CW-WR-76-015.13

FE-1726-11
Distribution Category UC-90e

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

PHASE I - PRELIMINARY ENGINEERING

QUARTERLY REPORT FOR THE

PERIOD JUNE 1 to AUGUST 31, 1976

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

September 15, 1976

Prepared for
Energy Research and Development Administration

Under Contract No. E(49-18)-1726

TABLE OF CONTENT

I. OBJECTIVE AND SCOPE OF WORK

Production of clean, cost-competitive electric power from coal requires advances in combustion and power conversion technology. One promising approach to improved power cycle efficinecy involves application of a Pressurized Fluidized-Bed (PFB) Combustor for combustion of high sulfur coal in the presence of a of a sulfur sorbent material. Bed temperature is controlled to maintain the bed temperature 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 substantially to bed gas temperature and mixes with the products of combustion after they are cleaned of particulates but prior to entering a 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, would supply energy to a gas turbine-generation unit, and a waste heat boiler at the exit of the gas turbine system would supply steam for a steam turbine-generator unit. A simplified flow diagram for the air-cooled PFB combined cycle system is shown in Figure 1.

The objective of this program is to evaluate the commercial potential of a power generating concept that includes the pressurized, fluidized-bed combustion of coal in conjunction with a combined gas-steam turbine cycle. The capability to burn high-sulfur coal in an environmentally acceptable manner is a major objective of the program. The program involves conceptual commercial design, supporting experimental work, and the design, construction and operation of a PFB pilot plant that 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 Staiton. Where applicable, existing systems and equipment for materials receiving, laboratories and facilities will be used for the pilot plant program.

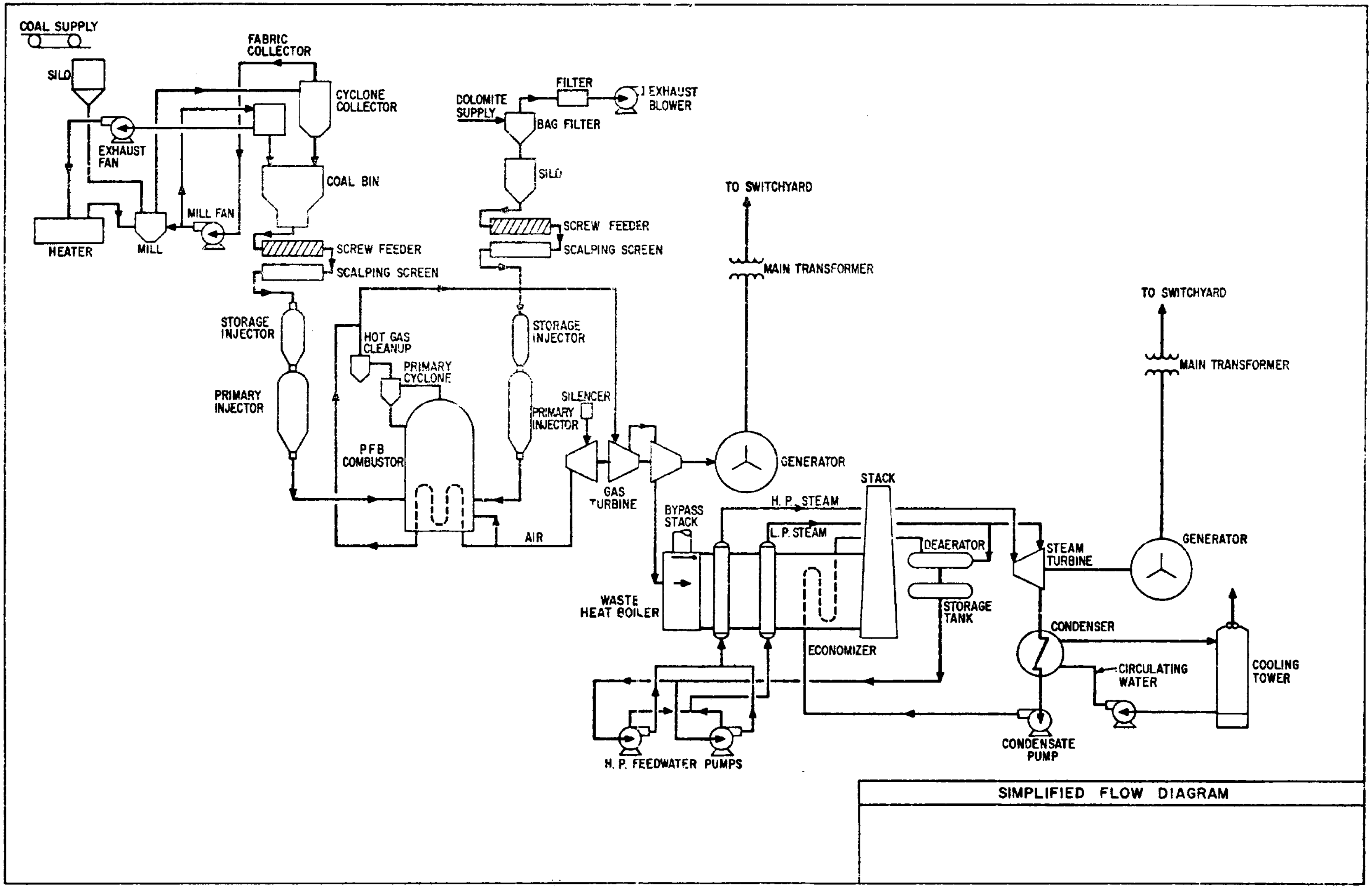

COAL SUPPLY
SILO
FABRIC COLLECTOR
CYCLONE COLLECTOR
EXHAUST FAN
COAL BIN
MILL FAN
HEATER
MILL
SCREW FEEDER
SCALPING SCREEN
STORAGE INJECTOR
PRIMARY INJECTOR
HOT GAS CLEANUP
PRIMARY CYCLONE
PFB COMBUSTOR
AIR
DOLOMITE SUPPLY
FILTER
EXHAUST BLOWER
BAG FILTER
SILO
SCREW FEEDER
SCALPING SCREEN
STORAGE INJECTOR
PRIMARY INJECTOR
SILENCER
GAS TURBINE
TO SWITCHYARD
MAIN TRANSFORMER
GENERATOR
STACK
H. P. STEAM
L. P. STEAM
BYPASS STACK
WASTE HEAT BOILER
DEAERATOR
STORAGE TANK
ECONOMIZER
H. P. FEEDWATER PUMPS
TO SWITCHYARD
MAIN TRANSFORMER
STEAM TURBINE
GENERATOR
CONDENSER
CIRCULATING WATER
COOLING TOWER
CONDENSATE PUMP
SIMPLIFIED FLOW DIAGRAM

Figure 1

The major tasks of this program are summarized as follows:

a. A conceptual design for a central station power plant consisting of a PFB combustor with a combined cycle power conversion system will be conducted.

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

c. The PFB pilot plant suitable for evaluation of the economic and engineering feasibility of the central station power plant concept will be designed and constructed.

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

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

II. SUMMARY

Phase I, Preliminary Engineering, Contract E(49-18)-1726, was initiated on March 1, 1976 and program accomplishments during the second quarter, June 1st through August 31st are summarized in the following:

The conceptual design of the commercial electric power generation plant using the PFB combustion process continued for the 300 - 500 MW central station. It includes three 100 MW gas turbine double-ender modules, and one steam turbine (470 MW total). Off-design performance analysis for the gas turbine and overall power plant has been completed for 20 to 100% gas turbine power and a range of ambient temperatures. Transient performance analyses including startup, load dump, etc. are continuing. Major component and equipment design is in progress. Gas turbine power train and auxiliary module, pressure fluid bed combustor and heat exchanger design and steam loop definition are nearing completion. Determination of coal and dolomite handling equipment, gas clean-up and overall plant arrangement are also nearing completion. Preliminary flow diagrams and the electrical one-line diagram have been completed. Work is continuing on the commercial plant environmental engineering and the plant capital and operating cost estimates.

The PFB pilot plant conceptual design was initiated and performance analyses of the gas turbine over a range of operating conditions was prepared. Pilot plant site evaluation continued and reports and analyses were prepared on real estate description, topographic analysis, soil boring sampling and analysis, and meteorologic and climatologic analyses. Work continued on the site master plan, resources and transportation studies, noise evalaution and the geotechnical analysis.

Technology support evaluation has continued in several major areas. Development of a brazing technique for fabricating PFB heat exchanger finned tubes is proceeding. Ultrasonic inspection methods for confirming fin attachment to the tubes have been developed. The design of the heat exchanger test module which will be performance tested in the NRDC test facility was completed. The initial heat exchanger tube specimens for testing in the existing Dorr-Oliver 12" atmospheric fluidized bed combustor have been manufactured and installed in the rig. Testing was initiated and will continue throughout the next quarter.

Heat exchanger tube specimens for long-term tests in Dorr-Oliver client existing commercial fluidized bed reactors were released to manufacturing. These specimens will be completed during the next quarter and will be installed at the earliest opportunity which occurs during the normal operating routine of these commercial reactors.

Testing of candidate materials for turbine blading and PFB heat exchanger tubes in existing laboratory test rigs to evaluate relative long term erosion/corrosion properties in a simulated environment was initiated.

Design of the Small Gas Turbine/Pressure Fluid Bed (SGT/PFB) operating parameters rig continued. Design and specifications of the components representing the longest manufacturing time cycle were completed. This included the PFB combustor, heat exchanger, 1st stage gas clean-up, and material storage, handling and injection equipment. Procurement of several long lead items including the PFB combustor, and material handling equipment has been initiated. Design and instrumentation definition of the remaining rig components is continuing.

Requests for approval of the subcontracts for Dorr-Oliver, Stone & Webster Engineering and NRDC were submitted to ERDA. Also subcontract approval for the coal and dolomite handling, preparation and injection systems for the SGT/PFB rig were requested. ERDA has approved only the coal preparation system during this reporting period.

III. WORK ACCOMPLISHED/WORK FORECAST

Phase I, the preliminary engineering portion of Contract E(49-18)-1726, was initiated on March 1, 1976 and includes eight (8) tasks as listed below:

Preliminary Engineering

Task 1 - Preliminary Engineering

- (a) Commercial Plant Conceptual Design and Analysis
- (b) Pilot Plant Conceptual Design and Analysis

Task 2 - Pilot Plant Preliminary Design

Task 3 - Site Evaluation

Task 4 - Pilot Plant Environmental Analysis

Task 5 - Technology Rigs

- (a) NRDC PFB Combustor Heat Exchanger Rig
- (b) 12" Fluo-Solids Reactor and Commercial Bed Tests
- (c) Materials Evaluation Rigs
- (d) Small Gas Turbine PFB Operating Parameters Rig

Task 6 - Management

Task 7 - Reliability and Quality Assurance

Task 8 - Documentation and Reporting

The milestones for Phase I are presented in Figure 2.

PHASE I PROGRAM MILESTONES

MILESTONE DESCRIPTION	DATE SCHEDULED	STATUS
PFB Commercial Plant Design Evaluation	Nov. 1976	
Pilot Plant Facility Recommendations	Jan. 1977	
Pilot Plant Facility Preliminary Design	Apr. 1977	
Site Evaluation Complete	Aug. 1976	
Pilot Plant Environmental Analysis	Apr. 1977	
NRDC Test - Initiate Test	Nov. 1976	
Dorr-Oliver 12" F.B. Reactor - Initiate Test	Sep. 1976	Completed
Commercial Rig - Initiate Test	Oct. 1976	
Turbine Corrosion - Initiate Test	July 1976	Completed
Heat Exchanger Tube Erosion - Initiate Test	July 1976	Completed
SGT/PFB Rig Design Complete (Critical Items)	July 1976	Completed
SGT/PFB Rig - Initial Test	Feb. 1977	

Figure 2

Task 1 - Preliminary Engineering

A. Commercial Plant Conceptual Design & Analysis
Plant Performance & Cycle Analysis

Work continued through the reporting period to define PFB commercial plant design and performance. Investigation of ambient temperature effects on performance was completed and results are presented in Figures 3-6. For cold-day (0°F) operation about 30% increase in net power output is indicated, with about 7% improvement in heat rate, for simple cycle operation. Operation is not limited by structural considerations, i.e., PFB pressure capability or rotor speed, for commercial plant design definition at this time. It is noted coal, sorbent, and bed off-take flowrates increase over 20% for cold day operation. PFB free-board pressure increases somewhat more than 14 psi for operation at 0°F, requiring this capability for the coal and sorbent injection system.

Overall performance of the simple cycle (gas turbine only) is shown graphically on Figure 3. Ratings are based on compressor turbine inlet temperature, as shown on Figure 4, where 90% rating corresponds to a fixed T.I.T. for 90% net power output at 59°F. Exhaust temperature and mass flowrate are shown on Figures 5 and 6 respectively.

Investigation of control of pressurized fluidized bed operating variables indicates that constant bed temperature for off-design operation is desirable both for bed sulfur retention and highest combustion efficiency, as well as for structural considerations and maintenance of insulation integrity.

Based on preliminary PFB Combustor and Cyclone flows and gas turbine performance data heat, mass and energy balance diagrams were completed for the following conditions:

Load	Gas Turbines	Steam Turbines
100 Percent	6	1
80 Percent	6	1
Max Obtainable	5	1
Max Obtainable	4	1
Max Obtainable	2	1

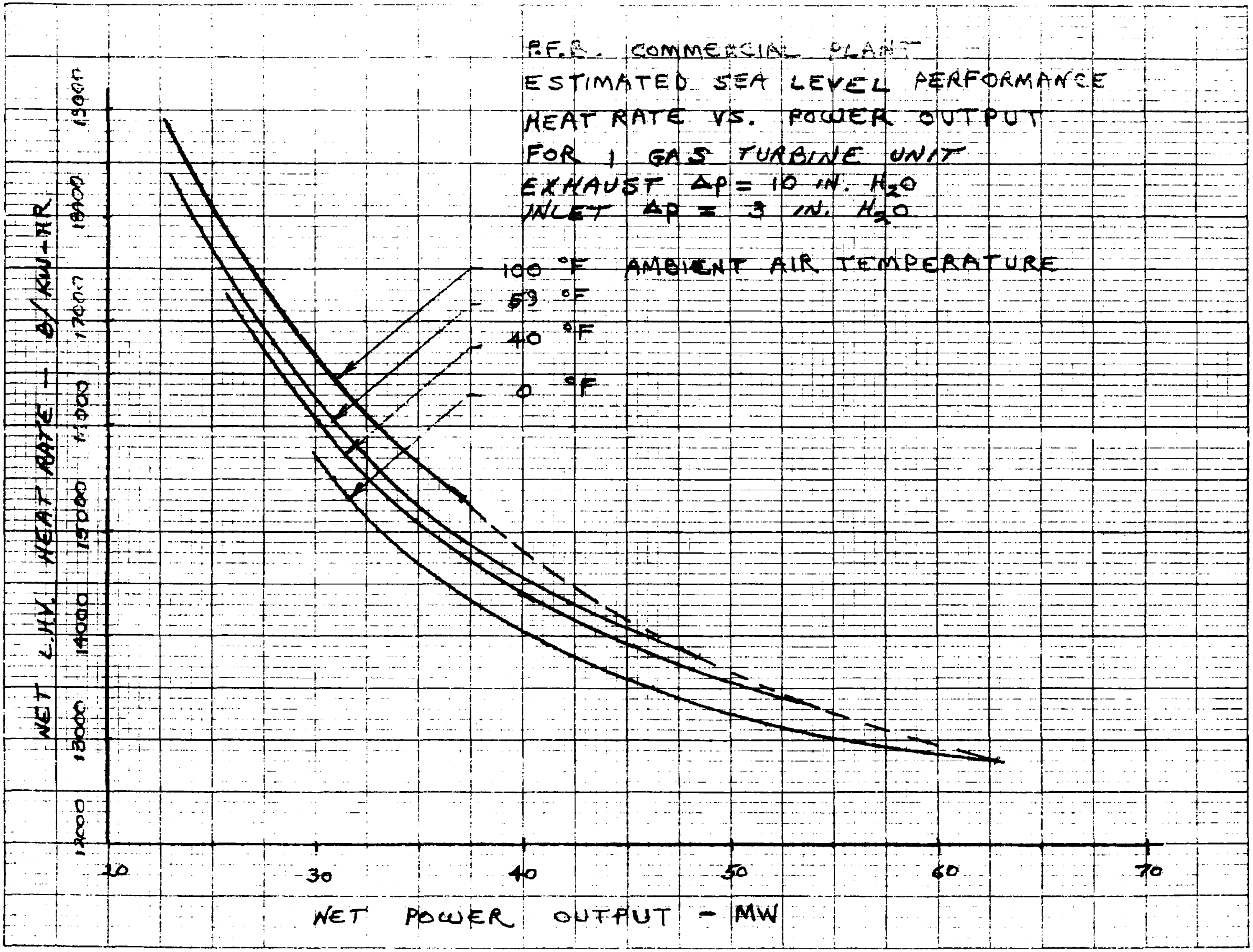

P.F.B. COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
HEAT RATE VS. POWER OUTPUT
FOR 1 GAS TURBINE UNIT
EXHAUST ΔP = 10 IN. H_2O
INLET ΔP = 3 IN. H_2O
100 °F AMBIENT AIR TEMPERATURE
59 °F
40 °F
0 °F
NET L.H.V. HEAT RATE — B/KW-HR
19000
18000
17000
16000
15000
14000
13000
12000
20
30
40
50
60
70
NET POWER OUTPUT - MW

Figure 3

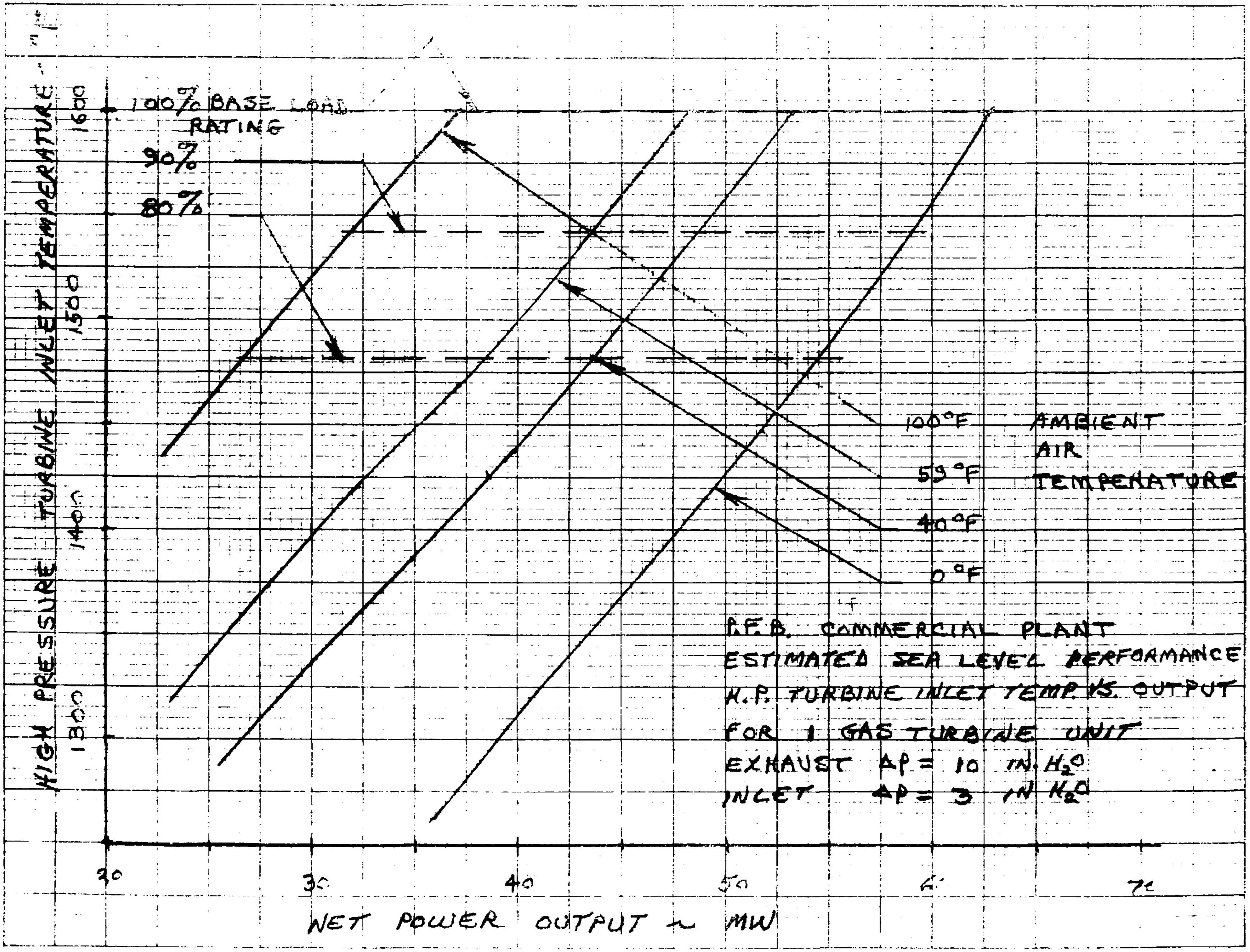

HIGH PRESSURE TURBINE INLET TEMPERATURE ~ °F
1600
1500
1400
1300
100% BASE LOAD RATING
90%
80%
100°F
59°F
40°F
0°F
AMBIENT AIR TEMPERATURE
P.F.B. COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
H.P. TURBINE INLET TEMP. VS. OUTPUT
FOR 1 GAS TURBINE UNIT
EXHAUST ΔP = 10 IN. H2O
INLET ΔP = 3 IN H2O
20
30
40
50
60
70
NET POWER OUTPUT ~ MW

Figure 4

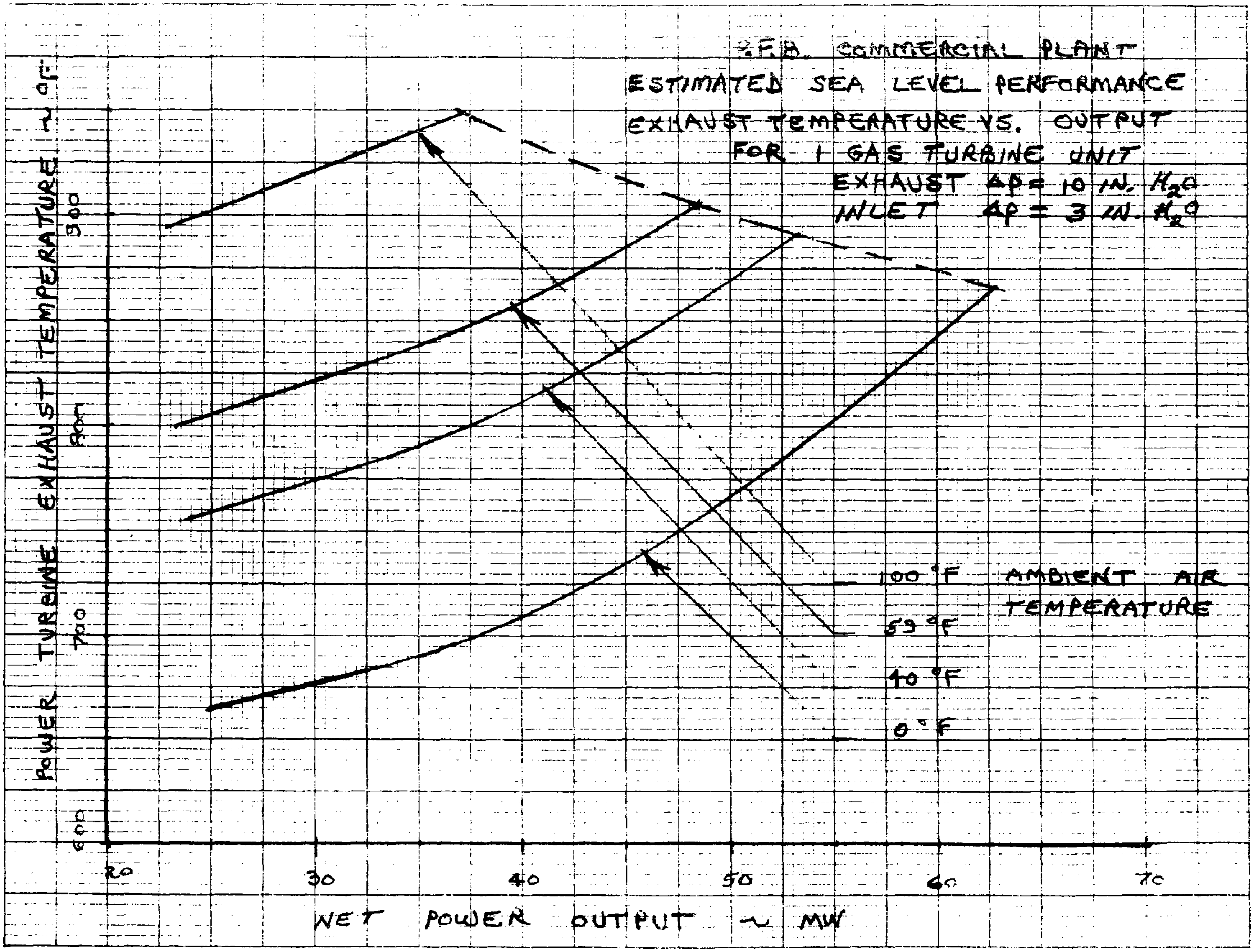

F.B. COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
EXHAUST TEMPERATURE VS. OUTPUT
FOR 1 GAS TURBINE UNIT
EXHAUST ΔP = 10 IN. H_2O
INLET ΔP = 3 IN. H_2O
POWER TURBINE EXHAUST TEMPERATURE ~ °F
900
800
700
600
100 °F
59 °F
40 °F
0 °F
AMBIENT AIR TEMPERATURE
20
30
40
50
60
70
NET POWER OUTPUT ~ MW

Figure 5

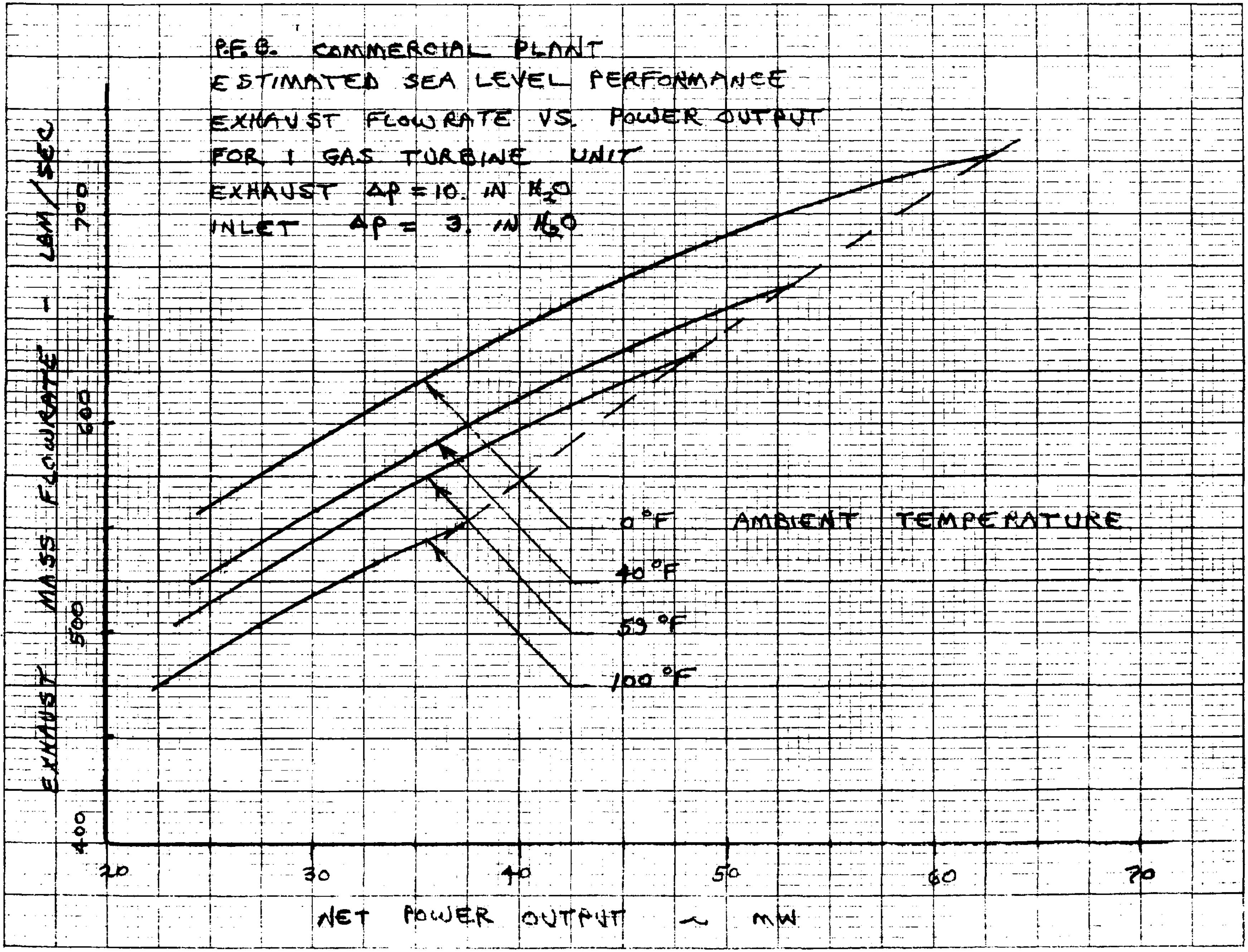

P.F.B. COMMERCIAL PLANT
ESTIMATED SEA LEVEL PERFORMANCE
EXHAUST FLOWRATE VS. POWER OUTPUT
FOR 1 GAS TURBINE UNIT
EXHAUST ΔP = 10. IN H2O
INLET ΔP = 3. IN H2O
0 °F AMBIENT TEMPERATURE
40 °F
59 °F
100 °F
EXHAUST MASS FLOWRATE ~ LBM/SEC
400
500
600
700
20
30
40
50
60
70
NET POWER OUTPUT ~ MW

Figure 6

The combined cycle heat rate at 100% load is 8498 BTU/KW HR.

Work Forecast

Low power operation in the start-up regime will be analyzed, with the commercial plant turbine's aerodynamic performance incorporated in the performance model. Steady-state commercial plant off-design performance will be checked with reference to performance with the preliminary turbine maps. Power turbine by-pass bleed both at low speed and for emergency dump will be investigated.

Off-design performance of the PFB with constant bed airflow to cooling and by-pass airflow aplit will be investigated.

Heat, mass and energy balance diagrams will be finalized for all operating conditions.

Component Design and Plant Arrangement

1. 100 MW Gas Turbine Power Train

The 100 MW alternator for each gas turbine module of the commercial PFB plant is driven at each end by two 50 MW industrial gas turbines. The conceptual design of the industrial gas turbine was started during this period.

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

Two coaxial air outlet and gas inlet ports are located on each side of the engine casing on the horizontal centerline. The hot gas duct is centered inside the compressor air duct to form an annular air flow passage.

The compressor section aerodynamic design is scaled directly from a Curtiss-Wright CWJ65-W15 gas turbine engine used in the MOD POD 8 electric power generation systems. Compressor air exits into a 2.20:1 area ratio annular diffuser which discharges into an annular air chamber between the compressor and turbine and bounded by an inner housing and outer casing. The compressor air then turns to leave through the two annular outlet ports in the sides of the casing. The hot gas inlet duct transitions from a circular inlet at the casing to a 180 degree annulus at the turbine inlet. The compressor air exits from the outlet port on the engine and the returning hot gas enters the inlet port on the engine at very low Mach numbers. Part of the compressor air is diverted around the hot gas inlet ducts to cool the turbine stator housing and interturbine housings.

The compressor-turbine rotor shaft assembly is supported by three pivoted shoe journal bearings and a front thrust bearing. Both two and three bearing shaft support systems were investigated for critical speeds. The results showed the 3-bearing design would have a satisfactory operating range between the 2nd and 3rd critical speeds when running at the design speed of 3712 RPM.

The power turbine is located behind the compressor turbine and shares the same inter-turbine bearing housing. A six port toroidal hot gas bleed manifold is located between the interturbine housing and power turbine. The bleed area was sized to by-pass 50% of the gas flow around the power turbine and into the waste heat boiler to prevent overspeed during emergency shut-down such as a circuit break. Bleed will also be used for phase synchronization before closing the breaker, and during gas generator start-up. The bleed flow is regulated by hot gas valves, presently located in the piping outside the acoustic enclosure.

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

The lubrication system utilizes gravity drain from the bearing cavities, precluding the need for scavenge pump and their related gear drive systems. Oil supply for both the turbines and alternator is from the auxiliary module.

Since the compressor is scaled from an existing design, the basic loading is unchanged and except for maximum pressure operation during cold day running, no changes except for blade materials are contemplated. Blade attachments will be re-designed to suit installation to the rotor drum.

The aerodynamics for both turbines, however, is revised for improved efficiency and both the blades and disks are designed for the uniform turbine inlet temperature profile provided by the hot gas inlet ducting.

Cooling of the 1st and 2nd stage compressor turbine disks is contemplated as a means of keeping the disk and tenon temperatures in line with economical material choices.

2. Auxiliary Module for 100 MW Gas Turbine

Design of the general arrangement of the auxiliary module for the 100 MW unit is continuing. The lower section of the module consists of a shallow reservoir which is mounted above ground on a concrete slab. Mounted on top of the reservoir are the pumps, filters, pressure relief, gas turbine controls, connecting piping, electrical junction box and conduit. The complete system is covered with an acoustical sheet metal enclosure supported on the foundation slab with walk around space.

Since this is a base loading plant, the lube oil pumping system will consist of a primary AC driven pump and a back-up full flow AC pump. To prevent loss of lube oil flow in case of pump failure, two battery driven half flow DC pumps will supply lube oil on run-down in case of AC power failure. All pumps are positive displacement screw type with flooded inlet and mounted through the reservoir top. Two full flow filters with extended area elements are mounted and piped so element change-out can be accomplished without interrupting the flow.

Low intensity electric heaters are mounted through the top of the reservoir to maintain oil temperature in the order of 80° to 90°F at low ambient temperatures. The lube oil cooler consists of a free standing air-to-oil type with the necessary enclosure to prevent fouling by snow or ice.

The required oil flow for the gas turbines, couplings and alternator is approximately 964 GPM. The fuel flow pumps are over-sized to allow the by-pass pressure regulator to operate without starving the bearing. The diaphragm type regulator controls the pressure at the outlet of the module to 30 PSI regardless of flow demand due to viscosity change and bearing clearance change. The AC pumps will require approximately 100 HP motors while the DC pumps require approximately 50 HP motors. Overload on the motors is prevented by a single pressure relief valve.

The oil from the pumps is piped to an outside air to oil heat exchanger which is sized to reject approximately 3.6 million BTU per hour. The oil from the heat exchanger is returned to the auxiliary module and is conducted through either of the dual filters. The flow can be diverted to either filter by a 3-way diverter valve. This allows filter element change-out without interrupting oil flow to the bearings.

The 3-way thermostatic valve controls oil by-pass around the heat exchanger thus providing oil to the bearings between 130°F and 160°F with ambient temperatures varying over a wide range up to 110°F.

The reservoir is sized for a 5 minute residence time plus 30 percent to reduce foaming and provide an air space over the oil for cross ventilation. Baffles are located in the reservoir to assist in deaeration and foam reduction.

Three 25 KW low intensity heaters are located through the top. During low ambient operation, the heaters will maintain oil temperatures between 80° and 90°F. An oil level switch is mounted on the top of the reservoir to signal high and low levels.

3. PFB Combustor/Heat Exchanger

The general arrangement for the PFB vessel has been established and is illustrated in Figure 7. The PFB is enclosed in a cylindrical vessel with hemispherical ends, internally insulated and mounted in an upright position on four support columns. Located inside the vessel is the distributor plate for air injection to fluidize the bed and the heat exchanger tubes to regulate the temperature of the bed.

The design concept for using straight-through single-pass heat exchanger tubes joined in bundles for a modular arrangement was prepared to show its feasibility in a commercial unit. The bundles consist of nine heat exchanger tubes in a square array which are joined to a header pipe at each end. Each header has a single port (collector tube) for either the entering or leaving air flow. The inlet collector tubes are secured to the distributor plate and to an inlet plenum. The outlet collector tubes are welded to a plenum chamber in the freeboard.

The sealed plenums above and below the heat exchanger tubes, keep the cooling air separated from the fluidizing air which is used for combustion of the coal. The outlet tube header is located sufficiently above the top of the bed to minimize particle impingement. The inlet header is protected from impingement by not fluidizing the bottom of the bed.

Each tube bundle is attached to the distributor plate through a thermal sleeve. The inlet plenum is suspended from the heat exchanger inlet pipes that extend through the distributor plate while the outlet plenum is supported on the columns of heat exchanger outlet pipes.

A major design concern was the serviceability of the heat exchanger tubes and of the insulated vessel wall. Both objectives are achieved by the feasible removal of the tube bundles from the vessel through the air outlet port at the top of the vessel. Also, there is a considerable amount of clearance space between collector tubes for serviceability in the tuyere air box and in the freeboard.

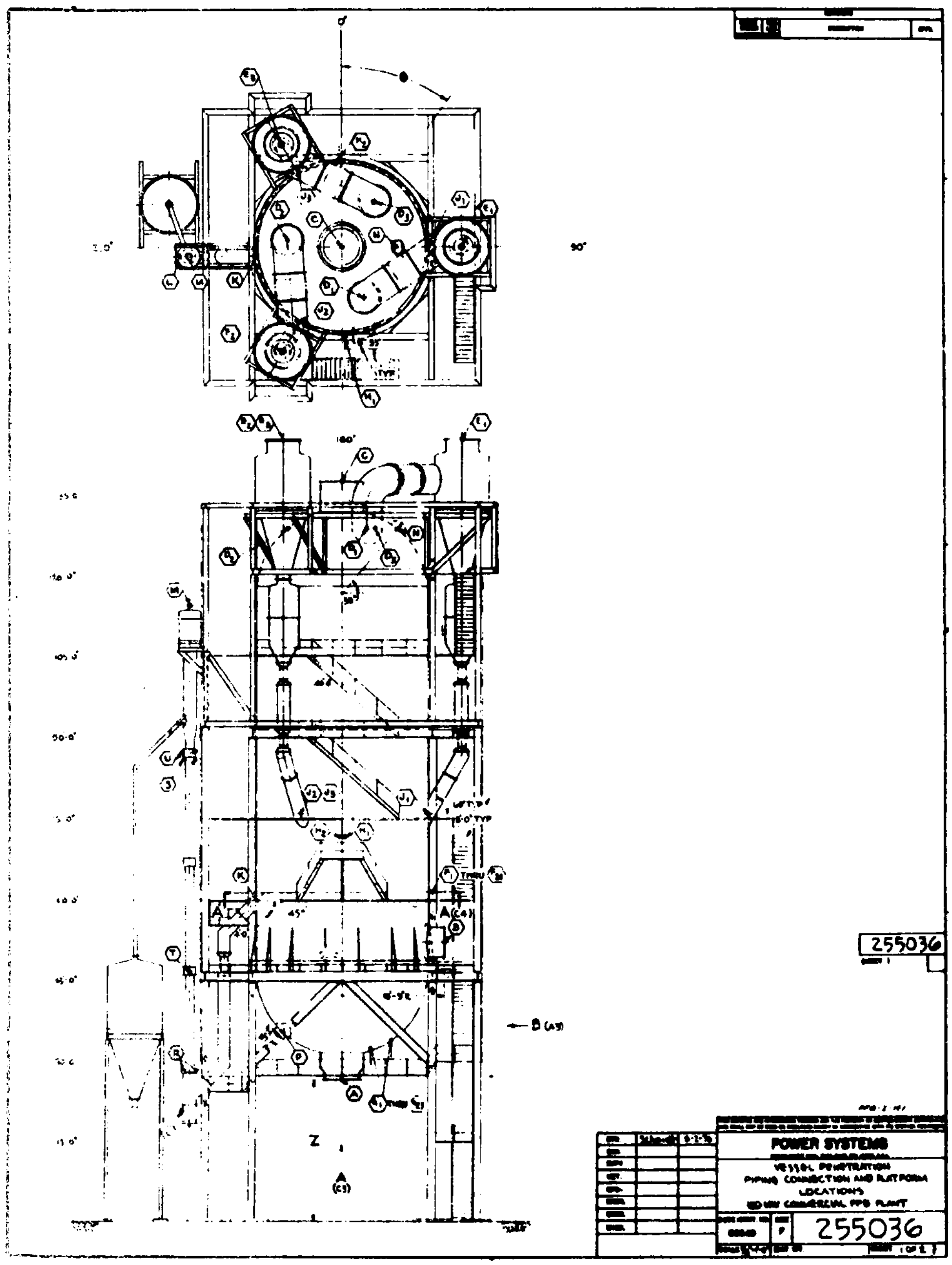


Figure 7

The primary advantage of this modular arrangement is the reduced number of penetrations in the distributor plate which permits adequate space for the support structure formed in a grid arrangement to carry the over one million pounds of load acting on the distributor bed plate. The entire internal structure including the heat exchanger tubes, tuyeres, coal and dolomite, distributor bed plate, inlet and outlet air boxes and the brick refractory insulation are supported off the pressure vessel wall by a continuous ring welded to the pressure vessel wall through a doubler plate and reinforced by gussets to uniformly distribute the shear and overturning moment loads. A detailed computer stress analysis of the grid supporting structure has been performed and the number, locations and sizes of the beams have been established.

The outside of the vessel is enclosed by four walls attached to a network of steel columns and beams on which is provided the various stairs and platforms needed for access to the vessel and its equipment. The wall structure also supports the three primary gas cleanup cyclones, trickle valves and ash return pipes at the upper half of the vessel. An ash removal cooler and cleanup cyclone is also mounted to the outside of the wall structure. The ash cooler empties into an ash receiver which is set on legs alongside the PFB vessel.

The location of the air, gas, ash, coal and sorbent penetrations were established.

The coal injection nozzles are located around the circumference of the vessel and through the bottom of the distributor plate. Each nozzle is spaced to have a selected area coverage throughout the bed cross-section. The nozzles are oriented so that the injected coal does not impinge directly on the heat exchanger tubes. Coal nozzles on the side of the vessel are shorter in length than those going into the bottom of the bed. Straight lengths are used to permit withdrawal of the nozzle while the vessel is operating under pressure. Nozzle removal is accomplished with air sealing and coal cut-off valves and a packing gland.

The design of the pressure vessel wall thickness and the type of thickness of the refractory insulation in the active bed region, freeboard region and top spherical head region has continued. The PFB unit will have a framework structure surrounding it with sheet metal walls which will eliminate concern for wind velocity while maintaining normal updraft convection.

Study is continuing on the use of fire-brick in the bed and freeboard regions, and, castable refractories in the top spherical head and other regions.

Several concepts are being considered for the bed region and freeboard region which will utilize fire-brick refractories for the hot lining and a layer of a castable refractory between the fire brick and the carbon steel shell. Present efforts are being directed to obtaining the best trade-off between the amount of refractory insulation, the outside shell temperature and stress.

4. <u>30 MW Unit Mechanical Design - PFB Combustor/Heat Exchanger Design</u>

A parallel effort is being directed on a PFB configuration for a 30 MW gas turbine generator module. The objective is to follow the modular concept by designing the PFB for shop fabrication and shipment to the site for installation. This PFB diameter is limited to approximately 12 feet outside diameter for shipping purposes. Three PFB's will be used for each gas generator. A double-ender arrangement using two contemporary sized gas generators are incorporated in the module for each 30 MW alternator.

A general arrangement for the reduced diameter PFB has been prepared. Except for size, the basic configuration is the same as for the 100 MW PFB. Fewer heat exchanger tube bundles are required and as a result the outlet air plenum was modified to have flanged connections for its complete removal through the outlet port in the top of the vessel head. The tube bundles now have a clear withdrawl path from the bed and through the outlet port, with the removal of the center heat exchanger tube bundle outlet pipe.

One primary cyclone clean-up is used per PFB. The cyclone is mounted at the top of the vessel. There is also one ash removal system on each vessel. Coal injection nozzles are spaced equally around the circumference of the vessel. The plot arrangement features three side-by-side PFB's per gas generator. An external framework is built around the vessel to support the access stairs and platforms.

5. Plant Flow, Piping and Electrical Diagrams and General Arrangement

The conceptual flow diagrams were prepared for:

a. Steam system
b. Feedwater system
c. Condensate system
d. Air and Combustion Gas

Work has been started on the following conceptual flow diagrams:

a. Fire protection and service water
b. Cooling water
c. Compressed air

The PFB/gas turbine area general arrangement drawings have been started. The control building general arrangement drawing was completed and the electrical one-line diagram was completed. Electric equipment (transformers, switchgear, etc.) has been sized and the arrangement of equipment in the control building and switchgear room completed.

Primary turbine building general arrangement drawings have been completed and piping composites were started for the low pressure steam, high pressure steam, condensate, and boiler feedwater systems between the waste heat boilers and steam turbine plant.

Plant "Description of Work" which forms the basis for the plant cost estimate was completed and is being updated as design progresses.

Various equipment manufacturers were contacted for information relative to size and price of their equipment.

Work Forecast

Complete engine general arrangement and critical speed analyses. Complete the auxiliary module drawings. Prepare preliminary specifications on the enclosure and oil heat exchanger to provide information for pricing.

Complete the drawing of the PFB vessel, vertical fuel nozzle assembly and identify instrument locations. Prepare material selection and detailed structural features for pricing purposes.

Continue sizing of the refractory insulation and the pressure vessel thickness. Perform a shell analysis of the pressure vessel wall and evaluate the effects of discontinuities and concentrated loads.

Release the drawings for turbine building general arrangement, control building, piping composites (steam, condensate, and feedwater) and 4,160 V and main one-line diagram.

Continue the plot plan showing the overall station arrangement, and instrumentation and control definition.

Complete the conceptual flow diagrams for fire protection and service water, cooling water and compressed air.

Continue estimating the capital cost of the plant.

Commercial Plant Environmental Engineering

The environmental engineering for the commercial plant was started for definition of:

a. Circulating water system
b. Liquid, solid, and gaseous waste systems
c. Hot-gas cleanup
d. Boiler makeup water treating.

Work Forecast

Continue with the environmental engineering effort including estimating the costs for the various systems.

B. Pilot Plant Conceptual Design and Analysis

The computerized model of the CW J65 gas turbine driven Total Energy System has been modified to simulate the Pilot Plant Coal-fired PFB system. The performance of the gas turbine section of this PFB system was analyzed and is summarized on Figure 8. Pressure drop of 4 inches H_2O at the inlet and 10 inches H_2O at the exhaust was used in the analysis. Part power operation from base to 20 percent power is shown.

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

The salient net results are the predictably lower cycle thermal efficiency and compressor rematch toward the surge line. In fact, the data indicate the necessity of building a control system to bypass the power turbine with some exhaust gas for low power operation to avoid surge. The amount of bypass in estimated to be 20 percent. Such a system is also needed for starting and heating the bed, while using the auxiliary burners. A power turbines bypass valve system will be included in the design of the pilot plant and its controls.

Performance of the gas turbine at standard ambient conditions was calculated to obtain compressor drive turbine inlet temperature and speed and power turbine inlet and outlet temperatures, compressor airflow, bed airflow and pressure ratio. Excess air variation in the fluid bed at a constant bed temperature of 1650°F is shown on Figure 9 together with the required turbine bypass bleed for surge avoidance. The locations of the base load and part power operating points were developed on the compressor map. Below 80 percent load, operation of the turbine bypass is required.

PFB PILOT PLANT

SIMPLE CYCLE PERFORMANCE DATA

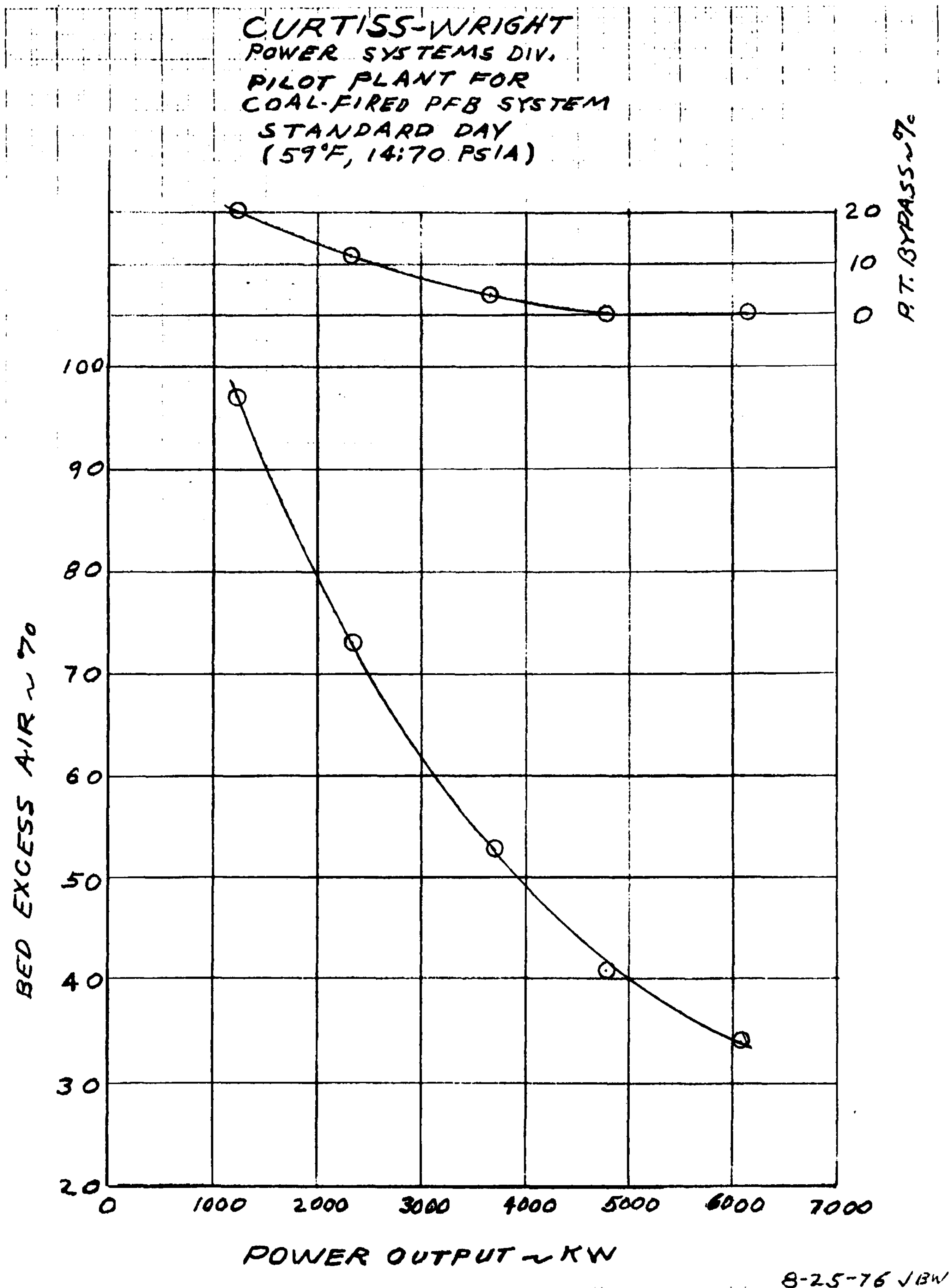
Overall Unit Performance - (Sea Level Standard)

Per Cent Gas Turbine Power	100	80	60	40	20
KW	6035	4760	3684	2330	1212
Heat Rate (LHV) B/KW - HR	18,718	20,190	22,790	29,800	47,100
Heat Release (LHV) B/HR X 10^6 (Based on Coal and Sorbent Combine LHV)	113.2	96.0	83.7	69.3	57.0
Heat Loss (Bed Material Off-Take) B/HR X 10^6	1.761	1.498	1.308	1.083	0.890
Exhaust Heat Loss (B/LBM)	231.0	215.3	197.3	175.0	155.1
Bed Solid Off-Take (LBM/SEC)	1.438	1.27	1.07	.89	.73
Coal Flow (LBM/SEC)	2.50	2.12	1.85	1.53	1.26
Sorbent Flow (LBM/SEC)	0.87	0.74	0.65	0.54	0.44

Fuel Heating Values

Coal and Sorbent Combined LHV (B/LBM Coal)	12,574
For a. Coal HHV (B/LBM Coal)	13,090
b. Coal LHV (B/LBM Coal)	12,691
c. Calorific Value for Coal Borne Sulfur (B/LBM/Coal) Assumes all Fuel-Borne Sulfur Reacts to SO_2	-163
d. Calorific Value for Bed Sulfation Reaction (B/LBM Coal)	+276
e. Calorific Value for Bed Calcination Reaction (B/LBM Coal)	-230
Combustion Efficiency (Per Cent) (Including heat transfer to surroundings)	99

Figure 8



CURTISS-WRIGHT
POWER SYSTEMS DIV.
PILOT PLANT FOR
COAL-FIRED PFB SYSTEM
STANDARD DAY
(59°F, 14.70 PSIA)
P.T. BYPASS ~ %
20
10
0
BED EXCESS AIR ~ %
100
90
80
70
60
50
40
30
20
0
1000
2000
3000
4000
5000
6000
7000
POWER OUTPUT ~ KW
8-25-76 JBW

Figure 9

A similar study of the performance and stability of the system with remote-mounted J65 burners was made. This system is satisfactory with the power turbine bypass system in use, for starting, bed heating and cooling.

Work Forecast

A power turbine bypass control schedule will be developed for non-standard day conditions and, following a decision on the optimum schedule, performance will be predicted for several power level settings.

Operating data for the existing waste heat boiler are being analyzed, and will be correlated with the gas turbine performance so that overall plant output can be evaluated.

Design Recommendations based on the performance data will be initiated.

Task 3 Site Evaluation

A Real Estate Report for the Pilot Plant site was prepared. Soil boring work for both the pilot plant site and SGT/PFB test rig site was completed and soil reports were prepared.

The meteorology and climatology sections have been completed for inclusion in the site evaluation report. Newark airport weather date has been summarized.

A preliminary topographic map was prepared and has been reviewed.

Site master plan and review of local codes, license and permit requirements is in progress.

Work Forecast

Complete the resources and transportation studies, site master plan, and review of the final tcpographic map.

Complete the geotechnical study for the site evaluation report.

Task 5 - Technology Support Rigs

Heat Exchanger Tube Fabrication

Brazing has been selected as the method of fin attachment for the initial heat exchange tube requirements (i.e., Dorr-Oliver 12" Fluo Solids Reactor). Fabrication techniques including assembly and braze parameters to produce this tubing are being developed in conjunction with Wall Colmonoy.

Fin straightening techniques and special fin indexing fixtures have been developed and utilized in the assembly of the tubing.

Several Cobalt braze alloys, Nicrobraz 210 and 300, were utilized to construct the Fluo Solids Reactor tubing. These alloys were chosen over nickel base alloys because they offer the best combination of high temperature strength and corrosion resistance. While both have similar compositions, the 300 alloy was included for evaluation because it has the ability to braze sections with gaps up to .010 inch. The 10 and 20 fin configurations were brazed with the 210 alloy and the 15 fin configuration with the 300 alloy. Using the same braze cycle, the 300 alloy exhibited more interaction with the base alloy. Its use was, therefore, limited to the one set of tubes. To use this alloy, additional tests will have to be run to obtain optimum braze parameters. All tubes have been brazed and final construction of the tube assembly is in progress.

Initial evaluation of the fabrication technique using the I.D. pleated fin for the 4 inch Schedule 40 configuration is in process. Several configurations have been prepared and each will be evaluated for ease of assembly and brazing to the I.D. wall. Braze alloy application techniques are being evaluated. Initial results indicate that controlled spraying of the braze alloy with a new binder provided excellent adherance to the fin material.

Discussions are continuing with various casting companies to determine the feasibility of producing cast tube sections with intregral OD and ID fins.

In order to assure complete metallurgical bond between the fins and tube, a non-destructive test using ultrasonic techniques was developed at Curtiss-Wright.

Work Forecast

Development work is continuing to determine the assembly techniques and braze parameters for the I.D. pleated fin configuration.

Design and cost aspects of an integral OD and ID finned tube casting will continue to be evaluated.

NRDC - PFB Combustor/Heat Exchanger Rig

Detail design of the test heat exchanger assembly has been completed. The design accommodates a 7 1/2 foot deep bed containing seven bayonet type cooling tubes. Four of the tubes are water cooled and serve only to control bed temperature. The remaining three tubes are connected in series and will be cooled with 200°F air. Air flow to the bed of 1.713 lb/sec at an inlet pressure of 87.0 psia is supplied to the tuyeres for combustion.

A thermal analysis was made to determine the finned tube wall temperatures to evaluate the relative thermal growths of the three air cooled tubes as a function of cooling airflow rate. Predictions of cooling air discharge temperatures were also completed. Selection of 0.43 lb/sec cooling air flow was established.

The basic assembly drawing of the heat exchanger has been completed including details for all components in preparation for hardware manufacture.

Copies of a proposed subcontract document for test service was submitted to NRDC/CSL for their review and acceptance and to ERDA for approval.

Work Forecast

Complete instrumentation drawing.

Obtain subcontract approval and forward heat exchanger installation drawings to NRDC/CSL so their test rig modifications can be initiated.

Initiate fabrication of the heat exchanger.

Dorr-Oliver 12 Inch Diameter Fluosolids Reactor

All equipment, except for the finned tubes, was manufactured or procured and installed on the 12 inch fluo-solids atmospheric reactor at Dorr-Oliver's Springdale Laboratory. Fabrication of the constriction plate for the hot reactor, and for a cold model, were also completed. These tests are designed to obtain initial gas-side heat transfer data and bed performance with heat exchanger tubes of various fin configurations.

The test plan was prepared and submitted to ERDA for approval.

The initial heat exchanger using a hairpin tube assembly without fins was completed, instrumented and installed in the test facility. Experiments with this unfinned tube to establish a baseline for comparison with the various finned tubes have started.

The finned tube sections for the remaining heat exchanger tube assemblies have all been completed and are currently being instrumented.

Work Forecast

Complete instrumenting the 10, 15 and 20 fin heat exchanger tube assemblies and prepare for test. Continue tests of heat exchanger tubes in the Fluo-Solids Reactor.

Commercial Fluid Bed Corrosion/Erosion Material Tests

Arrangements were made to install test fixtures incorporating various candidate materials in two Dorr-Oliver designed commercial fluidized beds. One bed is a municipal sewage sludge incinerator in Torrington, Conn., and the other is a Pfizer Co. limestone calciner in Adams, Mass. The environments in these two beds should bracket conditions expected in the coal/dolomite PFB and yield early data relative to the long term erosion/corrosion of the materials selected for test.

Verbal approval for the test at the limestone calcining facility has been granted. Written approval has been granted by the City of Torrington for the test to be conducted there. Test plans for the programs at both of these facilities have been prepared and submitted to ERDA.

All of the critical materials for the specimen tube sections have been procured. Fabrication of the complete test fixture assmblies is proceeding. Instrumentation design was established to obtain tube vibration data in order to provide insight into the dynamic environment of a large fluidized bed of considerable depth, particularly in regard to possible excitation of vertically orientated heat exchanger tube bundles. The Torrington, Conn. incinerator which will accommodate test specimens of approximately seven feet in length was selected to obtain initial vibration data. High temperature weldable strain gages will be mounted on the outside of tube specimens to measure vibratory stresses. A tri-axial accelerometer will be mounted at a tube closure outside the bed to detect amplitudes above 100 cps. Displacement pickups will be used to investigate the low frequency range 10 to 100 cps.

Work Forecast

Obtain test plan approval from ERDA.

Fabricate and instrument test fixtures assemblies for the two selected commercial fluid beds.

Turbine Materials Corrosion/Erosion Rig

The Turbine Materials Corrosion/Erosion Rig test is designed to evaluate relative resistance of turbine alloys to a simulated PFB turbine environment. The environment is created by addition of alkali metal salts to sulfur-bearing jet fuel at the time of combustion. Erosion is produced using an air stream entrained with 10 micron Aluminum Oxide particles which is aimed at the specimens. The specimens are exposed to the fuel combustion flame and operate at °F temperatures approximately 1600°F.

The test plan was submitted to ERDA outlining the specific test conditions, alloys to be run, and schedule of exposure time for each test. ERDA approval was received.

The unit to provide the abrasive particles and air stream to create erosion conditions was calibrated for particle velocity and flow. A temperature calibration test was run to determine the temperature distribution over the 2-1/8 inch length of the specimen at 0.20 inch intervals. A slip ring assembly allows the thermocouple measurement to be taken from the specimen rotating through the combustor flame exactly as the actual test specimens will be run. The temperature range was 1540°F at the tip, 1615°F at the mid station and 1445°F at the base.

The specimens for Test #1 were machined, coated as required and installed in the rig. Material for specimens of Hoskins 875 and Tophet A-Cb was received and is being fabricated into specimens for Test #2. Specimens to be coated with Co-Cr-Al-Y and Ni-Cr-Al-Y; and Pt- aluminide were prepared for application of coatings.

Test #1 consisting of samples of U-700, U-500, U-710, IN738, IN738 and S-31 with an aluminide diffusion coating, was initiated and 64 hours of specimen exposure has been accumulated.

Work Forecast

Test #1 will be completed and the evaluation of results will be initiated. Fabrication of specimens for Test #2 will be completed and testing will be initiated.

PFB Tube Materials Erosion Rig

The Erosion Rig is an externally heated fluidized bed of Aluminum Oxide which provides an environment of temperature and space velocity similar to the PFB combustor. Candidate nickel and cobalt base alloys for PFB heat exchanger tubes are being evaluated for relative erosion resistance. The rig was modified to achieve the required operating parameters and the specimens and holders were machined. The rig was run at design operating temperature and calibrated. The temperature of the bed stabilized at 1600°F $\pm$ 25°F. The design of the specimen holder was modified to minimize shielding of the specimens from the action of the bed material. The specimens have been measured for dimensions and surface roughness. The assembled specimen holder was installed in the rig and testing was initiated. To date, 120 hours of specimen exposure has occurred. The test is scheduled to run 1000 hours with observations at 250, 500 and 750 hours.

Work Forecast

Test #1 will be completed and specimens from test will be evaluated for erosion resistance. Specimens for Test #2 will be installed and testing will be initiated.

SGT/PFB Operating Parameter Rig

Detailed layouts of the PFB combustor (with the exception of the air distributor assembly) and ash return loop have been completed and released for procurement. The stress analysis of the distributor assembly was completed for the design which reduced the thermal gradients across the top of the distributor assembly. The air distributor assembly is presently being updated to reflect the latest air cooled tube configuration and the 8 in. cooling air connection is being rotated to simplify the cooling air supply lines from the facility air preheaters.

The site layout drawing for the SGT/PFB rig is in its final stages of completion utilizing descriptive data of system components received from equipment manufacturers.

A general arrangement drawing of the SGT/PFB with the combustor ash return, and ash removal in its steel structure is in progress. This drawing includes a Bill of Material of all components required to assemble the SGT/PFB in the structural steel support. A flow schematic of this SGT/PFB system is shown in Figure 10.

Preliminary layouts of the following were initiated:

1. Tuyere air supply pipe with valve, air straightener and orifice (5 inch diameter pipe).

2. Heat exchanger cooling air supply pipe with valve, air straightener and orifice (8 in. dia. line).

3. Air supply line from facility (10 in. dia. line).

4. Heat exchanger discharge line from PFB (10 in. I.D. refractory lined pipe).

5. Primary cyclone discharge to secondary clean up inlet (10 in. I.D. refractory lined pipe).

6. Combining of the secondary clean up flow with the PFB heat exchanger discharge line.

7. Quench chamber for the combined flow prior to exhausting to a silencer.

8. Positioning the small gas turbine engine in relation to the combined flow piping.

9. Sizing the main back pressure valve.

Specifications were prepared for valves, gas monitoring instrumentation and digital Control Center and several existing systems were investigated regarding potential use for the SGT rig. Final pressure and instrumentation drawings and a flow diagram have been completed.

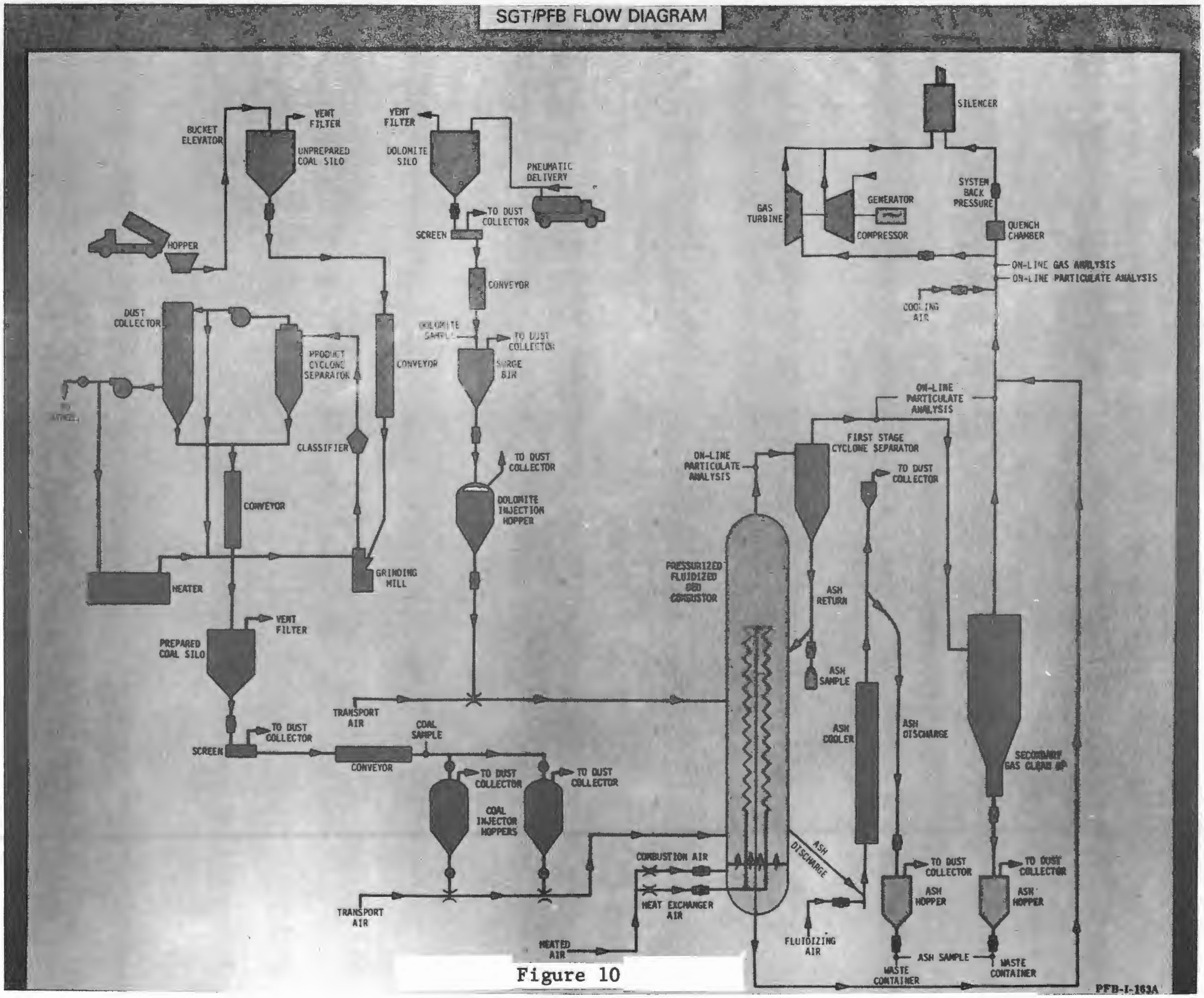

SGT/PFB FLOW DIAGRAM
BUCKET ELEVATOR
VENT FILTER
UNPREPARED COAL SILO
HOPPER
DUST COLLECTOR
PRODUCT CYCLONE SEPARATOR
CONVEYOR
CLASSIFIER
HEATER
GRINDING MILL
PREPARED COAL SILO
TO DUST COLLECTOR
SCREEN
TRANSPORT AIR
COAL SAMPLE
COAL INJECTOR HOPPERS
DOLOMITE SILO
PNEUMATIC DELIVERY
SURGE BIN
DOLOMITE INJECTION HOPPER
SILENCER
GAS TURBINE
GENERATOR
COMPRESSOR
SYSTEM BACK PRESSURE
QUENCH CHAMBER
ON-LINE GAS ANALYSIS
ON-LINE PARTICULATE ANALYSIS
COOLING AIR
FIRST STAGE CYCLONE SEPARATOR
PRESSURIZED FLUIDIZED BED COMBUSTOR
ASH RETURN
ASH SAMPLE
ASH COOLER
ASH DISCHARGE
SECONDARY GAS CLEAN UP
COMBUSTION AIR
HEAT EXCHANGER AIR
HEATED AIR
FLUIDIZING AIR
ASH HOPPER
WASTE CONTAINER
PFB-I-163A

Figure 10

Stress analysis of the SGT/PFB rig is nearing completion. All basic thicknesses per ASME Code Section 8, Division 1, have been established for the pressure retaining components with the exception of the air inlet pipes and PFB pressure vessel boundary attachments. A Division 2 analysis on the air inlet pipes will be prepared because of large thermal transients which will occur in these regions during system startup. A wind, weight and seismic analysis has also been made to augment the evaluation of stresses and deflections in PFB supports and erector steel.

Consideration has been given to the effect on the pressure boundary of internal pressure, refractory expansion and temperature in the Curtiss-Wright computer programs used in the analysis (Refractory Program Log 2278 and General Axisymmetric Shell Program Log 2072). Variations in environmental conditions were also considered to assess the impact of wind and ambient temperature on stress and operational limitations. Using the refractory program results, a correlation was established which predicts the combination of ambient conditions under which limited operation will be necessary to maintain refractory/steel shell stresses to allowable levels if external shielding of the PFB is avoided.

Analysis of PFB internals for the normal operating condition has been completed for the distributor box where Section 8, Division 2, requirements are the governing criteria because of the predominance of the radial thermal gradient effects. Additional thermal stress analysis was initiated in the localized region of the air inlet pipes to the distributor box under a startup condition. This work is proceeding as the thermal gradient profiles in the pipes become defined for the final design. Analysis of the cooling air tubes in the bed region for the normal operating condition is partially complete. The stresses in the region of the tube supports (to the distributor box) do not meet Section 8, Division 2, 35 m allowables, therefore, low cycle fatigue analysis is in progress.

Effort was also initiated to estimate the mechanical loads on the tubes due to fluidized bed operation (and possible sloshing due to seismic effects), so that lateral intra-tube connections and tube base support structural analysis can be completed.

Service and repair work continues at the boiler house to reactivate the coal handling and storage facilities. Design for installation of the PFB vessel, material handling system, control system and interface to facility systems has been initiated. Foundation design, drawings and specifications for the PFB vessel have been completed and issued to sub-contractors for bid.

Layout drawings showing the air inlet piping to the PFB vessel from the Facility Development Laboratory have been completed. Specifications for the expansion joints have been completed and issued to vendors for quotation. A preliminary layout of the control room showing various control board systems, motor control center and wire ways has been completed. Purchase orders for wire and wire ways have been issued.

Quotations were solicited and received for purchase of the coal grinding mill and dryer system. Vendor selection was made and the purchase order issued. Quotations were solicited for purchase of the coal and dolomite feed injection system. Quotations were solicited for the remaining items of the material handling system (feeders, silos and bucket elevators) and received. Vendors were selected and approval for release of purchase order has been requested from ERDA. Quotations were solicited for the fabrication of the SGT/PFB Combustor, cyclone and ash return loop and have been received. These are under review for vendor selection

Work Forecast

The air distributor assembly drawings will be released for manufacture. The site layout drawing and the general arrangement drawing will be completed. Final layout of the hot piping requirements, final process flow chart and instrumentation layouts will be initiated. Final valve, gas monitoring instrumentation and control software will be selected.

Service and repair work for reactivating coal handling and storage facilities at the boiler house will continue. Installation and facilities interface design of all systems will continue. Foundation bids will be received and a subcontractor will be selected.

System arrangement layout of the material handling, feed systems, injection systems and control logic information will be transmitted to vendors for proper interface design of the systems.

Task 6 - Program Management

The Phase I Program Schedule is shown in Figure 11.

Subcontracts were drafted covering the efforts of major subcontractors Dorr-Oliver Corp. and Stone and Webster Engineering Co. Also a subcontract draft was prepared covering the procurement of test services from NRDC/CSL for the evaluation of Curtiss-Wright's air tube heat exchanger design in the Leatherhead Research Stations PFB conbustor test facility.

These documents have been submitted to the subcontractors for review and to ERDA for approval.

Requests for ERDA approval have been submitted for procurement of the SGT/PFB rig's coal and dolomite storage, preparation and injection system. ERDA approval was received for the preparation system.

A program status review was held at Curtiss-Wright on July 13 and 14, 1976 with ERDA and Mitre representatives in attendance.

Work Forecast

Obtain ERDA approvals for outstanding subcontracts under review.

Task 7 - Reliability

The design arrangement and layout of this commercial PFB system implies a series Block Diagram Model for the reliability Analyses. Such a block diagram has been constructed containing a block for each module and an allocated reliability for the block. Where analyses has been unable to design detail, a predicted reliability is used for the module. Design details continue to be analyzed so that the Block diagram is up-dated, in an iterative process.

PROGRAM SCHEDULE

ENGINEER, DESIGN, CONSTRUCT, TEST AND EVALUATE A PRESSURIZED FLUIDIZED BED
PILOT PLANT USING HIGH SULFUR COAL FOR PRODUCTION OF ELECTRIC POWER
CONTRACT ERDA-CT-E(49-18)-1726

As of Date Aug. 31, 1976

			Project Start - 1976										1977				
EVAL	TASK NO.	WORK STATEMENT Phase I - Preliminary Engrg.	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
	1	PRELIMINARY ENGINEERING															
	2	PILOT PLANT PRELIMINARY DESIGN															
	3	SITE EVALUATION															
	4	PILOT PLANT ENVIRONMENTAL ANALYSIS															
	5	TECHNOLOGY RIGS															
	6	MANAGEMENT															
	7	RELIABILITY AND QUALITY ASSURANCE															
	8	DOCUMENTATION AND REPORTING															

Legend

- SCHEDULED
- PROGRESS
- SCHEDULE EXTENSION
- EARLY START

Figure 11

Task 8 - Documentation and Reporting

The following reports were submitted during the quarterly period:

A. Monthly Final Copy:

Technical Report - Monthly - June 1, 1976 to June 30, 1976
Technical Report - Monthly - July 1, 1976 to July 31, 1976
Financial Report - Monthly - June 1, 1976 to June 30, 1976
Financial Report - Monthly - July 1, 1976 to July 31, 1976
Financial Report - Monthly - August 1, 1976 to August 31, 1976

B. Final Copy of Previously Submitted Draft:

Quarterly Report - Technical - March 1, 1976 to May 31, 1976
Technology Support Test Plan - PFB Heat Exchanger Fin & Tube Materials Erosion Rig Evaluation
Technology Support Test Plan - Turbine Materials Hot Corrosion/Erosion Rig Evaluation
Technology Support Test Plan - Dorr-Oliver 12 inch Fluo-Solids Hot Reactor

C. Draft Copy:

Technology Support Test Plan - Commercial Fluid-Bed Long Term Erosion/Corrosion Test in a Municipal Sewage Incinerator
Technology Support Test Plan - Commercial Fluid Bed Long Term Erosion/Corrosion Test in a Limestone Kiln
Task 3 - Site Evaluation - Real Estate Report

D. Program Review:

Phase 1 - Preliminary Engineering Program Review - July 13, 1976

☆U.S. GOVERNMENT PRINTING OFFICE: 1978-740-094/1001