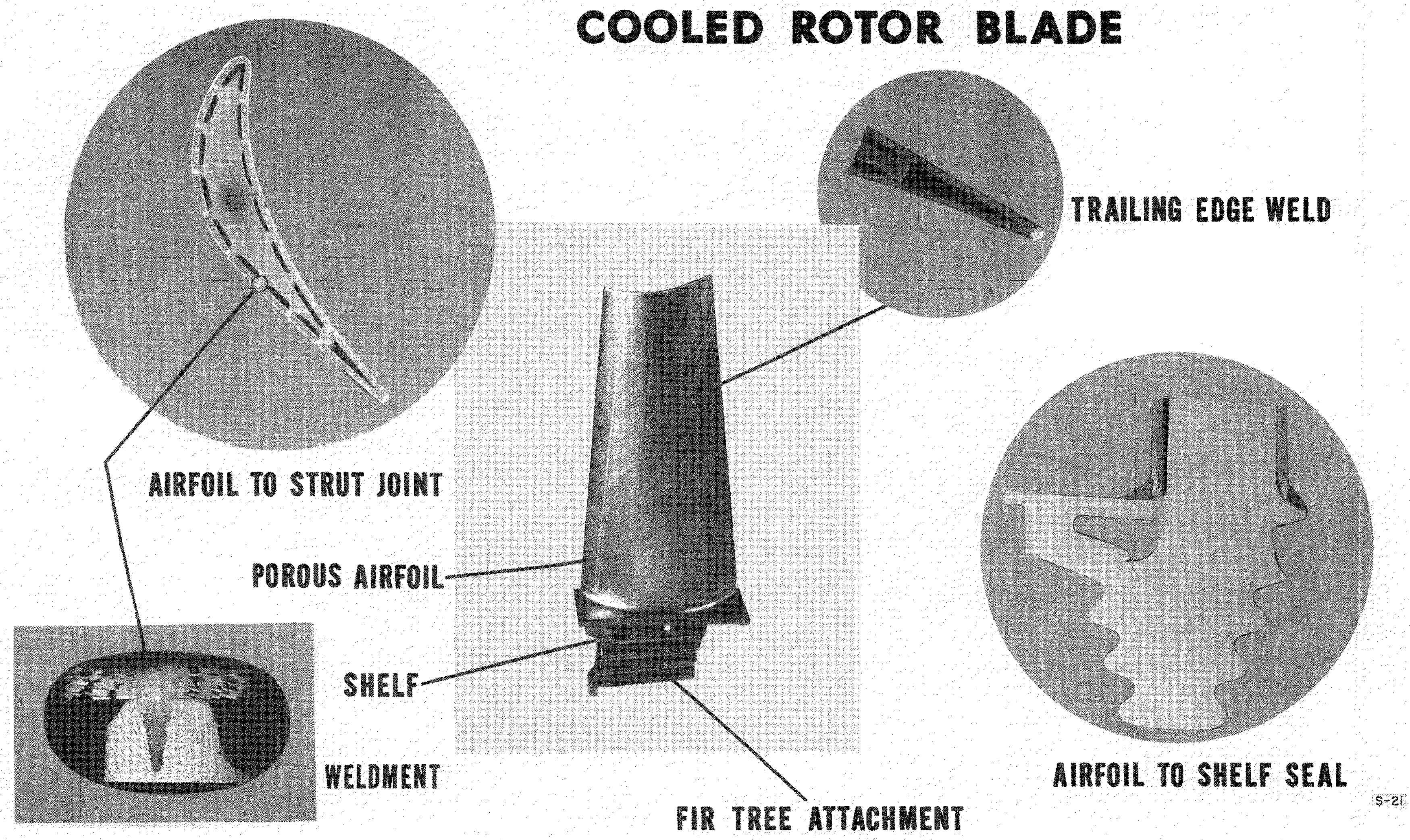


Figure 2.29

TABLE 2.9

BASIC POWER TURBINE CHARACTERISTICS

Power Turbine

Manufacturer	Orenda-Modified for Curtiss-Wright Gas Generator
Type	Single Flow
Model Number	OT-F-3, C-W Modification
Number of Expansion Stages	One
Speed	7500 rpm
Speed at which overspeed device operates	7850 rpm
Critical Speeds	8625 rpm
Type of Main Governor	Electro/Hydro/Mechanical
Bearing Description	Tilting Pad and Kingsbury Thrust
Weight	5800 pounds
Weight of heaviest service lift	600 pounds

Materials of Construction

Blades	Cast Shrouded Udimet 500
Inner Casing	Nodular Iron
Outer Casing	Cast Ni Resist C-4
Rotor Shaft	AMS 4340
Turbine Vanes	X-40 Cobalt Steel

TABLE 2.10

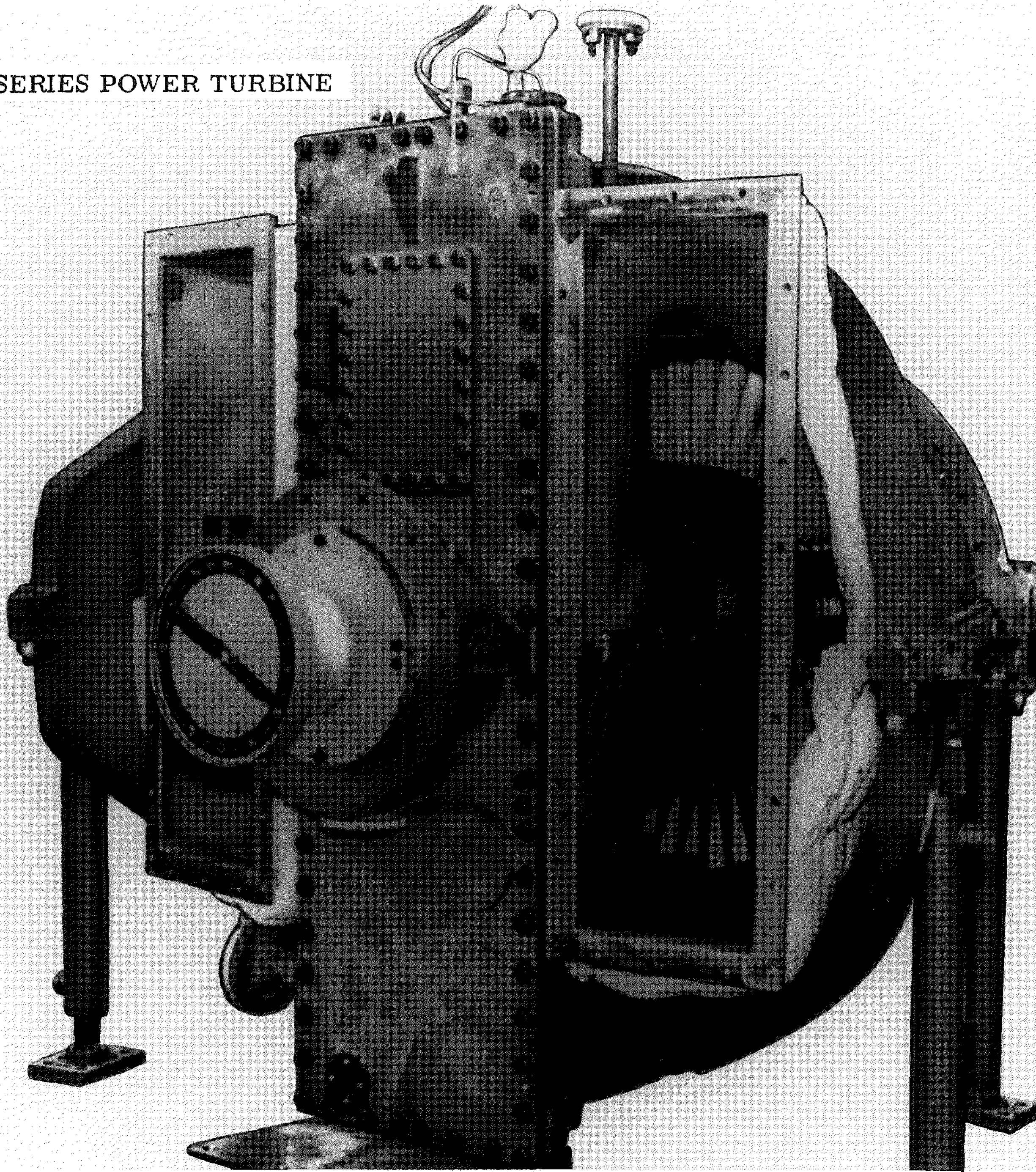
ALTERNATOR CHARACTERISTICS

Type	WGDGXY 800 EA4
For horizontal installation with	Brushless Excitation
Dimensions (Approximately)	
Length	161.4 in.
Height	70.9 in.
Width	70.9 in.
Rating	
Base Load @ p.f. 0.85	6000 KW
Peak Load @ p.f. 0.85	7000 KW
Voltage	13.8 KV, 60 c/s
Speed	1800 rpm
Insulation	Stator and Rotor Class F
Temperature rise @ 40°C amb temp and p.f. 0.85: @ Base Load 6000 KW:	
Stator	80°C
Rotor	80°C
According to NEMA Class B @ Peak Load 7000 KW 1000 h/year:	
Stator	105°C
Rotor	105°C
According to NEMA Class F	
Design efficiency with tolerance according to IEC Standards @ p.f. 1.0 and -	
5/4 Load	97.9%
4/4 Load	97.8%
3/4 Load	97.6%
2/4 Load	97.9%
Design efficiency with tolerances according to IEC Standards @ p.f. 0.85 and -	
5/4 Load	97.3%
4/4 Load	97.3%
3/4 Load	97.0%
2/4 Load	96.2%
Guaranteed efficiency without tolerances @ p.f. 1.0	
5/4 Load	97.7%
4/4 Load	97.6%
3/4 Load	97.4%
2/4 Load	96.6%
Guaranteed efficiency without tolerances @ p.f. 0.85	
5/4 Load	97.0%
4/4 Load	97.0%
3/4 Load	96.7%
2/4 Load	95.8%
Net Weight (Approximately)	30,429 lbs
Gross Weight (Approximately)	39,690 lbs

Figure 2.30 100%

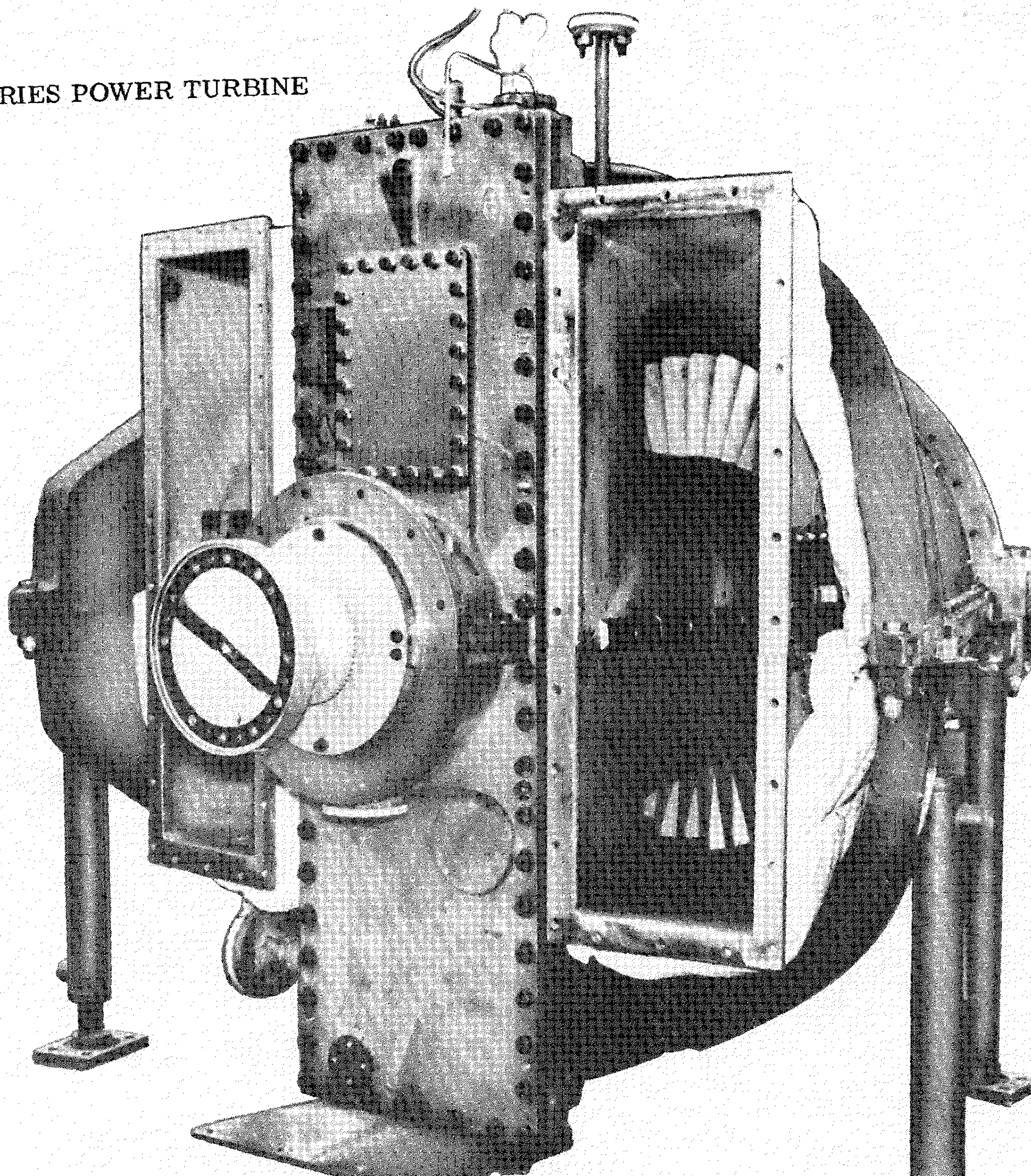
CW657 SERIES POWER TURBINE

CURTISS WRIGHT
POWER SYSTEMS



VIEW SHOWING OUTPUT SHAFT AND EXHAUST GAS OUTLETS

CW657 SERIES POWER TURBINE



VIEW SHOWING OUTPUT SHAFT AND EXHAUST GAS OUTLETS

V-1486

Figure 2.30

The reduction gear coupling, the turbine set and electric generator is a Falk Corporation Model 5145YOA horizontally offset gear manufactured to AGMA 421.06 standards. Speed reduction is accomplished with a pinion and main gear of herringbone tooth design (AGMA min. quality 12). The gears are mounted on four sleeve type journal bearings lubricated from the main oil supply system. Thrust pads are included on the low speed shaft to limit generator end float. End float is transmitted to a limiting coupling which allows sufficient lateral motion to align the generator magnetic center. Bearing thermocouples are monitored by the safety system to provide automatic shutdown in the event of excessive temperatures.

The gears are housed in a fabricated steel casing. The gear is rated at 10,000 hp which will accommodate the maximum peaking rating of the system. Performance characteristics are shown below:

Total Energy System Reduction Gear

Manufacturer	Falk Corporation, Milwaukee, Wisconsin
Model	5145YOA (Falk Drawing No. 508862)
Rating	10,000 hp
Service Factor	1.53
Gear Ratio	4.172
H.S. Shaft	7510 rpm
L.S. Shaft	1800 rpm
Heat Rejection	460,000 Btu/hr
Oil Flow	62 gpm

Turbine Module and Auxiliaries - The existing turbine module (Figure 2.31) which houses the gas generator and power turbine will be modified as follows:

a. Length will be increased to provide space for the turbine bleed manifold.

b. Roof and side walls will have holes to allow compressor discharge, turbine inlet and turbine bleed piping to pass through.

c. The base length will be increased for the longer assembly, and new mount provisions will be made for the gas generator bleed manifold and power turbine assembly.

d. The liquid and gas fuel systems will be removed from the module.

e. The gas generator lube oil and air start systems will be relocated to permit engine removal through the right wall. The generator lube oil system will be moved forward to retain the same relative position with respect to the engine.

The turbine module enclosure consists of the inlet plenum, gas turbine, generator, and lube oil cooler enclosures. A monorail with supporting structures is included for gas generator removal. A secondary air inlet and exhaust system with ventilation for turbine and generator compartments is included as well as access, plenum, and septum doors.

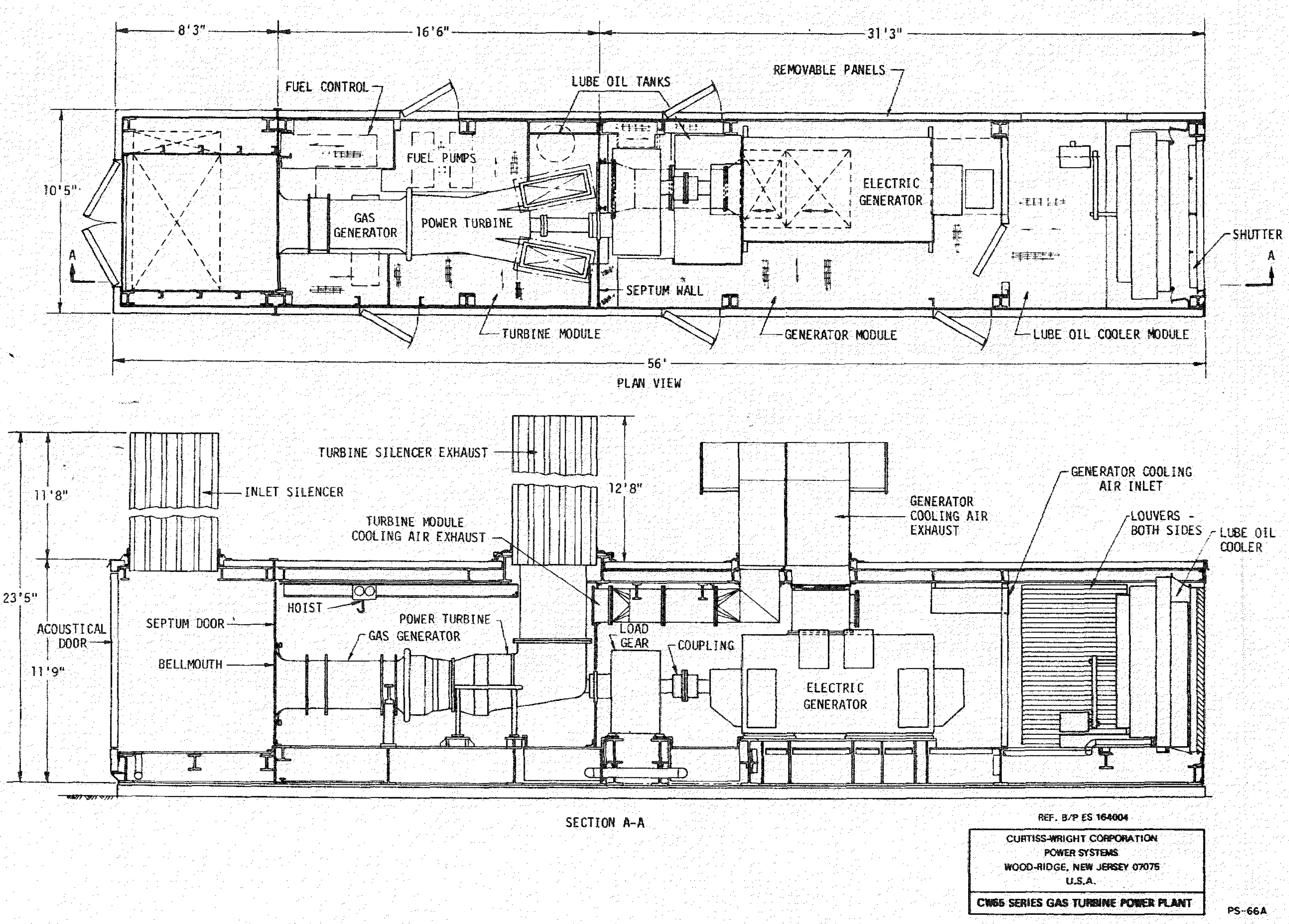

8'3"
16'6"
31'3"
FUEL CONTROL
LUBE OIL TANKS
REMOVABLE PANELS
FUEL PUMPS
10'5"
GAS GENERATOR
POWER TURBINE
ELECTRIC GENERATOR
SHUTTER
A
A
SEPTUM WALL
TURBINE MODULE
GENERATOR MODULE
LUBE OIL COOLER MODULE
56'
PLAN VIEW
TURBINE SILENCER EXHAUST
INLET SILENCER
11'8"
12'8"
GENERATOR COOLING AIR INLET
GENERATOR COOLING AIR EXHAUST
TURBINE MODULE COOLING AIR EXHAUST
LOUVERS - BOTH SIDES
LUBE OIL COOLER
23'5"
ACOUSTICAL DOOR
SEPTUM DOOR
HOIST
POWER TURBINE
GAS GENERATOR
LOAD GEAR
COUPLING
11'9"
BELLMOUTH
ELECTRIC GENERATOR
SECTION A-A
REF. B/P ES 164004
CURTISS-WRIGHT CORPORATION
POWER SYSTEMS
WOOD-RIDGE, NEW JERSEY 07075
U.S.A.
CW65 SERIES GAS TURBINE POWER PLANT
PS-66A

Figure 2.31

In order to attenuate the sound levels generated by the gas generator, power turbine and electric generator the power train is surrounded by an acoustic enclosure of four inch thick panels consisting of an outer solid shell and inner perforated sheet between which is packed dense fiberglass fill.

Inlet Silencing - A primary silencer services the gas generator inlet. This consists of parallel acoustic splitters installed in a rectangular steel shell. The acoustic structure consists of galvanized perforated face sheets packed with acoustical fill. A secondary air inlet silencer services the air entering the machinery enclosure. The silencer is attached to the top of the inlet plenum with provision for separation of flow between the primary and secondary systems. The acoustic structure is similar to the primary system although the density of acoustical fill is lower.

Gas generator starting is accomplished with a pneumatic starter operated in conjunction with the plant air supply system.

Two distinct lubricating systems provide an independent oil supply for both the gas generator and the power drive system comprising the power turbine, reduction gear, and electric generator.

a. Gas Generator Lubricating Oil System

Oil is drawn from the 40 gallon gas generator tank by the engine oil pump passing through a 40 mesh strainer at the pump inlet. The pump is modified to discharge high pressure oil into a 10 micron filter. The oil is returned from the filter to the pump where it is introduced into the engine. Oil is returned to the tank by means of pump and accessory gearbox scavenge gears. Pressure switches are included to protect the filter against excessive pressure losses from clogging and to protect the engine against loss of pressure.

b. Main Lubricating Oil System

The main lubricating oil system provides pressure lubrication to the power turbine, reduction gear, and electric generator. Two pancake type oil tanks mount in the skid base. The after tank, supplying the system has a 218 gallon operating capacity. The forward or return oil tank has an operating capacity of 268 gallons. The tanks are interconnected at the base by a cross-over tube. Each tank has a heating element to permit oil warming prior to start. The supply tank contains two electrically driven pumps, one a 460 volt three phase A.C. system and the other a 120 volt D.C. system. Pump redundancy has been included to permit operation under black start or other emergency conditions.

The lubricant is pumped from the supply tank to an aircooled, finned tube heat exchanger. Cooling is supplied by a six foot diameter fan. Some pertinent characteristics are summarized below:

Manufacturer.	.MRM Corporation, Massilon, Ohio
Model No.	9W-7L-1F6
Type.	Forced Draft, Single Bay
Oil Capacity.	46,920 pph
Heat Exchanger.	738,000 Btu/hr
Pressure Loss	13.5 psi
Oil Temperature	156°F
Oil Temperature Out	121.5°F

The entire system is protected by pressure and temperature switches and indicators, and a low level switch and alarm. Faults in the system either annunciate or subject the system to automatic shutdown.

2.4.3 PFB Combustor and Gas Turbine Interconnecting Piping

The main compressed air and hot gas field piping interconnects the PFB combustor vessel, primary and secondary cyclones and gas turbine. 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 the duct routing system is shown in Figures 2.32 and 2.33 and also on the plant arrangement drawings - Figures 2.7 and 2.8. Table 2.11 provides sizes and insulation liner configuration for the duct system.

The piping is divided into two categories, unlined piping that goes from the compressor discharge to the PFB and lined piping that goes from the PFB to the turbine. The unlined piping is 2-1/4 percent CR - 1 percent Mo steel and the lined piping is carbon steel. The unlined piping operates at 500°F except for the auxiliary combustor section that will be operating at 1100°F during the start-up cycle. All the unlined piping will be insulated on the outside to reduce heat loss to the ambient air.

The lined piping will have an internal liner operating at 1650°F (maximum) and an outside pipe temperature at 300°F (maximum) and 250°F (design nominal).

There are three lined pipe sizes, a 42 inch pipe with a 30 inch I.D. liner, a 28 inch pipe with an 18 inch I.D. liner and a 52 inch pipe with a 34 inch liner. The liner is .095 inch thick of AISI 310-S stainless steel and is wrapped in a 1 inch insulating blanket compressed to 1/2 inch thick. A slotted 30 degree cone is welded to the liner and the I.D. of the external pipe to provide the support for the liner. Wire anchors are welded to the pipe I.D. in a plane near each pipe joint. These anchors secure castable refractory material to the pipe. Castable refractory fills the space between the pipe I.D. and the Inswool on the liner. Slip joints in the liner are provided at each pipe joint to allow for thermal growth of the liner between sections.

The piping is made from standard pipe and fittings except for a few fabricated items.

Figures 2.32 and 2.33 also show the location of bellows expansion joints provided for the unlined piping. These joints are located to minimize the piping

PFB COMBUSTOR PIPING
TOP ELEVATION

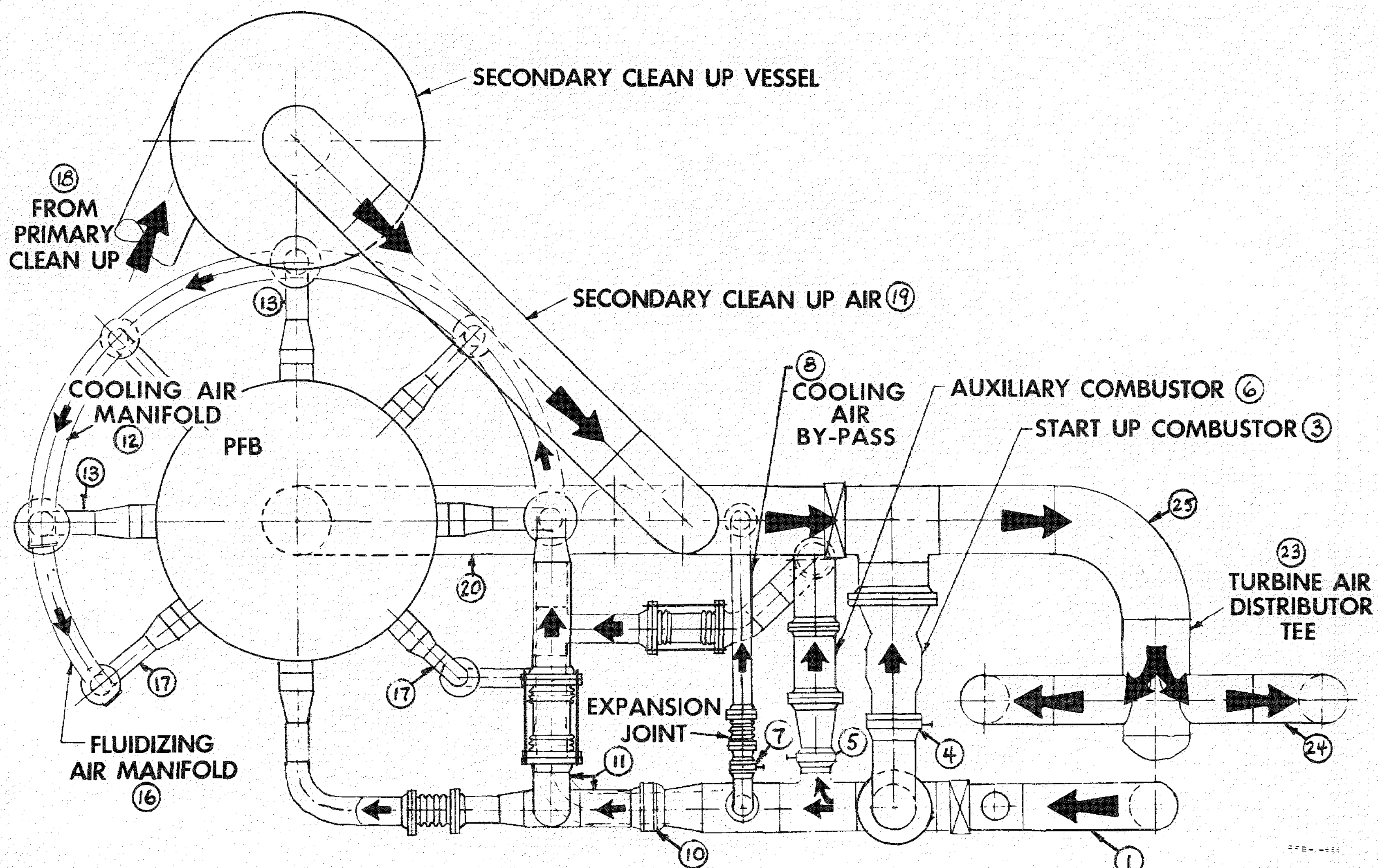


Figure 2.32

PFB COMBUSTOR PIPING

SIDE ELEVATION

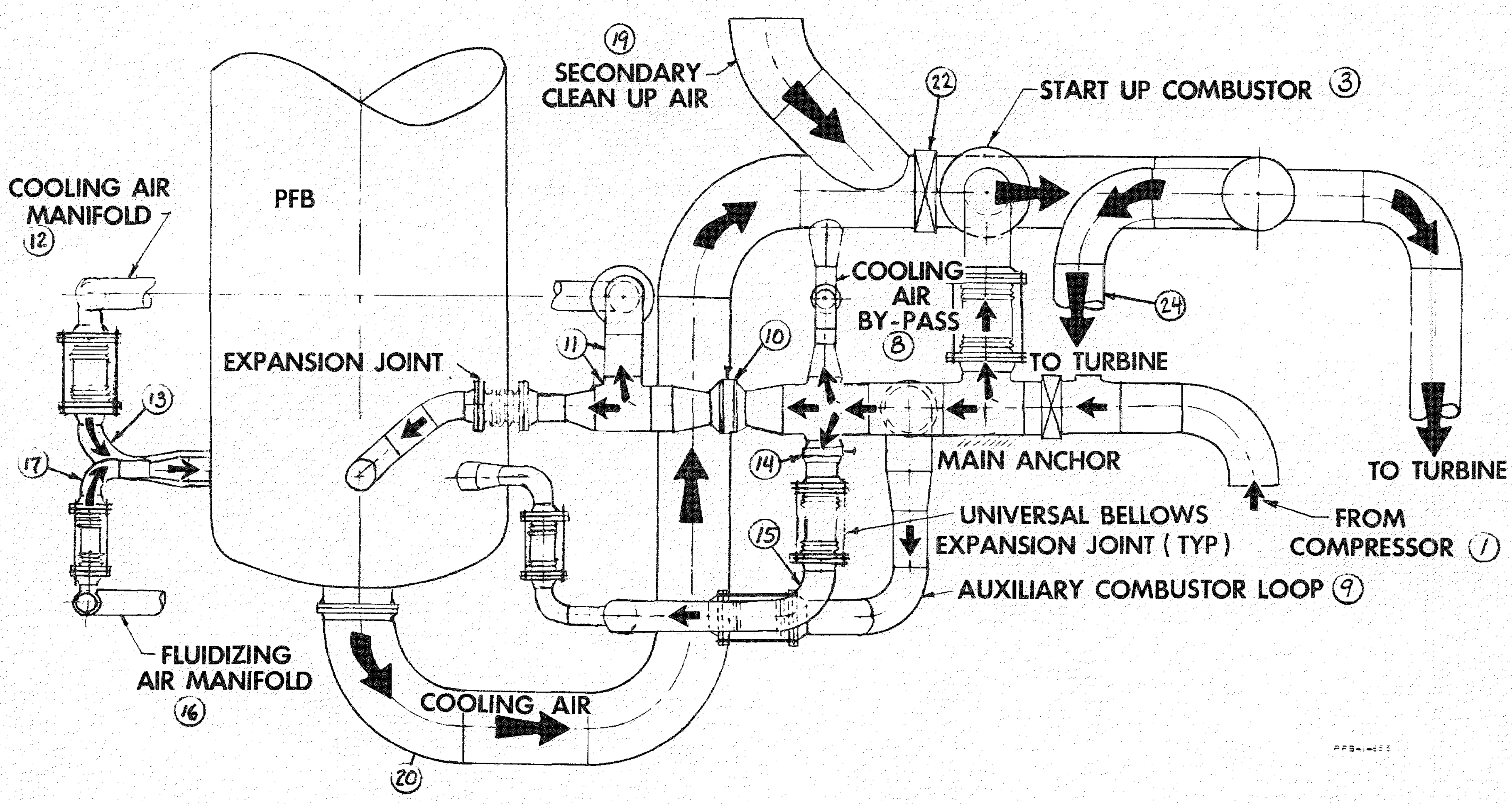


Figure 2.33

TABLE 2.11

PILOT PLANT AIR/GAS PIPING

Item*		Pipe Size	Liner Size
1	From Compressor	30 in. Standard Wall	None
2	Check Valve	30 in.	-
3	Start-up Combustor	-	-
4	Start-up Combustor Butterfly Valve	30 in.	-
5	Auxiliary Combustor Butterfly Valve	20 in.	-
6	Auxiliary Combustor	-	-
7	Cooling Air By-Pass Butterfly Valve	12 in.	-
8	Cooling Air By-Pass Loop	12 in. Standard Wall	None
9	Auxiliary Combustor Loop	20 in. Standard Wall	None
10	Cooling Air Butterfly Valve	24 in.	-
11	To Cooling Air Manifold	26 in. Standard Wall	None
12	Cooling Air Manifold	22 in. Standard Wall	None
13	Cooling Air Inlet to PFB	16 in. Standard Wall	None
14	Fluidizing Air Butterfly Valve	20 in.	-
15	To Fluidizing Air Manifold	20 in. Standard Wall	None
16	Fluidizing Air Manifold	16 in. Standard Wall	None
17	Fluidizing Air Inlet to PFB	12 in. Standard Wall	None
18	Primary Cyclone to Secondary Clean-up	52 in. Standard Wall	34 in. I.D.
19	Secondary Clean-up to Mixing Lateral	42 in. Standard Wall	30 in. I.D.
20	Cooling Air Outlet to Mixing Lateral	42 in. Standard Wall	30 in. I.D.
21	Mixing Lateral	42 in. Standard Wall	30 in. I.D.
22	Start-up Isolator Butterfly Valve	42 in. (Refractory Lined)	30 in. I.D.
23	Distributor Tee	42 in. Standard Wall	18 in. I.D.
		28 in. Standard Wall	18 in. I.D.
24	To Turbine	28 in. Standard Wall	18 in. I.D.
25	To Distributor Tee	42 in. Standard Wall	30 in. I.D.

*Refers to Figures 2.32 and 2.33

stresses due to thermal growth. The length of runs in the off-set of the lined piping are adequate so that the piping (seamless) will not be over stressed due to thermal growth.

A bypass loop (not shown) is provided for unloading the power turbine. At full power operation approximately 50 percent of the gas flow must be bypassed around the turbine to prevent an overspeed condition if the alternator trips out. The balance of the gas flow continues through the turbine into the waste heat duct. The bypass valves also operate during start-up and synchronization.

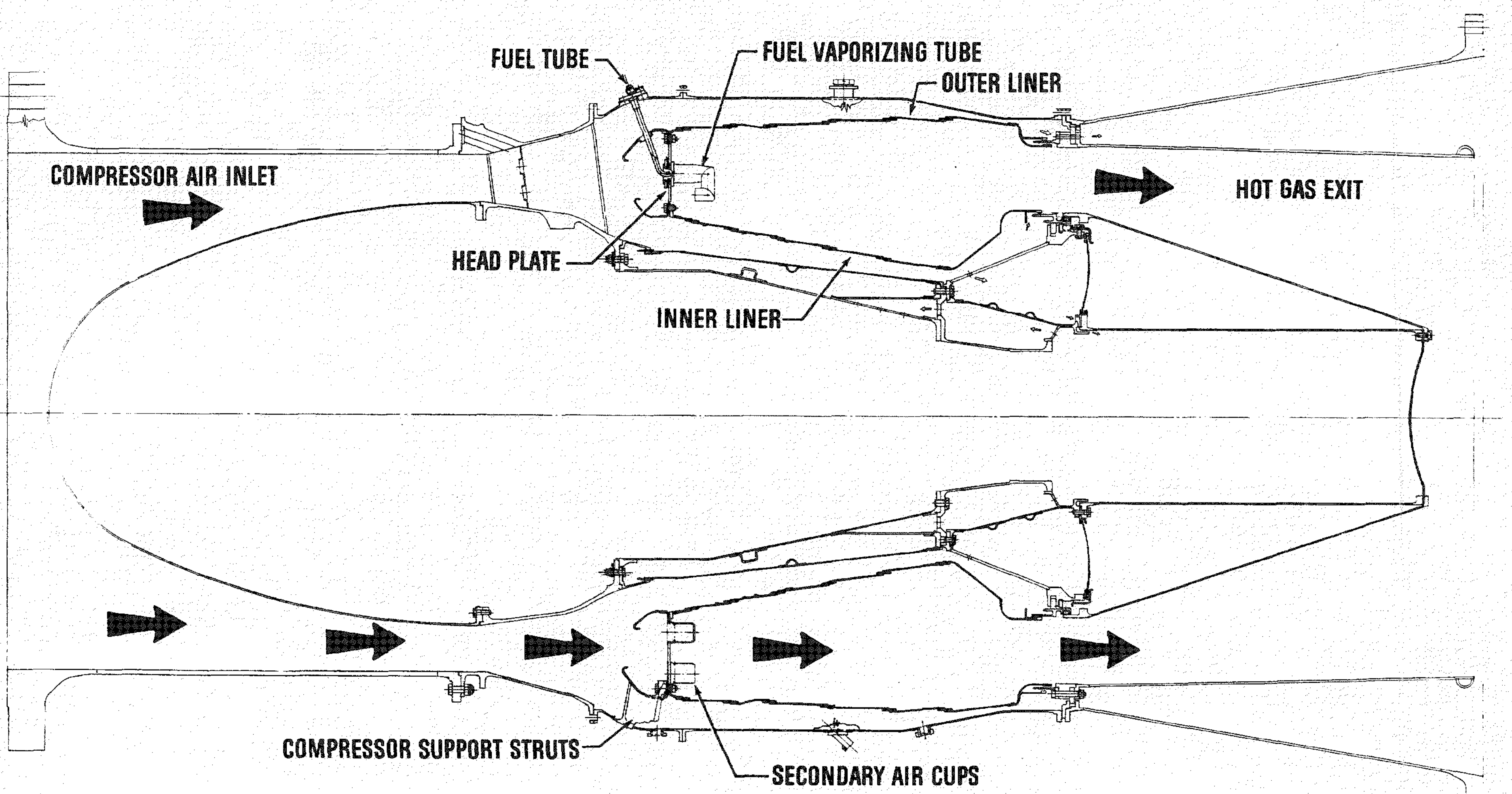
Gas Turbine Start-Up Combustor - The start-up combustor consists of standard CW 6518 gas generator components including center main bearing support, combustion chamber inlet housing, inner and outer air inlet scoops, combustion chamber housing, inner and outer liners, burner support plate with 36 primary air-fuel vaporizing tubes and secondary air cups and inner heat shield (shown in Figures 2.25 and 2.34).

In operation, the center main bearing support forms a diverging annular duct section to reduce air velocity and increase air static pressure entering the combustion chamber. Air enters the combustion chamber through the headplate and mixes with fuel entering the fuel vaporizing tubes. Combustion is initiated with a spark discharge and is sustained in the forward section of the combustor. Air not used for combustion is directed along the surfaces of the combustion chamber inner and outer liners to maintain temperatures compatible with the liner material. Further along the liner the air not used for combustion passes through holes in the liners to mix with the combustion gases, resulting in a reduction in hot gas temperature.

The stainless steel combustion chamber inlet housing accommodates the 36 internal fuel tubes, two pilot flame and igniter assemblies and a drain elbow which permits fuel to drain from the combustion chamber when the unit is not operating. The inlet housing incorporates the combustion chamber support fairing struts, and attaches to the center main bearing support at the front and the combustion chamber housing at the rear. The internal fuel tubes extend into the primary air-fuel tubes, while the pilot flame and igniter assemblies extend through fairings in the inlet housing to the front of the combustion chamber. The combustion chamber outer housing is a cylindrical exterior case which attaches to the combustion chamber inlet housing forward while the rear flange serves to secure the exit transition duct.

The combustion chamber inner and outer liners are assembled from a series of high temperature steel sections with corrugated stiffeners welded between them to provide liner cooling air distribution. Combustion takes place in the area between the outer cylindrical liner and the conical inner liner. Sections of both inner and outer liners also incorporate air holes for cooling and controlling the temperature pattern. The burner headplate support assembly is a plate attached to the front of the combustion chamber liners to form the front wall of the combustion chamber. The plate supports the 36 primary fuel-air tubes and 36 secondary air distributing cups, and the combustion chamber inlet air inner scoop. The combustion chamber inner heat shield is a conical steel shield which is also the support cone for the inner liner rear fish-mouth labyrinth seal.

PILOT PLANT
CW6515 START-UP COMBUSTOR



PFB-I-657

Figure 2.34

The inlet to the start-up combustor is a 30 inch diameter pipe that mounts on the forward outer flange of the center main bearing support housing, and an elliptical centerbody is mounted on the forward inner flange of the center main bearing support. The outlet of the combustor exits through a 1.9 area ratio annular diffuser into a 30 inch I.D. pipe. A 30 inch butterfly valve is mounted upstream of the start-up combustor to regulate the flow through the combustor. The start-up combustor is located in an enclosure with the auxiliary combustor and adjacent to the turbine module.

Auxiliary (Fluidizing Air) Combustor - During the start-up cycle an auxiliary heater is required to heat the fluidized bed to 1000°F prior to injecting fuel into the bed. An existing can type combustor was selected on the basis that it would provide the desired temperature atthe pressure and airflow required (Figure 2.35). The combustor is mounted within a 12.5 inch diameter pipe (2-1/4 percent CR - 1 percent Mo). The outlet flange of the combustor is attached by a fish-mouth seal to a flat support plate, and this support plate is sandwiched between two pipe flanges. The front end of the combustor is supported from the pipe with the same mounting arrangement used in the gas turbine engine from which the combustor is derived.

A 20 inch butterfly valve controls the airflow to the auxiliary combustor. A pipe reducer (20 inch by 12.5 inch) will form the transition between the exit of the butterfly control valve and the pipe encompassing the combustor rig.

2.4.4 Combustion Gas Particulate Removal

Primary Cyclone - The primary cyclone (Figure 2.36) 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. The cyclone is constructed with a refractory liner and steel shell.

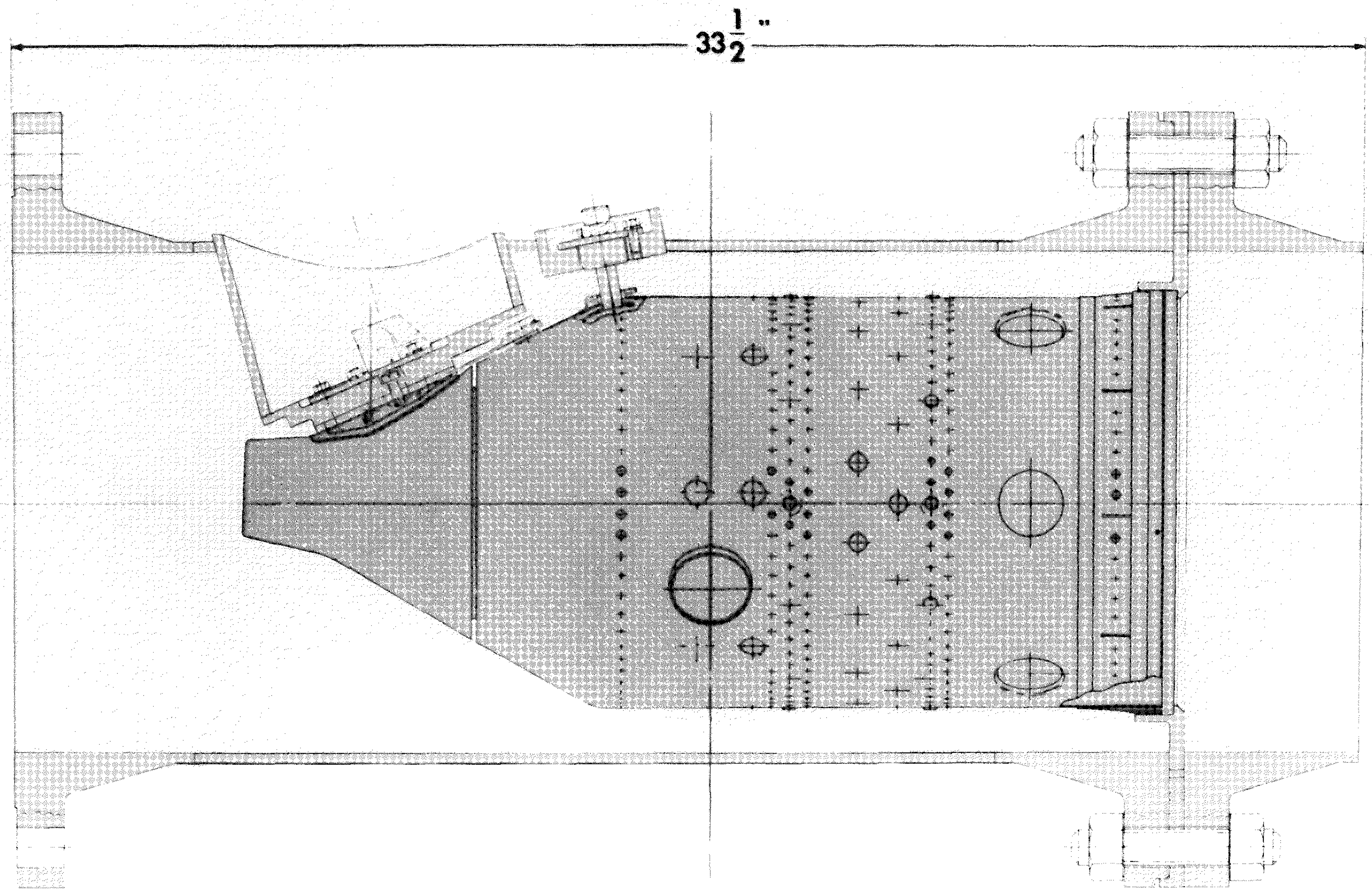
Designed in the manner closely following conventional cyclone design, the cyclone consists of a tangential inlet nozzle, the cone section attached to the upper barrel section and a removable vortex finder (or outlet tube). The cyclone is internally lined for both abrasion resistance and thermal insulation, each separate layer thus forming a composite lining. The vortex finder is readily removable, if necessary, through a flanged connection and is constructed of SS-316L.

The cyclone shell is designed, fabricated and tested according to ASME Code, Section VIII, Boiler and Pressure Vessel, at the design pressure of 105 psig and the design temperature of 250°F.

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.

Figure 2.53 8076

PILOT PLANT PFB AUXILIARY COMBUSTOR



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PILOT PLANT PFB

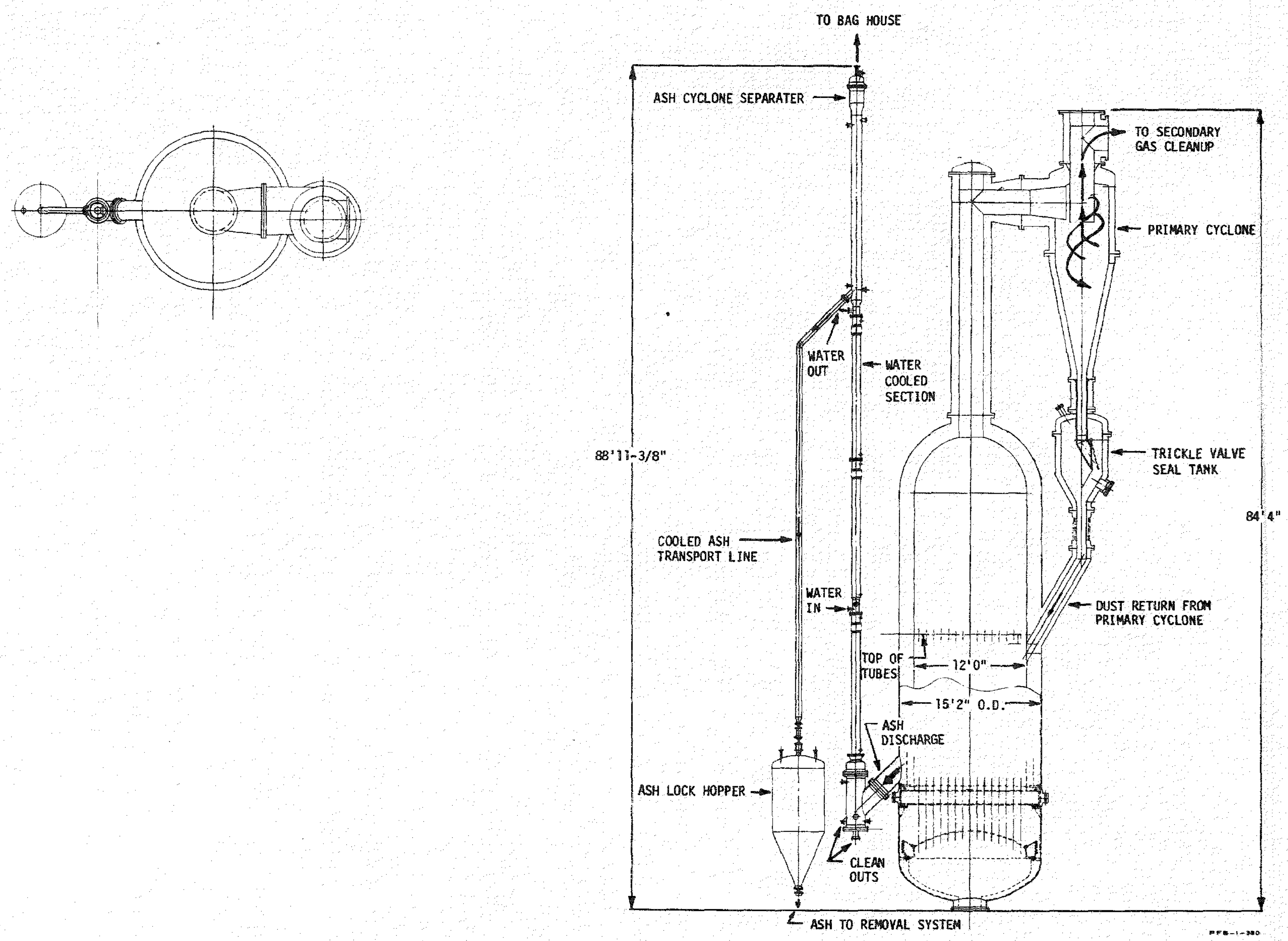

Figure 2.36

Trickle Discharge Valve - Particles collected in the cyclone are recirculated back to the reactor bed through a pipe connection. Due to pressure differential incurred between the reactor bed and the cyclone discharge, collected particles could be flushed back into the cyclone, instead of flowing down to the bed, unless a means is provided to prevent it. A trickle valve mechanism is adopted for this purpose.

Attached to the bottom of the cyclone discharge, the valve is normally closed. It remains closed until the static head of accumulated particles in the dipleg exceeds the pressure differential. The valve then swings open, discharging the particles, until the pressure differential exceeds the static head of the particles.

The valve is contained in the pressure seal tank to adapt to the high pressure operation. The seal tank is also designed, fabricated and tested according to ASME Code, Section VIII, Boiler and Pressure Vessel.

Secondary (Aerodyne) Cyclone - The secondary hot gas clean-up particulate separator will be used to remove particulate matter from the hot gas of pressurized fluidized bed combustor primary separator. The secondary separator will be arranged as shown in Figures 2.7 through 2.10.

The hot gases exiting the primary separator must be cleaned of particulate to a sufficient grain loading to minimize gas turbine blade erosion and to comply with emission standards. Inlet grain loading and particle size distribution were determined in laboratory tests conducted by Dorr-Oliver.

The secondary separator will be sized and designed so that under any operating condition that reasonably may exist, the outlet dust loading will not exceed .0368 grs/acf. The outlet dust loading is based on the weight of particulate matter per actual cubic foot of flue gases leaving the secondary separator. The pressure drop through the hot gas clean-up separator system at the design operating condition must not exceed 1 psi.

The operating design conditions for the secondary separator are as follows:

Flue gas flow to secondary separator @ 1640°F.	20,400 acfm
Static pressure at secondary separator inlet	94.2 psia
Secondary separator inlet grain loading.	0.0368 grs/acf
Particle density	90 ppcf

The secondary hot gas clean-up particulate separator and components thereof are designed, fabricated, tested, and stamped in accordance with Section VIII, Division 1, of the ASME Boiler and Pressure Vessel Code for Pressure Vessels.

Vendors were given the above design criteria. On this basis, a cyclone collector was specified having an efficiency of roughly 90 percent and providing an outlet loading of 0.0368 grs/acf.

The secondary separator is 13-1/2 ft O.D., 33-1/2 ft high, weighs approximately 202,000 lbs, and is refractory brick-lined. The supporting structure and foundation is designed so that an alternate separator might be substituted for testing, at which time structural modifications will have to be made.

The cyclone operates as follows: 20,400 acfm of flue gas is conveyed to the lower gas chamber past an orifice plate and a stationary turning vane which imparts a rotary motion to the gas. Centrifugal force directs the particulate toward the outer wall of the vessel where it is engaged by a secondary gas stream of 8100 acfm and is directed spirally downward. Particulate is collected in the base of the vessel and conveyed to a silo. The flue gas which is cleaned to 0.0368 gr/acf is combined with cooling air from the PFBC resulting in an overall grain loading of 0.0123 gr/acf entering the gas turbine.

2.4.5 Material Handling

Coal Handling System - Figure 2.37 shows the conceptual flow diagram of the PFB Pilot Plant coal handling system. Figures 2.7 through 2.10 show the arrangement of equipment.

A new car thawing and soaking shed is provided to house one thawing car and one soaking car, when required. The shed is 120 ft long by 20 ft wide by 25 ft high, including superstructure, siding, roof, and substructure. The shed is open-ended and long enough to encompass one car thawing and one car soaking. Propane gas operated infrared car thawers complete with supports, piping, and storage are provided. The cars then move over to an existing track hopper equipped with an existing car shaker. A new track hopper shed 55 ft by 20 ft by 28 ft high is provided over the hopper. The hopper discharges into an existing apron conveyor operating at a rate of 100 tons per hour (tph) which feeds coal into the existing bucket elevator.

The existing elevator discharges onto an existing drag chain conveyor over seventeen existing 100 ton capacity concrete coal bunkers. The bunkers provide 15 days of coal storage. New sheet metal covers are provided, as well as seventeen new air-operated gates located at the hoppered outlets.

The hoppers discharge onto a new 15 tph enclosed drag chain conveyor. This conveyor discharges onto a new 15 tph enclosed drag chain conveyor equipped with a two-way outlet which is provided for conveying coal from the existing boiler house to the coal storage bin system or to trucks for SGT unit and pilot plant reserve (15 day supply) coal pile. This new conveyor is supported by suitably spaced A-frames in the yard between the boiler house and coal feed system. One new 15 tph 8 by 5 bucket elevator, including 3 hp drive, hopper at grade, and discharge chute, is provided as an emergency backup system for filling the coal surge bin located ahead of the grinding mill.

The surge bin located ahead of the grinding mill is 10 ft diameter by 15 ft high and has a 1 hour storage capacity of approximately 10 tons. The surge bin is fabricated of A36 steel and includes a controlled shutoff gate. Coal is discharged from the coal surge bin through air lock vane feeders to the coal crushing mill and separator.

The coal grinding (roller mill) system has a capacity of 15 tph and is furnished with a mill having a 60 hp motor, a centrifugal fan having a 100 hp motor, a classification separator, cyclone separator, a fabric filter collector with exhaust blower having a 20 hp motor, a heater for heating gases used in the conveying air stream, and all necessary coal and air ducts. The mill

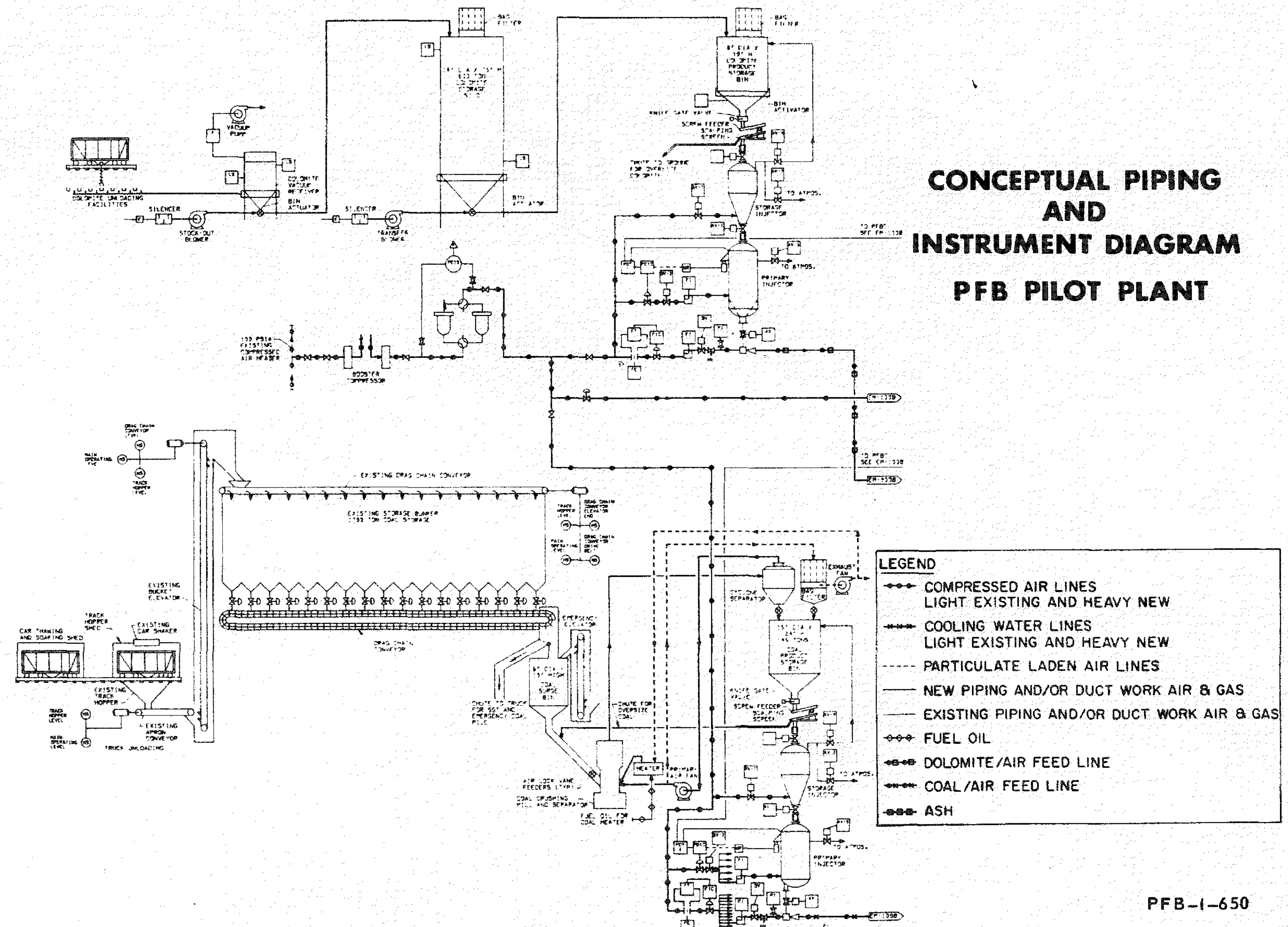
CONCEPTUAL PIPING AND INSTRUMENT DIAGRAM
PFB PILOT PLANT
LEGEND
COMPRESSED AIR LINES LIGHT EXISTING AND HEAVY NEW
COOLING WATER LINES LIGHT EXISTING AND HEAVY NEW
PARTICULATE LADEN AIR LINES
NEW PIPING AND/OR DUCT WORK AIR & GAS
EXISTING PIPING AND/OR DUCT WORK AIR & GAS
FUEL OIL
DOLOMITE/AIR FEED LINE
COAL/AIR FEED LINE
ASH
PFB-1-650

Figure 2.37

inlet and cyclone separator and bag filter outlets are all provided with feeders and valves. After being dried and crushed the coal is conveyed pneumatically to a storage bin. Coal and air are separated at the bin with the cyclone separator and fabric dust collector. The milled coal storage bin is located above the PFB coal feed injector system, is 15 ft diameter by 25 ft high, and includes a shutoff gate.

Coal from the milled product storage bin is transported to the feed control system by a screw feeder, with oversize product being screened and returned to the coal crushing mill and sized product being discharged to the coal feed system storage injector.

The coal injection system has a feed capacity of 12,500 pph and includes a coal weigh system, a storage injector, air and motor operated valves, injection rate control, air pressure control and transport piping to the combustor. Coal flows pneumatically through 12 feed lines from the injector vessel to the combustor. The combustor burns up to 5 tons of coal per hour.

Controls for both the mill system and the injection system are located locally and in the control room.

Dolomite Handling System - Figure 2.37 shows the conceptual flow diagram of the PFB Pilot Plant dolomite handling system.

On-site track work exists for unloading dolomite as well as coal. Dolomite of specified particle size distribution is removed from the railroad car hoppers through flexible hose connectors to a header at various locations along the car. Dolomite is then transferred to a vacuum receiver pneumatically by a vacuum pump at the receiver. A vibratory bin actuator transfers dolomite from the receiver through an air lock vane feeder where it is transferred pneumatically by a stock-out blower to the 600 ton, 18 ft diameter, 75 ft high storage silo (16 day supply). The dolomite car unloading to the storage silo is at a rate of 20 tph.

Dolomite dust is removed from the storage silo by a bag filter attached to the silo. A vibratory bin actuator transfers dolomite from the silo through an air lock vane feeder where it is transferred pneumatically by a transfer blower to the 18 ton capacity, 10 ft diameter by 15 ft high, product storage bin. The bin provides 12 hour storage. Dolomite dust is removed from the product storage bin by a bag filter attached to the storage bin.

Dolomite from the storage bin is transferred by a vibratory bin actuator to the feed control system by a screw feeder at 5 tph, with oversize product being screened and discharged to waste while sized product is discharged to the dolomite feed system storage injector. The dolomite injection system has a feed capacity of 6000 pph and includes a dolomite weigh system, a storage injector, air and motor operated valves, injection rate control, air pressure control and transport piping to the PFB combustor. Dolomite flow pneumatically through one or both of two feed lines from the storage injector vessel to the combustor.

Ash Handling System - The purpose of the ash handling system is to transport, cool and discharge the ash generated in the pressurized fluid bed combustor. The PFB ash discharge system comprises a cooling section, disengaging section, cyclone, pressure seal leg and ash bin and is shown in Figure 2.36. Figure 2.38 shows a conceptual flow diagram of the system.

The solids from the PFB reactor are discharged to a standpipe by means of a refractory lined, inclined pipe having an I.D. of 8 inches. The solids are lifted in the standpipe by fluidizing air entering at the bottom. The overall height of the standpipe is 80 feet. The standpipe has a 46 foot water-jacketed column. The water cooled section is designed to cool the solids to below 600°F.

Cooled solids are lifted further and fluidized to an expanded section in the next 20 feet of the standpipe. This section has a solids 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 foot section to provide sufficient pressure drop to the hopper to operate it as an atmospheric bin. The bin is placed on weigh cells for monitoring the discharge rates.

Contaminated fluidizing air is passed through an internal cyclone located at the top of the standpipe. The standpipe has another expanded 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 4600 pph of ash from the PFB combustor enter the cooler through the 8 inch I.D. pipe. Approximately 66 gpm of cooling water are supplied to the ash cooler from the plant mixed water loop. Two streams of compressed air at 100 psia are supplied to fluidize and cool the ash. The lower stream of 145 scfm and the upper stream of 300 scfm keep the ash flowing through the cooler. Ash from the cooler discharges into an 8 ft diameter x 16 ft straight-side height, 20 ton capacity, surge bin. The design of the ash handling system is based on 15 percent ash coal and 100 percent collection of spent dolomite.

Solid waste from the pressurized fluidized bed combustor and the secondary hot gas cleanup system is collected in the ash surge bin, and then conveyed to the existing storage silo located in the boiler house. The material is loaded from the silo into trucks and disposed of off site.

The solids are composed of fly ash, calcium sulfate, and a calcium and magnesium oxides. Based on a bulk density of 90 ppcf and a 60 percent plant capacity factor, approximately 6.24 acre-ft of this material will require disposal annually.

2.4.6 Steam System

Waste Heat Recovery Boiler - An unfired waste heat boiler (Figure 2.3) has been included in the total energy system to utilize recoverable heat from the gas turbine exhaust gases for the production of steam.

CONCEPTUAL PIPING AND INSTRUMENT DIAGRAM PFB PILOT PLANT

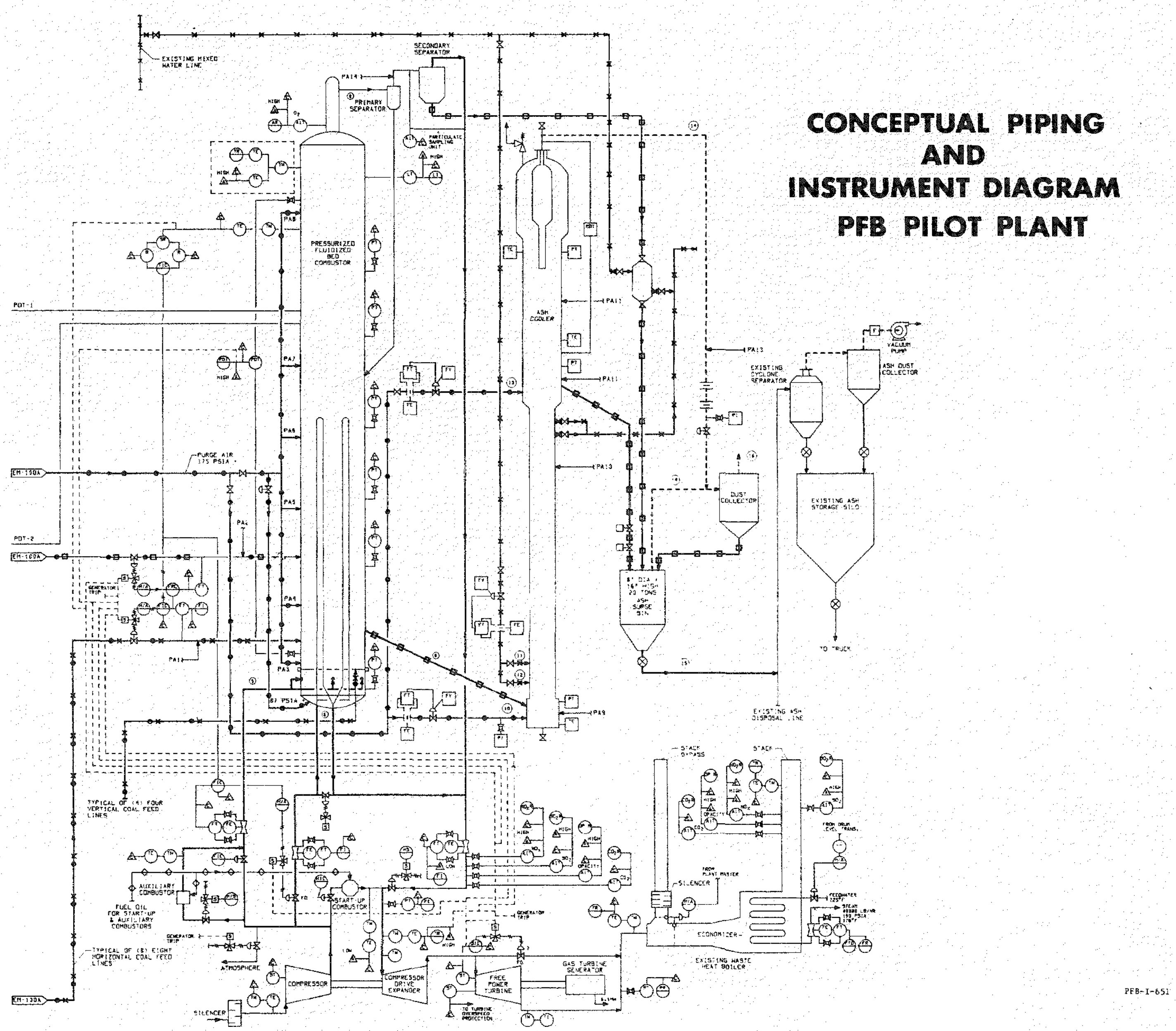

Figure 2.38

It is a drum-type, self-supporting, package boiler capable of generating approximately 50,000 pph of steam at 190 psia, 377°F. The conceptual flow diagram shown in Figure 2.38 shows the boiler. The package includes drum and header, economizer, bypass duct and stack, damper, and exhaust stack, inlet duct, ladders, platforms, insulation, lagging, 10 gage reinforced steel casing, and standard boiler trim including safety valves.

All component parts of the boiler were design, fabricated, tested, and inspected in accordance with the ASME Boiler Code, Section I, and the State of New Jersey Boiler Code. All tubes in the economizer coil are 2 inches (2-3/8 in. O.D.) schedule 40 pipe per ASTM Specification A-53 Grade B. Tubes in the steam coil are 3 inches (3-1/2 in. O.D.) schedule 40 pipe per ASTM Specification A-53 Grade B. All return bends are A-234 WPB material specification. All headers and cross-over piping is A-53 Grade B pipe of required schedule to meet the code requirements.

The tubes in the economizer and steam coils are finned with carbon steel fins welded to the prime tube. The fin thickness is 0.03 in. thick. The economizer coil and steam coil were designed to use steel fins, 1 inch high spaced eight per inch.

The internal tube supports are as follows:

a. Below 110°F - High Temperature Cast Iron
b. 1100°F - 2000°F - Cast 25-12 Chrome-Nickel Alloy

Only four or less rows of tubes are supported on each casting. End tube sheets are 1/4 inch minimum steel plate, protected by 4 inches of refractory lining using 10 BWG sleeves. All supports are attached to the main buckstays thus insuring that no load is transmitted to the skin.

The structural design is in accordance with the AISC Code. The main buckstays were designed to support the weight of the entire system, including coils, piping, steam drum, skin, refractory, and miscellaneous platforms and ladders.

The boiler skin is 11 gage steel with steel clips for refractory anchors. The skin was stitch welded to the buckstays on the outside.

Sufficient channels and angles were included to assure rigidity.

The entire structure and the loading diagrams were based on the following wind load:

Bottom.	30 ft	20 psf
Next.	20 ft	25 psf
Next.	50 ft	30 psf
Cylindrical shape factor.		0.60

A castable refractory good for 1800°F is used to insulate the shell of the boiler. It is securely anchored to the skin with clips and pneumatically applied. Thickness was selected to hold the skin temperature below 250°F. The following refractory thicknesses were used:

a. Boiler skin . . . . . . 4 in.
b. Stack (bypass). . . . . 2 in.
c. Header covers . . . . . 2 in.
d. Inlet duct. . . . . . . 2 in.
e. Exhaust stack . . . . . . None

A 4 ft diameter by 12 ft seamless steam drum with internal separators was designed for 200 psig and 390°F. This vessel is code stamped.

The exhaust gas stack is mounted on top of the boiler and is fabricated of 3/16 in. steel plate. The bypass stack is 6 ft O.D. and constructed of 3/16 in. steel plate with 2 in. of refractory lining. The inlet diffuser is of 3/16 in. Corten material with external insulation. The remaining duct is of carbon steel material 3/16 in. thick with 4 in. of internal refractory lining. All ducts were fabricated to permit bolting in the field. Two louver type dampers are provided to bypass the gas turbine exhaust. The frames are of carbon steel with Corten blades and shafts. Each are provided with air operators.

2.5 Plant Operation and Control

The control of the pilot plant will be based on commercial plant control concepts and will include utility level components throughout. The adaptation of the existing "Total Energy" gas turbine driven generator to the coal burning PFB configuration permits use of the existing, proven generator protection and control components as well as the basic gas turbine start sequencer. These systems are proven utility type components with 20,000 hours of base load service experience. These systems will be integrated into a plant coordinated system.

The plant control system will utilize a commercial process control computer which will provide plant reporting and data logging functions as well as the loading, sequencing and alarm/monitoring requirements. This control will interface with and optimize the operation of the many subsystems in the same manner as a full scale commercial plant will function.

The coordinated plant control will integrate the unit systems so that a megawatt demand set point will automatically establish PFB firing and gas turbine loading. The energy input response will be coordinated with other systems response characteristics to maximize performance consistent with component durability requirements. The subsystems to be integrated are:

a. Coal drying and grinding
b. Dolomite preparation
c. Coal injection system
d. Dolomite injection system
e. Bed level control
f. Bed temperature control
g. Gas turbine governor
h. Electric generator synchronizer and protection system
i. Ash removal system
j. Waste heat boiler control
k. Particulate on-line monitor
l. Gas analysis on-line monitor - SO_2, NO_x, O_2, CO, CO_2
m. Safety systems
n. Particulate-stack monitor

Since the steam generated in the waste heat boiler is used for process and heating rather than driving a steam turbine, there is a less complex control loop, however, boiler level (2 mode) and pressure are maintained. Overall plant performance will be continuously calculated and periodically reported automatically along with other routine plant data.

The digital process computer will provide supervisory (set point) control of the analog control loops to optimize individual loops as a function of plant load, etc. It will also monitor, log and alarm the various plant parameters. It will also provide supervisory sequence control of the distributive sequencer control station.

Sufficient instrumentation will be provided to permit safe operation of the plant when the computer system is out of service. The operation of these devices will be from the main panel or local stations depending on their degree of importance.

2.5.1 Control Systems Description

Equipment selected for control of the pilot plant consists of "state-of-the-art" process control electronic devices including analog and digital components, sequencers, relaying, operator panels (manual and auto control) and data reporting printout devices. A central digital computer will have supervisory capability for coordinating and directing various subsystems. This process control is the heart of the total instrument and control system for the pilot plant. However, the system is designed to permit plant operation with local/manual control whenever the computer is off-line for any reason.

The major control subsystems will operate, sequence, protect and alarm the following:

a. Coal preparation
b. Coal and dolomite injection
c. Ash lock hopper sequencing
d. Gas turbine control
e. Electric generator protection
f. PFB combustor control.

These systems will interface with the process computer and will be directed by it in response to overall system requirements. The various subsystems will repeat all pertinent information back to the computer for performance evaluation, data accumulation, reporting, alarming, etc. The operator in the main control room will have full reporting and process status information available at all times via TV type display, hard copy printout, process graphics display, plus the traditional annunciator display.

System flexibility is inherent in the computer supervised system since logic changes can be incorporated by simple software statement revisions without having to shut down. It is anticipated that this feature will expedite the initial start-up phase since the coordination and control of the combustors, air valves, feed systems, ash systems etc will require modification as experience in operation is obtained.

2.5.2 Control Method

Figure 2.39 is a schematic presentation of the gas turbine, PFB, power turbine and alternator configuration showing the piping and valving interconnections. The method of control of the facility as described herein refers to this diagram to show the various relationships:

a. Gas Turbine - The start-up of the gas turbine will be accomplished with the start combustor and utilizing a commercial fuel governing system manufactured by the Woodward Governor Company. This will be a conventional speed governor with overspeed and overtemperature

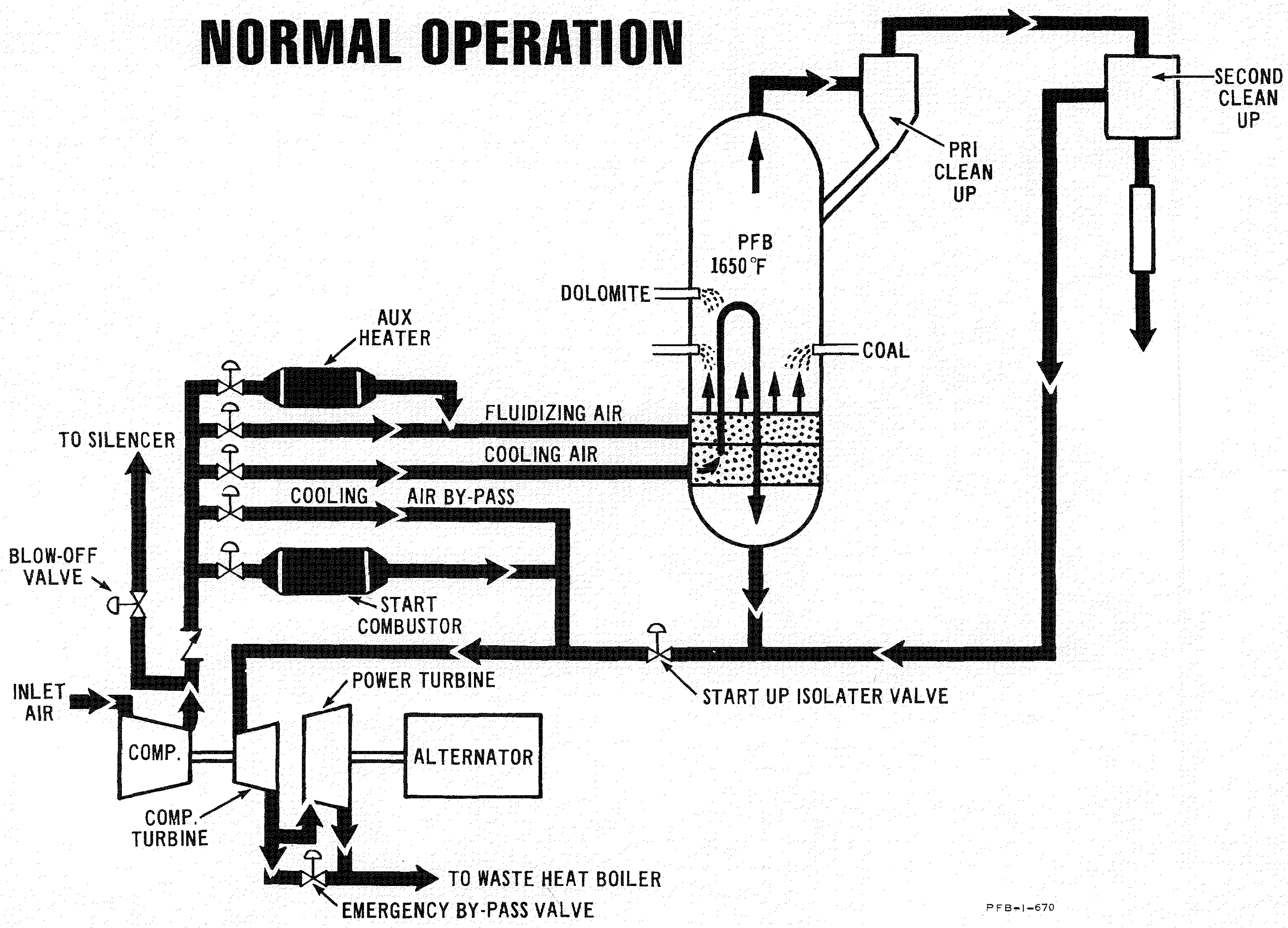
NORMAL OPERATION
SECOND CLEAN UP
PRI CLEAN UP
PFB 1650°F
DOLOMITE
COAL
AUX HEATER
FLUIDIZING AIR
COOLING AIR
COOLING AIR BY-PASS
TO SILENCER
BLOW-OFF VALVE
START COMBUSTOR
INLET AIR
POWER TURBINE
START UP ISOLATER VALVE
COMP.
ALTERNATOR
COMP. TURBINE
TO WASTE HEAT BOILER
EMERGENCY BY-PASS VALVE
PFB-I-670

Figure 2.39

protection. Valves 2 thru 5 and 7 will be closed during this phase of the starting sequence. Valve No. 6 is open. The gas turbine and power turbine sequencing will be accomplished with a Struthers-Dunn solid state programmable sequencer.

b. PFB Pressurizing - With the gas turbine at a stabilized idle, valve 5 will be opened slightly to gradually pressurize the PFB vessel. When the pressure is equalized across valve 10, it is fully opened.

c. PFB Fluidizing - Valve 5 is opened with flow control to establish minimum fluidizing air velocity. The engine governor maintains turbine speed by adjusting fuel flow to the start combustor within allowable temperature limits. The auxiliary heater is ignited and brought to its programmed temperature schedule. As the total system heats up the start combustor fuel flow will automatically cut back to compensate for the heat from the fluidizing air loop. To minimize heat stress, some heated air will be bled into the cooling air inlet chamber.

d. PFB Light-Off - At 900°F liquid fuel is injected into the bed. Additional fluidizing air is provided via valve 4. The start combustor fuel flow continues to reduce. At 1200°F bed temperature, coal is injected (along with dolomite) and bed temperature is raised to 1650°F. The start combustor fuel is turned off and valve 1 is closed at the same time valve 2 is opened. Fluidizing air flow is maintained by modulating valve 2. During this sequence, valve 6 has been kept open to bypass the power turbine. The waste heat boiler has been converting this heat to steam.

e. Synchronizing - The generator is sequenced to come on line and valve 6 is modulated by a speed control loop to bring the generator to synchronous speed. The Bessler synchronizer is controlling the valve to electrically synchronize the generator to the utility bus - the breaker closes and the valve 6 loop is directed to close valve 6. The unit is on line generating power.

f. Loading - The electrical demand setting causes an increase in coal flow. As the bed temperature tries to expand the 1650°F set point, valve 3 is opened and valve 2 is closed as necessary to maintain bed temperature as well as fluidizing air velocity. At the power set point all systems remain stable. At this condition valves 4, 5 and 10 are full open: valve 1 and 7 are closed and valves 2 and 3 are modulating to maintain bed temperature and fluidizing air velocity.

g. Normal Shutdown - Reduce coal flow. Power output will drop to zero at which time the breaker opens. The generator is off line. With zero coal flow, the system will slow down. Valves will all be closed.

h. Emergency Trip - In case of a severe emergency, such as a breaker trip, valve 6 opens full, valve 7 will open full. Check valve 8 will prevent any reverse air flow from the PFB while valve 7 prevents the compressor from going into surge. Fuel flow is also stopped. This emergency action is required to prevent the generator and gas turbine from overspeeding.

Section 3.0

MAINTENANCE OF THE PFB

The vessel for the PFB consists of an upper and lower shell joined together by a bolted flange. The support for the vessel is attached to the upper shell which allows the lower shell to be lowered thus exposing the heat exchanger and vessel liner for repair. In addition, the upper vessel has four 30 inch manways for access to the interior. Two are located in the spherical head and two in the cylindrical portion located above the top of the heat exchanger tubes. Two 36 inch manways are located in the lower shell for access into the heat exchanger plenum.

Listed below are the major elements of the PFB which probably will require maintenance:

a. Heat Exchanger Tubes
b. Tuyeres
c. Upper Vessel Liner
d. Distributor Plate Insulation
e. Coal Supply Guns
f. Windbox and Lower Section

The following are the intended procedures for maintaining these elements:

a. Heat Exchanger Tubes - The heat exchanger tubes may be removed individually from the PFB with a specially designed hoisting rig. Any tube at any location may be removed without disturbing adjacent tubes. When it is determined that a tube or tubes must be replaced, the PFB is shut down and the tubes to be removed are located. When a major portion of the tubes must be replaced the lower vessel may be lowered exposing the tubes. However, if only a few tubes need replacing this may be accomplished by using the manways in the upper and lower vessel. From the upper vessel the ash, coal and dolomite will be removed from the area surrounding the tubes to be removed. The upper circular tube support rings are removed by grinding off the tack welds on the retaining pins, removing the pins and lifting off the support rings.

   A shackle is attached to the tube trunnion. In the lower vessel heat exchanger plenum the two circular structural seal welds of the concentric support assembly are cut off. This allows the concentric support assembly and the insulation surrounding the inner heat exchanger tube to be removed. This provides access to the outer heat exchanger support. A special power driven cutting tool is installed around the inner insulated tube. The outer tube adapter is cut just above the area where the outer tube is sealed to the windbox. With a cable attached to the top shackle the tube may now be lifted up and out of the PFB.

Figure 3.1 shows a sketch of a hydraulic tube puller that Dresser Industries is proposing for removing the remaining outer tube adapter stub. The tapered tube pulling spear is threaded into the tube stub. The adapter is attached to the hydraulic cylinder that provides the pulling force. The reaction force is taken through the ram chair cylinder into the windbox lower plate.

b. Tuyeres - In order to replace tuyeres heat exchanger tubes must be removed to provide access to any interior tuyeres that need replacing. The ash, coal and dolomite should be removed from the surface of the heat exchanger and distributor assembly especially in the areas where tubes and tuyeres are to be removed. After cleaning, that portion on the upper end of the socket that is formed into a wrenching slot in the Gland nut, is removed by grinding or cutting. Pins in the special Gland nut wrench engage the two slots and the Gland nut is removed. A shackle is attached to the lug on top of the tuyere and a cable hoist pulls the tuyere out of the conical seat. After cleaning the internal area of the socket a new tuyere may be inserted and the Gland nut torqued tight. Note that the Acme threads are coated with the graphite-red lead lubricant before assembling. After the Gland nut is torqued the upper end of the socket is formed into one of the wrenching slots on the Gland nut to lock the Gland nut.

c. Upper Vessel Liner - In order to repair damaged bricks or castables of the upper vessel liner, the lower vessel is lowered until the tops of the heat exchanger tubes clear the area of the liner to be repaired. Through the upper manways, pie shaped sectional supports are assembled and joined together. These supports rest on the top of the tube trunnions to provide a working platform. From here the damaged bricks and castables may be replaced or repaired following standard manufacture procedures.

d. Distributor Plate Insulation - In order to repair the castables covering the distributor plate of the windbox, the lower vessel must be lowered to expose the windbox. If necessary, heat exchanger tubes must be removed to provide access to the damaged area. The castables in this area are removed from the top plate of the windbox. The outer edges of the repair area are undercut to lock the repair castables into the surrounding castables.

e. Coal Supply Guns - The coal supply guns may be removed occasionally for replacement or to clear coal jams. These coal guns may be removed while the PFB is operating. The following are the steps required to remove a coal gun:

1. Close the 3/4 in. coal supply ball valve.

2. Disconnect the 1/2 in. pipe supplying the coal and remove so that the gun may be removed.

3. Remove the locking yolk from the retaining assembly. This will allow the coal gun inner pipe to be withdrawn.

HYDRAULIC TUBE PULLER

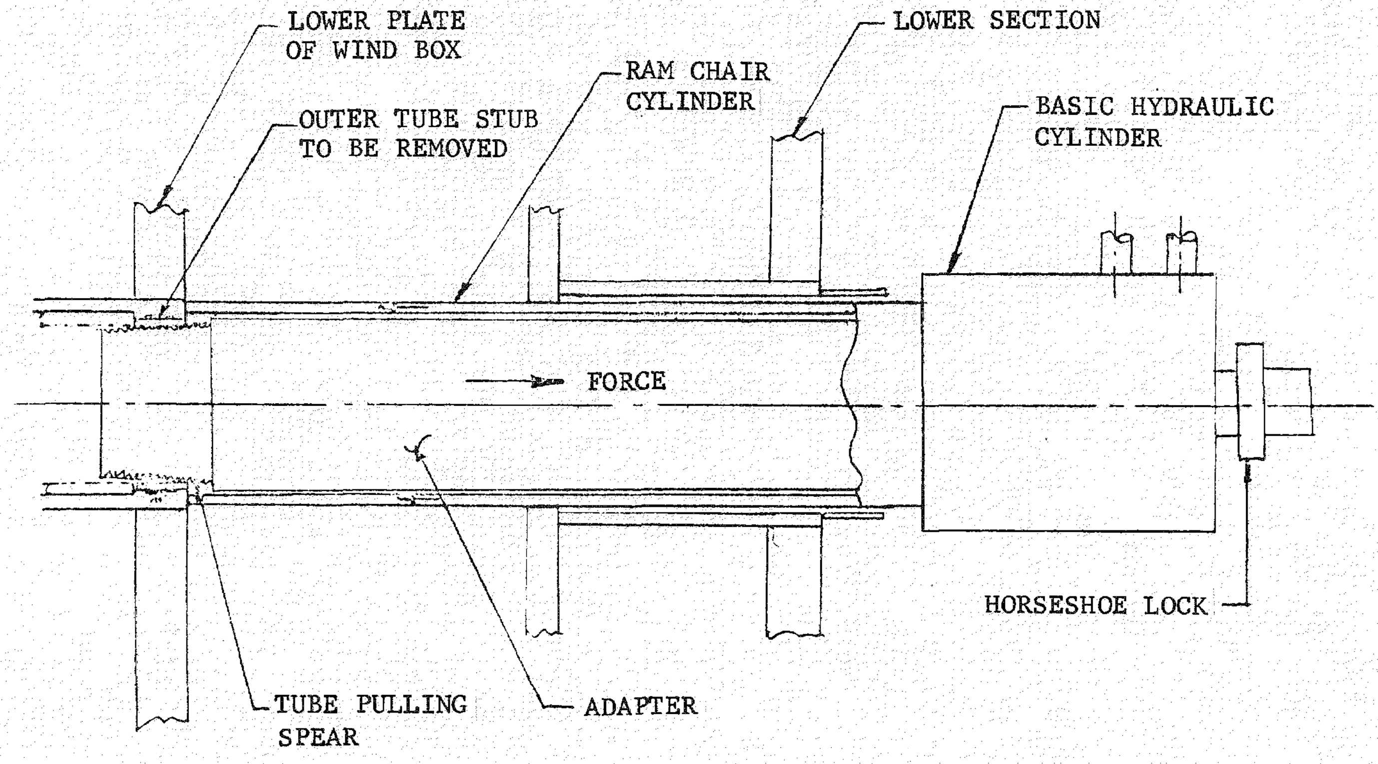

Figure 3.1

4. Withdraw the 3/4 in. inner pipe until the upper end passes the 2 in. ball valve.

5. With the end of the 3/4 in. inner pipe within the stuffing box, close the 2 in. ball valve.

6. With the 2 in. ball valve closed the 3/4 in. inner pipe may then be completely withdrawn from the stuffing box.

7. A ram rod may now be used to clear a coal jam or the pipe may be replaced.

A reverse procedure is used for reinstalling the coal feed gun.

The auxiliary oil gun assembly and the sorbent feed gun assembly may be removed in a similar manner.

f. Windbox and Lower Section - Four clean-out ports have been provided in the lower plate of the lower section. Access to these clean-out ports is through the manways in the lower shell. After removing the insulation cover from these ports the 2 in. 150 lb flanges are removed to provide access for vacuuming out ash that may accumulate on the bottom plate due to sifting down from the tuyeres.