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LONG TERM MATERIALS TEST PROGRAM:
ANNUAL REPORT AND QUALIFICATION TEST PLAN
OCTOBER 1979 --- SEPTEMBER 1980

By

GENERAL ELECTRIC COMPANY
Energy Systems Programs Department
Schenectady, New York

April 1981

Prepared for

UNITED STATES DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
Morgantown, West Virginia

Under Contract No. DE-AC21-79ET15457

TECHNICAL INFORMATION CENTER
UNITED STATES DEPARTMENT OF ENERGY

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ABSTRACT

This report summarizes the progress made on the LTMT Program during its first year and documents the test planning required to perform the Qualification Test. The objective of the Qualification Test is to check out the proper functioning of the Test Rig and to demonstrate its capability to produce a representative PFB off-gas environment for long term candidate-material testing.

During the first year of the program, the project has progressed from the concept stage to the start of construction. Ninety-five percent of the equipment has been ordered and renovations to accommodate the test rig have been initiated at the Malta Site.

The initial effort focused on the test rig configuration and selection of the candidate turbine materials. The preliminary design phase was officially culminated by the presentation and acceptance of the Preliminary Operations Plan to DOE during April, 1980. The detailed design was sub-contracted to Rist-Frost Associates, the architect engineer. By mid-June, 1981, the design of the major components was substantially complete allowing a detailed external design review to be performed. The design was accepted, and purchase orders for the major components were placed.

In parallel with the design effort, two materials-screening tests have been initiated. One thousand hours of testing on the oil-fired small burner rig and the first 250-hour segment on the erosion/corrosion simulator has been completed.

TABLE OF CONTENTS

Section	Title	Page
1	SUMMARY	1-1
2	INTRODUCTION	2-1
3	TEST DESIGN AND OBJECTIVES (TASK 1) AND LONG TERM MATERIALS QUALIFICATION TEST PLAN OBJECTIVES (TASK 1.1)	3-1
3.1	Long Term Materials Test (LTMT) Objectives	3-1
3.2	Qualification Test Objectives	3-1
3.3	Environmental Requirements For Emission Testing	3-1
3.3.1	Flue Gas Stream	3-1
3.3.2	Dust Collection System	3-2
4	LONG TERM MATERIALS TEST DESCRIPTION	4-1
4.1	General Layout and Design Point Data	4-1
4.2	Special Instrumentation and Data Acquisition	4-3
4.2.1	Particulate Measurement	4-3
4.2.2	Alkali Measurement	4-6
4.2.3	Gas Sampling System	4-8
5	PREQUALIFICATION CHECKOUT	5-1
5.1	Instrumentation Calibration	5-1
5.1.1	General	5-1
5.1.2	Coal and Dolomite Handling System	5-1
5.1.3	Compressor Tests	5-3
5.1.4	System Pressurization and Depressurization Tests	5-3
5.1.5	Bed Pressure Drop Test	5-4
5.2	Ignition Tests	5-4
5.3	Heat Exchanger Tests	5-7
5.4	Coal Firing Experiments	5-8
5.5	Pressure and Temperature Buildup To Design Conditions	5-11
5.6	Alkali Sensitivity To Bed Residence Time	5-12
5.7	Low Velocity Test Section (LVTS) Checkout	5-13
5.8	Cooling Chamber Test	5-13
6	QUALIFICATION TEST	6-1
7	SYSTEM DESIGN (TASK 1.2)	7-1
7.1	Overall System Design	7-1
7.2	Coal and Dolomite Feed	7-1
7.3	Combustor Design	7-4
7.4	Hot Gas Cleanup	7-12
7.5	Heat Loss Summary	7-14
7.6	Low Velocity Test Section	7-14
7.7	High Velocity Test Section	7-22
7.8	Gas Sampling Probe	7-25
7.9	Instrumentation and Controls	7-26

TABLE OF CONTENTS (Cont'd)

Section	Title	Page
8	TEST OPERATIONS (TASK 2.0)	8-1
9	MATERIALS EVALUATION (TASK 3.0)	9-1
10	PROGRAM MANAGEMENT (TASK 4.0)	10-1
11	MATERIALS SCREENING TESTS (TASK 5.0)	11-1
11.1	Small Burner Rig	11-1
11.2	Erosion/Corrosion Simulator	11-4
12	MATERIAL SYSTEM SELECTION (TASK 6.0)	12-1

LIST OF ILLUSTRATIONS

Figure No.	Title	Page
4-1	Long Term Materials Test Facility Process Flow Diagram	4-2
4-2	Long Term Materials Test Facility	4-4
4-3	Dust/Alkali Sampling System	4-5
4-4	Cumulative Dust Load Versus Particle Size	4-5
4-5	Expected and Measured Alkali Vapor Levels in Flue Gas	4-7
4-6	Alkali Sampling System	4-7
4-7	Gas Analysis System	4-9
4-8	Data Acquisition System (Temperature vs. Operating Hours)	4-10
4-9	Data Acquisition System (Outlet Temperature vs. Operating Hours)	4-10
4-10	Data Acquisition System (Pressure-Feed vs. Operating Hours) . . .	4-11
5-1	Operating Map Flow Through Bypass	5-5
5-2	Operating Map of Coal-Fired Flow Through Orifice	5-10
5-3	Cooling Air Inlet Temperature Requirements	5-13
6-1	LTMT Operating Map	6-2
7-1	Long Term Materials Test Facility	7-2
7-2	Screw Compressors (180 SCFM each)	7-3
7-3	General Arrangement of Long Term Materials Test Facility	7-5
7-4	Heat Loss Through Combustor Wall in Freeboard	7-6
7-5	Fluidizing Grid Design	7-6
7-6	Spent Material Cooling Chamber	7-8
7-7	Bed Off-Take System Temperatures	7-8
7-8	Bed Cooling Rate	7-9
7-9	In-Bed Heat Exchanger Area	7-9
7-10	Design of In-Bed Heat Exchanger	7-11
7-11	Insulation Thickness vs. Flue Gas Delta Temperature	7-12
7-12	Primary Cyclone	7-13
7-13	Cumulative Dust Load vs. Particle Size	7-14
7-14a	Assembly of Low Velocity Test Section Concept #1	7-16
7-14b	Interface Control for Low Velocity to High Velocity Test Sections	7-17
7-15	Uncooled Specimen Design	7-18
7-16	Cooled Specimen Design	7-18
7-17	Cooled Specimen Assembly	7-19

LIST OF ILLUSTRATION (Cont'd)

Figure No.	Title	Page
7-18	Specimen Cooling Arrangements	7-20
7-19	Effect of Dust Thickness on Specimen Surface Temperature if No Control Action Taken	7-21
7-20	Specimen Cooling Air Requirements	7-21
7-21	Cooling Air Inlet Temperature Requirements	7-22
7-22	High Velocity Test Section Cascade	7-23
7-23	High Velocity Test Section Pressure Vessel	7-24
7-24	HVTS Erosion Pin and Orifice	7-25
7-25	Insulated Tees and Gas Sampling Schematic	7-26
7-26	Process and Instrumentation Diagram for Long Term Materials Test Facility	7-29
10-1	Program Master Schedule, Long Term Materials Test Program	10-2
10-2	Cost Performance of LTMT	10-4
11-1	Schematic Cross Section of Small Burner Test Stand	11-1
11-2	Erosion/Corrosion Simulator	11-4
11-3	Contour Traces of FSX-414 Before and After 250 Hours of Erosion/ Corrosion Testing (Test #1) Leading Edges are Shown at Bottom of Page	11-6
11-4	Contour Traces of GE-2541 Clad IN-738 Before and After 250 Hours of Testing in the Erosion/Corrosion Simulator (Test #1). Leading Edge is at Bottom of Page	11-6
12-1	Specimen Replacement Schedule	12-3
12-2	Preliminary Materials Test Matrix for High Velocity Test Unit . .	12-3

LIST OF TABLES

Table No.	Title	Page
3-1	Operating Permit Requirements	3-2
4-1	Test Rig Design Point Operating Conditions	4-3
5-1	Instrumentation Checklist	5-2
7-1	Cascade Test Conditions	7-24
7-2	General Startup Procedure	7-28
7-3	Normal Shutdown	7-30
10-1	DOE Cost Performance: Purchased Parts Estimates (\$ x 1000)	10-3
11-1	Alkali and Sulfate Concentrations (Weight Percent)	11-2
11-2	Erosion-Corrosion Test Matrix	11-5

Section 1

SUMMARY

The 1979-1980 annual report serves two functions: to review the year's progress and to present the Qualification Test Plan.

The objective of the Qualification Test is to demonstrate that a representative PFB off-gas environment has been created for the downstream materials test and to verify the viability of the equipment. The test plan is presented in Section 3.2; the year's status is presented in the remaining sections.

During the first year of the Long Term Materials Test (LTMT) program, October 1979 to October 1980, the project has progressed from the concept stage to the start of construction. Ninety-five percent of the equipment has been ordered and the New York State Energy Research and Development Authority (NYSERDA) has started the building and grounds renovations.

The initial effort focused on the selection of the candidate turbine materials and the rig configuration. The February 28 and 29 PFB Materials Program Review provided an opportunity to summarize GE's experience with gas turbine materials, reach a consensus on the pertinent test conditions, and alter the rig configuration to include a bypass and parallel feed train. The preliminary design phase was concluded by the presentation of the Preliminary Operations Plan to DOE on April 4, a deliverable. The plan was accepted by DOE.

Rist-Frost Associates of Glens Falls, N.Y., our architect-engineer, began the detailed design of the LTMT rig on March 20 and delivered the last of the drawings in mid-August. The design of the major components was substantially complete by mid-June and was thoroughly reviewed by an external design review team on June 19. At that time, the design was deemed well executed, enabling orders to be placed based on previously solicited quotes.

The combustor design is based on the previously successful Coal Utilization Research Laboratory 12-inch ID rig. It has been modified to accommodate

a 6-inch refractory lining and to meet ASME fired pressure vessel code requirements. The bed will operate at 150 psia, 1750°F and 20% excess air. The expanded bed height will be 5.3 ft and has a 3 ft/sec fluidizing velocity. A 90% sulfur capture is felt to be achievable with the 1.8 second residence time and a 1.5 Ca/S ration.

Several configuration changes have been included during the final design phase. First, the exhaust heat exchangers were replaced by dilution air. All three cyclones have been mounted in one pressure vessel to reduce heat loss and the coal/dolomite storage vessel has been replaced with a 1-1/2 ton storage capacity mixer. Also the number of 1/4 inch OD pin specimens in the low velocity test section (LVTS) has been increased to 180. In retrospect, the design of the control system has been the most difficult task.

The candidate turbine coatings and claddings list has been updated to reflect the increase in available specimen locations. The Low Velocity Test Section will now have 120 uncooled specimens (1650°F) and 60 cooled specimens (1450°F). This plus the addition of FSX-414 (turbine nozzle base material) has expanded the total matrix to 1170 specimens utilizing 12 coatings and claddings.

The two materials screening tests are underway. The oil-fired small burner rig has completed 1000 hours of testing. The specimens were coated with a slurry of third cyclone catch and exposed at 1575°F. A highly corrosive atmosphere was not achieved; during retesting potassium will be added to the products of combustion. The first 250-hour erosion/corrosion simulator test has been completed using large particles (28% > 10 µm). The velocity was 960 ft/sec and it was fired at 1600°F. Erosion was evident on all specimens, as was internal oxidation. The second test, with normal size particulates (5% > 10 µm) is underway.

Section 2

INTRODUCTION

The General Electric Company is actively pursuing the commercialization of the Pressurized Fluidized Bed/Combined Cycle (PFB/CC) for power generation. This commitment is based on the advantages of the PFB cycle:

- High plant efficiency - Future plants project to 40% efficiency versus the present day coal-fired 35% with stack gas scrubbing
- Low emissions - 90+% sulfur removal and 1/3 the EPA requirement for NO_x
- High pressure - Allows a deep bed and therefore smaller combustor size
- Can burn any quality coal
- Dry solid waste product

The high plant efficiency is partially attributable to the power recovered by expanding the PFB off-gas through the gas turbine. However, as determined early in the PFB/CC development program, both a high efficiency particulate cleanup system and protective coatings and claddings are required to protect the gas turbine blading from erosion and corrosion. The LTMT will fill the latter technology gap by building on the encouraging but limited materials testing conducted by GE at Exxon's Miniplant and the National Coal Board's Coal Utilization and Research Laboratory rig in Leatherhead, United Kingdom.

The LTMT's operating point and dust loading, after cleanup, have been carefully selected to reproduce those which will be found in GE's commercial PFB/CC offering. More specifically, the LTMT's contribution is as follows:

- Long-term corrosion data. Specimen exposure times of up to 14,000 hours will provide a definition of the corrosion life curve. The initial corrosion rate will be determined as well as whether there is a corrosion breakaway point after extended exposure.
- Test a large number of materials inexpensively. The low \$122/test hour operating cost plus the 207-specimen capability will permit multiple data points, sampling at well spaced time intervals (250, 500, 1000, 5000 hours, etc.) and a large variety of candidate materials.

- 1750°F bed/1650°F test section temperatures. The high system temperatures are representative of the eventual commercial offering. LTMT system heat losses have been minimized to avoid supplemental gas firing and the associated uncertainty with condensation and revolatilization of the alkali vapor.
- Two specimen metal temperatures (1450°F and 1650°F). The 1450°F metal temperature is typical of the expected maximum gas turbine nozzle and bucket metal temperatures. The 1650°F metal temperature will provide data above the hot corrosion threshold.
- Uncouple corrosion and erosion effects. Corrosion resistance will be established in the low velocity test section while the downstream high velocity test section will test for the synergistic effects of erosion and corrosion.

The Long Term Materials Test is jointly sponsored by General Electric, the Department of Energy and the New York State Energy Research and Development Authority. General Electric is providing \$1 million for the purchase of the test rig. New York State ERDA is providing \$.75 million in site renovations and is leasing the building to GE. The Department of Energy is providing \$4.9 million for operating costs, design support, and the purchase of the LVTS.

Section 3

TEST DESIGN AND OBJECTIVES (TASK 1) AND LONG TERM MATERIALS QUALIFICATION TEST PLAN OBJECTIVES (TASK 1.1)

3.1 LONG TERM MATERIALS TEST (LTMT) OBJECTIVES

The overall objective of the 14,000-hour LTMT is to provide an economical assessment of the long-term corrosion response of gas turbine materials due to exposure in a PFB exhaust. Long-term corrosion effects will be evaluated from specimens exposed in the low velocity test section, while synergistic erosion/corrosion effects will be evaluated from specimens in the high velocity test section.

Specific objectives of the LTMT are to:

- Provide an actual PFB environment of uniform and known conditions representative of commercial PFB/CFCC operation
- Identify promising corrosion resistant materials for use in PFB/CFCC demonstration/commercial plants
- Evaluate the effect of temperature in reducing corrosion attack by utilizing cooled and uncooled specimens
- Evaluate, as a secondary objective, the synergistic erosion/corrosion effects on the materials in the high velocity test section

3.2 QUALIFICATION TEST OBJECTIVES

The qualification test plan will define the various tests required to:

- Verify the capability of the combustor and hot gas cleanup equipment to provide the proper PFB environment to evaluate the corrosion and erosion effects on the selected turbine materials
- Establish safe operating procedures while developing operator familiarity with the facility
- Demonstrate compliance with the environmental limits specified in the operating permit

3.3 ENVIRONMENTAL REQUIREMENTS FOR EMISSION TESTING

3.3.1 FLUE GAS STREAM

The pollutants identified in the flue gas stream are sulfur dioxide, particulates, nitrogen oxides and carbon monoxide. Permissible emission limits (in units of lb/hr) are identified for each of these pollutants in the permit issued by the New York State Department of Environmental Conservation (Encon) to allow construction of the LTMT. (See Table 3-1) The permits issued by Encon (A414000017500002I and

A414000017500002C) require reporting to Encon measurements of sulfur dioxide and particulates emissions within 60 days of startup in order to Encon approval to operate the LTMT. These data requirements should not impose any special requirements since they represent data planned as part of the normal test program. In addition to the sulfur dioxide and particulate emissions data required to be reported to Encon, measurement will also be made during this startup period of the carbon monoxide and nitrogen oxide emissions in order to verify the accuracy of the calculations used in estimating the amounts of these emissions. These data will determine whether or not any modification is required in the emission limits specified in the Encon permit approving operation of the LTMT. The pollutants being emitted are to be measured during steady state operation at the operating conditions to be used during the materials testing program.

Table 3-1
OPERATING PERMIT REQUIREMENTS

Pollutant	Estimated (lb/hr)	NYS Allowable (lb/hr)
Particulates	0.83	0.96
SO ₂	1.05	3.04
NO _x	0.48	0.48
CO	0.30	0.30

The operating permit from Encon can only be issued for a maximum period of three years. Therefore, it is anticipated that we will need to apply for renewal of the permit. It is not expected that Encon will require submission of any emissions data with the application for renewal of the permit, but will only require verification that the operation is the same as when the permit was originally issued. It is considered prudent, however, to have a minimum amount of data available to verify that we are meeting our permit limits in the event a challenge is raised by neighboring property owners. This presents no problem for sulfur dioxide or particulate which will be regularly measured as part of the LTMT test program. To provide data on carbon monoxide and nitrogen oxides, the measurements made during initial startup are to be repeated at yearly intervals.

3.3.2 DUST COLLECTION SYSTEM

The dust collection system is substantially over-designed for the particulate emission level allowed by our construction permit from Encon. There is no requirement from Encon to submit any emissions data for this system. Therefore, the only data requirement for the dust collection system is that we verify through a suitable acceptance test that the equipment as delivered and installed is performing according to specifications.

Section 4

LONG TERM MATERIALS TEST DESCRIPTION

4.1 GENERAL LAYOUT AND DESIGN POINT DATA

Figure 4-1 is the process flow diagram. Test rig operating conditions are listed in Table 4-1. Refer to Figure 4-2, the Long Term Materials Test Facility schematic, during the following discussion.

Coal and dolomite, delivered in separate 55-gallon sealed drums, are fed into a mixer which combines the solids and acts as storage vessel. A bucket elevator transports the solids from the mixer to either one of two solids feed lockhoppers. From the lockhoppers, the solids flow by gravity into the solids feed hopper and then to the rotary feeder which controls the rate of solids feed to the air transport line feeding the combustor.

The combustor in-bed heat exchanger will remove heat from the bed such that with a bed temperature of 1750°F at 150 psia, the excess air is 20%.

Hot (1750°F) combustion products leave the combustor and flow through three stages of cyclones before entering the materials test sections. Two test sections, designed to evaluate candidate gas turbine materials in a PFB flue gas environment, are arranged in series. The first of these is the low velocity test section designed to study long term materials corrosion effects. An orifice designed to operate choked at the design conditions is located just downstream of the low velocity test section. The function of the orifice is to maintain the proper flow rate of flue gas for a particular pressure and temperature. The flow characteristics of the combustor and the choked orifice are such that the fluidizing velocity is independent of pressure and is a function only of gas temperature in this facility. As shown in Figure 4-2, the combustor, hot gas cleanup and test sections are closely coupled to minimize heat losses.

After passing through the orifice, the flue gas enters the high velocity test section designed to study erosion effects on airfoil-shaped materials specimens. Diluent air from a blower is added to the hot gas at the exit of the high velocity test section to cool the gas to 1100°F before flowing through the main exhaust

Figure 4-1. Long Term Materials Test Facility Process Flow Diagram

valve to the stack. A bypass line around the test sections is provided for startup purposes. During startup, cooling air is injected into the bypass line upstream of the valve to keep the gas temperature below 1100°F. A key design requirement is to maintain a hot gas temperature entering the low velocity test section at 1650°F with a combustor bed temperature of 1750°F.

Table 4-1
TEST RIG DESIGN POINT OPERATING CONDITIONS

Coal flow rate	131 lb/hr (1.5 T/day)
Total air flow	1459 lb/hr (324 scfm)
Dolomite flow	41 lb/hr
Combustion products flow	0.4405 lb/sec (1586 lb/hr)
Gas temperature at L.V. test section	1650°F
Gas pressure at L.V. test section	145 psia
Gas pressure at H.V. test section inlet	41 psia
Gas temperature at stack inlet	1100°F
In-bed heat exchanger duty	801,000 Btu/hr (52% of Coal Heating Value)
Alkali concentration	Function of coal composition (see Figure 4-5)
Particulate load	27.96 lb/hr
Leaving combustor	
Leaving 1st stage cyclone	
Leaving 2nd stage cyclone	
Leaving 3rd stage cyclone	
Flue gas pollutants	1.05 lb/hr
SO ₂	
NO _x	
CO	

4.2 SPECIAL INSTRUMENTATION AND DATA ACQUISITION

4.2.1 PARTICULATE MEASUREMENT

The purpose of the particulate measurement is to establish the particulate concentration leaving the cleanup system to assist in evaluating erosion effects on the high velocity test section specimens and to demonstrate compliance with the operating permit.

1	COAL/DOLOMITE FEED	9	SPENT BED MATERIAL
2	MIXER	10	LVTS SPECIMENS
3	BUCKET ELEVATOR	11	SPECIMEN COOLING AIR MANIFOLD
4	COMBUSTOR	12	HVTS PRESSURE VESSEL
5	IN-BED HEAT EXCH.	13	BYPASS
6	LOCKHOPPER	14	CYCLONES
7	ROTARY VALVES	15	DUST/ALKALI ANALYSIS
8	AIR TRANSPORT LINES	16	GAS ANALYSIS

Figure 4-2. Long Term Materials Test Facility

Figure 4-3 shows the dust sampling system, which is located ahead of the low velocity test section. Time required to obtain the average sample will be approximately two hours. An isokinetic vortex mixing plate upstream will produce an even particulate distribution across the pipe. The dust samples collected will be evaluated on site by a technician trained to use the Coulter method. Figure 4-4 presents the estimated dust load. The dust load will be maintained as close as possible to the band of projected turbine tolerance and previous cascade test results.

Figure 4-3. Dust/Alkali Sampling System

Figure 4-4. Cumulative Dust Load Versus Particle Size

The system description is as follows:

- Flue gas into dust probe is controlled by the downstream flow control valve (Kates) to ensure isokinetic sampling
- Shutoff valve (Kamyr) is provided to isolate system
- A conoseal union joint (Aeroquip) is incorporated into the system as a connect/disconnect point for duct sampling or alkali sampling
- First cooling coil reduces the gas temperature to about 500°F to accommodate the Balston filter housing rating of 1000°F max at 100 psia
- Dust is collected by a Balston total filter (Grade BH) enclosed in an oven at 400°F to keep the gas temperature above the dew point. Temperature and pressure measurements are taken at this point.
- The second cooling coil lowers the gas temperature to about 80°F as required by the rotameter.
- A second Balston filter with automatic drain is provided to collect any particulate not retained by first stage
- The dryer (Perma Pure) removed most of the moisture content and lowers the gas dew point to about 40°F
- The flow control valve (Kates) automatically compensates for any pressure variations. The flow rate is set by a dial
- The rotameter (Brooks) provides visual indication of the flow

4.2.2 ALKALI MEASUREMENT

The purpose of the alkali sampling is to determine the alkali vapor content of the PFB effluent (parts per million by weight). The alkali sampling train cyclone and filter dust will also be analyzed to complete the definition of the alkali available for corrosion. The alkalies will reach the turbine parts through vapor condensation and dust deposition.

The alkali sampling system and test procedure has been designed to accommodate the following:

- Maintain the sample gas at 1650°F until it reaches the ice bed to prevent the alkali vapor from condensing prematurely
- Minimize cyclone/dust carryover into ice bath since 90% of the available alkalies are carried with the particulates
- A minimum of 1 hour of sample time is needed to obtain an average sample and to assure at least 100 ppm in the steel ball wash solution
- Multiple samples must be taken since the data is expected to scatter
- Take an isokinetic sample

The expected alkali content is 0.3 to 10 ppm; see Figure 4-5. The water wash solution and dust samples will be analyzed off-site for Mg, Ca, K, Na, Cl and sulfate.

Figure 4-5. Expected and Measured Alkali Vapor Levels in Flue Gas

Figure 4-6 presents the alkali sampling system. The expected sampling time is one to four hours and will be determined during the qualification test procedure. Turnaround time to evaluate the samples is approximately four days.

Figure 4-6. Alkali Sampling System

The alkali sampling system description follows:

- Flue gas into probe is controlled by downstream flow control valve (Kates) to provide isokinetic sampling
- Shutoff valve (Kamyr) provided to isolate system
- Conoseal union joint (Aeroquip) is incorporated as a connect/disconnect point for dust and alkali sampling system
- Cyclone and filter are enclosed by a pressure vessel which in turn is enclosed by an electric oven operating at 1650°F to ensure isothermal sampling
- Gas is then expanded in a 2" OD tube containing steel balls to capture the alkali content
- Dryer (Perma Pure) provided to dry and lower the gas dew point to about 40°F
- A flow control valve (Kates) automatically controls the flow dialed and compensates for any pressure variations
- Rotameter (Brooks) provides visual indication of flow

4.2.3 GAS SAMPLING SYSTEM

The gas sampling system will provide continuous monitoring of O_2 , SO_2 and CO_2 . O_2 is a measure of excess air, which will be maintained at greater than 20% to prevent the formation of reducing zones in the combustor. SO_2 is a measure of the sulfur capture ratio. Deviations from 90% will require changes in the coal/dolomite ratio added to the mixer to regulate sulfur capture as coal and dolomite composition varies. CO_2 is a backup measure of excess air in case the O_2 instrumentation fails.

Figure 4-7 is a sketch of the gas analysis system used to make continuous evaluations of O_2 , CO_2 , and SO_2 . The procedure is described below.

- A gas conditioning system is provided next to the pickup point to clean up the flue gas of particulates. It also lowers the temperature and pressure required by the analyzers, providing at the same time a lower dew point (approx. 40°F) for the gas. This arrangement eliminates the provision of any heated line to transport the gas to the control room where the analyzers are located.
- A dryer (Perma Pure) is provided in the control room to further ensure the elimination of any moisture present in the gas.
- Auto zero and span calibration modules are provided to each analyzer, which upon command will zero and span the output of each instrument independently. These modules incorporate a lockout feature to hold the last reading prior to auto zero span, thus allowing the process to continue uninterrupted during calibration.
- Adjustable high and low alarm contacts are incorporated into the analyzers to provide signals to the existent control system

Figure 4-7. Gas Analysis System

Equipment to measure NO_x and CO will be rented during the qualification test and annually throughout the test to satisfy the operating permit conditions.

4.2.4 DATA ACQUISITION SYSTEM

A 250-channel HP85/3497A data acquisition system will monitor all thermocouples and transducers. The system, which is expandable to 999 channels, will scan the 250 channels once each minute. Each scan will evaluate each channel for high and low level settings. If data observed is beyond alarm limits, alarms will be sounded and if necessary, immediate test shutdowns commence.

Scanned data will be stored once every five minutes on a disc recording device. On a regular basis (probably weekly), the pertinent data will be stored in a permanent manner on tape, disc or graphic display (see Figures 4-8, 4-9, and 4-10).

Two 24-channel recorders will present a continuous record of pertinent data that will quickly indicate trends and real time operating points. One recorder will monitor 24 temperatures, while the other will monitor transducers for flow and pressure.

In addition to the data recording system there is considerable hard wired safety logic which will prevent unsafe operating practices such as series opening of lockhopper valves or operating with vessel shell temperatures above design limits.

Figure 4-8. Data Acquisition System (Temperature vs. Operating Hours)

Figure 4-9. Data Acquisition System (Outlet Temperature vs. Operating Hours)

Figure 4-10. Data Acquisition System (Pressure-Feed vs. Operating Hours)

Section 5

PREQUALIFICATION CHECKOUT

The prequalification checkout will verify that the instrumentation and equipment is functioning and will develop startup and shutdown procedures.

5.1 INSTRUMENTATION CALIBRATION

5.1.1 GENERAL

To evaluate test conditions, critical instrumentation will be calibrated against NBS-traceable standards and checked at regular intervals. Records will be maintained for all instrumentation calibrations to assist in the evaluation of the specimen histories.

Prior to the ignition test, all pressure, flow, temperature, and level instrumentation has been checked for operability and correct polarity. The continuity of switches, alarms, lights, interlocks, and shutdown relays has been verified. Calibration curves will be programmed into the HP85 data acquisition system.

Table 5-1 presents an example of the record that will be maintained for instrumentation. It requires the checkout of lights, alarms, switches, shutdown relays and interlocks. The technician will initial the data sheet when the proper installation, setpoints and continuity of the instrumentation has been verified.

The following equipment can be calibrated at the earliest convenience after installation: coal and dolomite handling system, compressors, system pressurization and depressurization.

5.1.2 COAL AND DOLOMITE HANDLING SYSTEM

The mixer, lockhopper and feed hopper operational logic, including level detectors and indicators, is functional from a check following installation.

The mixer and storage feed lockhoppers weighing systems will be calibrated by incrementally filling the components with known weights.

Table 5-1
INSTRUMENTATION CHECKLIST

DESCRIPTION	TEST SIGNAL INPUT	LIGHTS		ALARM	LEVEL		SHUTDOWN			POSITION SWITCH		SWITCH			INDICATOR	INTERLOCK	CHECK	
		MAIN PANEL	REMOTE PANEL		UNITS	VOLTS	RELAY	LEVEL		RIGHT OPEN	LEFT CLOSED	UNITS	LEVEL					
								UNITS	VOLTS				UNITS	VOLTS			DATE	INITIAL
Low Velocity T.S. Temperature	TE 579-1	TL 579-1		TAH 579-1								TSH 579-1	-	-				
	579-2	579-2		579-2								579-2	-	-				
	579-3	579-3		579-3								579-3	-	-				
	579-4	579-4		579-4								579-4	-	-				
	579-5	579-5		579-5								579-5	-	-				
Pressure	TE 573	TL 573																
	FI 296											PSL 296	-	-				
High Velocity T. S. Temperature	TE 581-1	TE 581-1		TAH 581-1	-	-	SD1R	-	-			TSH 581-1	-	-				
	581-2	581-2		581-2	-	-	SD1Q	-	-			581-2	-	-				
	581-3	581-3		581-3	-	-	SD1P	-	-			581-3	-	-				

Rotary feeders will be calibrated over the range of speed by the following procedures:

- Disconnect the flange below the rotary valve
- Measure coal/dolomite flow per unit time as valve speed is varied in 10% increments over its range
- Plot rotary valve speed vs. feed rate

5.1.3 COMPRESSOR TESTS

Compressors will be operated to determine the quantity of oil carryover. Demister drains downstream of the compressor will be checked for oil. If oil is present, the compressors will be readjusted.

The compressor autostart feature, which automatically starts the next compressor as needed, will be checked by allowing exhaust pressure to drop below the set point. Flow and pressure stability will be evaluated by noting compressor performance characteristics throughout the qualification test plan. The compressor pressure relief valves are mounted at the compressor outlet. The settings and reseating capability will be checked during cold pressurization of the system. Since the maximum compressor pressure is 165 psig (180 psia), there is no chance of system overpressure.

5.1.4 SYSTEM PRESSURIZATION AND DEPRESSURIZATION TESTS

The system will have to be pressurized and checked for leaks whenever components are changed or added. To do this, valves FCV 152, 153, and 154 will be shut. If the test sections are not in place, an end plate will be used to seal the test section connecting flange. Pressure will be established and maintained at 150 psia while technicians check for a leak free system. Any leaks must be eliminated and the system rechecked.

The system pressure characteristic will be determined by evaluating several pressurization rates. Recording the response for at least four valve positions will confirm that the valves are correctly sized. Depressurization rates should also be varied to cover the range that could occur during emergency shutdowns.

An overpressurization check can be performed during one of the runs by raising pressure to 165 psig and verifying that the compressors will not exceed this.

Pressurization data to be taken include:

Location	Computer	Chart Recorder
2 Combustor Pressures	Yes	Yes
2 Cyclone Pressures	Yes	Yes
2 Cyclone ΔP 's	Yes	Yes
5 LVTS Pressures	Yes	Yes
3 LVTS ΔP 's	Yes	Yes
2 HVTS Pressures	Yes	Yes
5 HVTS ΔP 's	Yes	Yes

5.1.5 BED PRESSURE DROP TEST

The bed pressure drop test will be performed cold at atmospheric pressure. The objective is to calibrate the pressure drop measurement system and determine the range of air purge flows required to keep pressure lines clear without affecting pressure measurements.

The test will consist of adding spent bed material in 12" increments until a bed height of 8 ft is reached. At each height, data will be taken at fluidizing velocities of 2, 3 and 4 ft/sec to observe the effect of changes in fluidizing velocity on bed level and to evaluate the bed level response obtained from ΔP measurements.

Bed pressure drop test data will include:

Identification	Computer	Chart Recorder
2 Combustor Pressures	Yes	Yes
4 Combustor ΔP 's	Yes	Yes
2 Flows	Yes	Yes
2 Cyclone ΔP 's	Yes	Yes

5.2 IGNITION TESTS

The objectives of the ignition tests are to document a procedure that minimizes the time required to heat the bed to approximately 700°C (1292°F), the temperature at which coal will ignite, and to develop data relating cooldown time to fluidizing velocity after propane flow is terminated.

The manufacturer's curing and bake-out procedures have been completed. The rate of change of temperature for the first operational heat up should not exceed 200°F/hr. Subsequent heat-up cycling can be done at any normal rise rate.

Figure 5-1 presents an estimated operating map showing air flow vs. bed temperatures from 100 to 1400°F. Superficial velocities are labeled. The map will be used as a guide to show the operator how to adjust air flow and temperature while maintaining excess air > 20%.

Figure 5-1. Operating Map Flow Through Bypass

The ignition test will be performed at atmospheric pressure by injecting an 18" to 24" expanded height startup bed of spent material into the combustor with the bed coolant system in operation (if it is available).

Ignition start and stop experiments will consist of:

- Fluidizing the bed (1 to 1-1/2 ft/sec)
- Igniting the torch
- Adjusting the fuel/air ratio and propane flow so that the flame settles into the bed (as indicated by thermocouples)
- Obtaining flame proved signal
- Verifying propane cutoff is effective

Propane flow to the bed can occur only when the torch is on or the bed is above 1000°F. Shut off the torch with temperature above and below 1000°F and observe propane flow to the bed

- When bed temperature is 700-800°C (1292-1472°F), turn off the ignition and pull it out

Experience at the Coal Utilization Research Laboratory (CURL) in the United Kingdom indicates the startup velocity should be 1 to 1-1/2 ft/sec., increasing to 2 or 3 ft/sec as the bed heats up. This will require reducing the air flow to compensate for the increase in volume with temperature. It should take approximately 40 minutes to raise the bed temperature to 1300°F.

Terminate propane flow and maintain air flow until bed temperature is reduced to ~ 100°C (212°F) before shutting down air flow and slumping the bed. Repeat the cooldown at different air flow rates to establish a desirable range of air flow during the shutdown procedure.

The result of the torch start and stop experiments will be a procedure that specifies the correct combination of fuel/air ratio to minimize the time required to heat the bed to approximately 700 to 800°C (1292 to 1472°F), (the temperature at which coal will ignite), a range of air flows, and the effect on the cooldown cycle.

As the bed temperature increases, the hot piping hangers will be visually checked for clearance and free movement at each 300°F increment. This visual check to ensure freedom from binding due to thermal expansion will be repeated during the first heatup following addition or replacement of any components throughout the LTMT program.

The ignition tests will be repeated several times, according to the following general guidelines from CURL, to develop operator familiarity with the process by recording and evaluating the effects of parameter changes.

- Begin with 18-24 inches of bed material so that bed surface is below the heat exchanger surface
- Begin circulating bed coolant
- Begin admitting main air and increase until the bed P taps begin to oscillate indicating a fluidized bed
- Light off the ignitor (torch)
- Admit propane to bed. The ΔP taps will show a violent swing when ignition of the main propane occurs. A continuous popping sound indicates the bed is either too rich or too lean. The initial mixture should be fairly rich in oxygen with 5% or 6% O_2 in the exhaust.
- After several trials have developed familiarity with the ignition and bed warmup procedure, demonstrate that the bed temperature can be maintained in the range of 700-800°C (1292 to 1472°F) on propane with the bed height raised to 3 ft.
- Do not operate with O_2 less than 1% on propane
- Do not burn propane above about 2 atmospheres pressure because the intensity is so great it will sinter the bed

Data for ignition tests include:

<u>Identification</u>	<u>Computer</u>	<u>Chart Recorder</u>
22 Combustor Temperatures	Yes	16
2 Combustor Pressures	Yes	1
4 Combustor ΔP 's	Yes	2
2 Combustor Flows	Yes	2
10 Combustor Shell Temperatures	Yes	10
Propane Flow	Yes	1
3 Cyclone Temperatures	Yes	3
6 Cyclone Shell Temperatures	Yes	6
2 Cyclone Pressures	Yes	2
2 Cyclone ΔP	Yes	2
Gas Analysis O_2	Yes	Yes
CO_2	Yes	Yes

After observing shell and combustor temperatures on the computer, any out of line will be placed on the chart recorder. This may be an indication of refractory problems or a faulty thermocouple.

5.3 HEAT EXCHANGER TESTS

The heat exchanger design will be verified during the coal firing experiments if it is available. With the bed temperature at 1750°F, bed height at 6 ft, pressure at 150 psia and a fluidizing velocity of 3 ft/sec, a heat balance will be performed to determine the heat transfer coefficient. If the excess air is $\geq 20\%$, the test will be continued. If the excess air is $< 20\%$, the heat exchanger will have to be replaced with one of lower surface area.

The test will be repeated at several cooling flows to evaluate sensitivity.

If the heat exchanger is not available, the coal firing and pressurization experiments will proceed and the heat exchanger will be verified later.

Data for heat exchanger tests follows.

<u>Identification</u>	<u>Computer</u>	<u>Chart Recorder</u>
22 Combustor Temperatures	Yes	8
2 Combustor Pressures	Yes	2
4 Combustor ΔP 's	Yes	2
2 Combustor Flows	Yes	2
10 Combustor Shell Temperatures	Yes	3
3 Coal Feed Temperatures	Yes	2
8 Coal Feed Pressures	Yes	2
3 Coal Feed Weight Systems	Yes	2
4 Coal Feed Level Indicators	Yes	3
2 Coal Feed Rotary Feeders	Yes	1
3 Bed Heat Exchanger Temperatures	Yes	3
3 Bed Heat Exchanger Pressures	Yes	3
1 Bed Heat Exchanger Flow	Yes	1
1 Bed Heat Exchanger ΔP	Yes	1
3 Cyclone Temperatures	Yes	1
2 Cyclone Pressures	Yes	1
2 Cyclone ΔP 's	Yes	2
6 Cyclone Shell Temperatures	Yes	6

5.4 COAL FIRING EXPERIMENTS

The bed will be fired to 700°F (1292°F) on propane according to the procedure developed during the ignition tests (Section 3.2). The bed level will be raised to 3 feet, with spent bed material. Experience at CURL suggests that dolomite tends to disintegrate due to the calcination at atmospheric pressure of both calcium and magnesium. This produces fines which are elutriated from the bed. At higher pressures, only the magnesium calcines. Thus the recommendation is made to use Molochite or spent bed material to build up the bed during the startup process.

During startup, the bed buildup can be accomplished by:

- Feeding coal with excess inert
- Feeding inert from the spare feeder
- Feeding a combination of coal/dolomite from one feeder and inert material from the other feeder
- Dumping inert material from above the bed

The change from propane to coal during startup is quite rapid. The sequence to be followed is:

- Turn on the coal feed

- When the O_2 level starts down or temperature increases $20^\circ F$, cut the propane fairly abruptly. The objective is to feed the coal such that the O_2 level is the same as it was before cutting the propane
- Establish a steady condition with excess air $\geq 20\%$
- Increase coal feed and raise the bed temperature to 1500 to $1750^\circ F$
- Experiment with the bed buildup procedures and feed rates to be used while maintaining excess air $> 20\%$. The first attempt to reach a 6-ft bed height will be at $1500^\circ F$ to $1600^\circ F$, to allow for temperature fluctuations during buildup. Based on the results, increase bed temperature on subsequent trials.
- Shutdown coal flow and cool bed at different air flow rates to establish the most desirable cooldown procedure

The transition from propane to coal is smoother as the temperature increases. Thus, the transition should be performed at 1300, 1400 and $1500^\circ F$ to establish the most acceptable temperature range.

Figure 5-2 is an estimated operating map showing air flow vs. bed pressure for bed temperatures from $1400^\circ F$ to $1750^\circ F$ when the bed is coal-fired and all flow passes through the test section. The dashed line is the region of subcritical flow through the orifice at $1400^\circ F$. Assuming an air flow of 275 lb/hr at $1400^\circ F$, Figure 5-1 shows the bed pressure would be ~ 0.7 psig when flow is through the bypass. At the same flow and temperature, Figure 5-2 shows the bed pressure would be ~ 6.5 psig when flow goes through the test section. Thus, an increase in pressure will accompany the change in flow from the bypass to the test section. The operator should maintain excess air $\geq 20\%$ while adjusting coal and air flow to reach desired operating conditions.

The most convenient startup procedure would be to use the coal/dolomite mixture for bed buildup to avoid filling one set of feedhoppers with inert material. Therefore, a trial run will be conducted using coal/dolomite for bed buildup to compare with spent bed material startup times.

A recent experiment at Grimethorpe was not successful. However, a leaky seal was discovered, and material thought to be elutriated was accounted for. Thus, it is worthwhile to try starting up on the coal-dolomite mixture as a convenience considering the number of startups that will be conducted.

The coal firing experiments will result in a procedure for transferring from propane to coal and building the bed height to 6 ft at 1500 to $1750^\circ F$, and a correlation of cooldown rates and air flows to establish appropriate action in future system failures. As part of the cooldown experiments, a minimum bed temperature will be established for refiring on coal.

Data for coal firing experiments will include:

Identification	Computer	Chart Recorder
22 Combustor Temperatures	Yes	4
2 Combustor Pressures	Yes	2
4 Combustor ΔP 's	Yes	3
2 Combustor Flows	Yes	2
10 Combustor Shell Temperatures	Yes	3
3 Coal Feed Temperatures	Yes	3
8 Coal Feed Pressures	Yes	4
3 Coal Feed Weight Systems	Yes	2
4 Coal Feed Level Indicators	Yes	2
2 Coal Feed Rotary Feeders	Yes	1
3 Bed Heat Exchanger Temperatures	Yes	3
3 Bed Heat Exchanger Pressures	Yes	3
1 Bed Heat Exchanger Flow	Yes	1
1 Bed Heat Exchanger ΔP	Yes	1
3 Cyclone Temperatures	Yes	3
2 Cyclone Pressures	Yes	2
2 Cyclone ΔP 's	Yes	2
6 Cyclone Shell Temperatures	Yes	3
Gas Analysis O_2	Yes	1
CO_2	Yes	1
SO_2	Yes	1

If the bed heat exchanger is not available, proceed with the test.

Figure 5-2. Operating Map of Coal-Fired Flow Through Orifice

5.5 PRESSURE AND TEMPERATURE BUILDUP TO DESIGN CONDITIONS

The combustor will be stabilized with a 3-ft bed at 1500°F to 1600°F with a fluidizing velocity of 3 to 4 ft/sec and at ~ 15.5 psia according to the procedures previously developed. The 1500°F to 1600°F bed temperature provides operating margin for upsets or errors in the first pressurization procedure.

Bed material is fed in to raise the bed level to 6 feet. As the cooled tubes in the heat exchanger are progressively immersed in the bed, the operating pressure, air flow and coal feed rate are increased to maintain an approximately constant bed temperature and fluidizing velocity with excess air $\geq 20\%$.

Combustor pressure will be increased to 150 psia according to the following guidelines:

- Watch bed ΔP while increasing pressure and maintain slight but not too violent fluctuations
- Increase pressure in 5 psi increments, adjusting air flow to maintain bed ΔP fluctuations, and coal flow to maintain O_2 level. Continue until operating pressure (150 psia) is reached.
- Take a complete set of dust and alkali samples at 50, 100 and 150 psia. Raise the bed temperature to 1750°F at 150 psia with a fluidizing velocity of 3 ft/sec and obtain dust and alkali samples
- Reduce coal flow to return bed temperature to 1500°F. Depressurize, maintaining excess air $\geq 20\%$

After evaluating temperature transients, the procedure will be repeated at a higher temperature and faster pressurization rates.

The intended results of experiments performed will be:

- Development of startup and shutdown procedures selected to ensure safe operation of the facility while minimizing start-up and shutdown time
- Familiarization of operating personnel with the sensitivity of various parameters
- Development of operating maps

The cooling chamber test (Section 5.8) shows the procedure to verify the design requirements.

Data for pressure and temperature buildup to design conditions will include:

<u>Identification</u>	<u>Computer</u>	<u>Recorder</u>
3 Coal Feed Temperatures	Yes	1
8 Coal Feed Pressures	Yes	2
3 Coal Feed Weight Systems	Yes	1
4 Coal Feed Level Indicators	Yes	1
2 Coal Feed Rotary Feeders	Yes	1
3 Bed Heat Exchanger Temperatures	Yes	3
3 Bed Heat Exchanger Pressures	Yes	3
1 Bed Heat Exchanger Flow	Yes	1
1 Bed Heat Exchanger ΔP	Yes	1
22 Combustor Temperatures	Yes	13
2 Combustor Pressures	Yes	2
4 Combustor ΔP 's	Yes	3
2 Combustor Flows	Yes	2
10 Combustor Shell Temperatures	Yes	5
3 Cyclone Temperatures	Yes	1
2 Cyclone Pressures	Yes	1
2 Cyclone ΔP	Yes	1
6 Cyclone ΔP Shell Temperatures	Yes	1
Gas Analysis O_2	Yes	1
CO_2	Yes	1
SO_2	Yes	1

5.6 ALKALI SENSITIVITY TO BED RESIDENCE TIME

With pressure at 150 psia, bed temperature at 1750°F, obtain alkali samples for bed heights of 4, 5, 6, 7 and 8 feet. This will demonstrate the sensitivity of alkali content with bed residence time and may establish an allowable operating band on bed height as it affects residence time.

A complete set of dust, alkali and gas samples should be taken at each bed level. If the alkali sampling system is not available for the qualification test plan, this data should be obtained as soon as possible after the equipment is installed.

5.7 LOW VELOCITY TEST SECTION (LVTS) CHECKOUT

The LVTS is not expected to be available and is not required for the preceding tests. Installation of the LVTS must be followed by a pressurization check and expansion check every 300°F during the first heatup.

The initial test will be performed with thermocouples mounted on several instrumented specimens to demonstrate the cooled specimens can be maintained at 1450°F (200°F below the exhaust gas temperature of 1650°F) with the combustor at rated conditions. To observe the sensitivity of specimen temperature to air flow, cooling air will be adjusted to ± 10 , 20 and 30%. After steady state is reached at each new flow, the cooling air temperature will be adjusted to return the specimen temperature to 1450°F. This will allow a check of cooling air inlet temperature requirements at design conditions (see Figure 5-3) and a sensitivity evaluation of changes in key parameters.

Figure 5-3. Cooling Air Inlet Temperature Requirements

5.8 COOLING CHAMBER TEST

The cooling chamber test will be performed as soon as there is bed material to be cooled. It must be verified that the average temperature of the bed material is reduced from 1750°F to below 700°F over a 30-minute period, and that the temperature of the 6-inch steel containment pipe is below 1000°F.

Section 6

QUALIFICATION TEST

The qualification test is a 100-hour run utilizing three-shift operation to demonstrate the capability of continuous operation at design conditions.

Startup and shutdown will follow the procedures described in Section 5. All available data will be monitored on the data acquisition system. The first 50 to 75 hours will be used to fine tune the controls and observe normal operating behavior. During the last part of the checkout, data to satisfy the operating permits will be taken.

The 100-hour qualification test run will provide an opportunity for a final shakedown of the data acquisition system. The following data will be monitored continuously and recorded every 15 minutes. Out-of-tolerance conditions will be recorded more frequently until the variables return within the tolerance level. The weekly average and deviation will be developed from the 15-minute data samples:

- Cooled specimen temperatures
- Low velocity test section gas temperature
- High velocity test section gas temperature
- Bed temperature
- Oxygen level
- SO₂ level

Figure 6-1 is an estimated operating map at rated conditions for the combustor and heat exchanger. Although data will be available from the prequalification checkout, the long-term qualification test presents the opportunity to vary parameters at pressure to verify or modify Figure 6-1.

A mass balance is obtained by taking a dust sample downstream of the cyclones as described in Section 4.2.1. Samples will be taken from each cyclone catch and size distributions obtained by the Coulter method. The summation of the sample result and cyclone catches according to weight proportions is the particulate concentration leaving the bed. The total measured dust load will be compared to the estimated particulate distributions presented in Figure 4-4, to demonstrate that

the combustor particulate emissions are representative or that changes will be required in the cleanup system.

A coal sample will be sent to a lab to obtain Proximate and Ultimate analyses as well as sodium, potassium and chlorine content and size distribution.

A chemical analysis of dolomite will include sodium, potassium, and chlorine as well as size distribution.

Bed off-take and cyclone catches will be analyzed for constituents, water soluble sodium, potassium and chlorine and carbon content.

Combustion efficiency will be calculated by analyzing the particulate sample and cyclone catches for unburned carbon. Combustion efficiency is the ratio of heat input (coal lb/hr * Higher Heating Value) minus energy content of unburned carbon (lb carbon in residue * 14093 Btu/lb) to the heat input.

Following the extended qualification test run, the facility will be shut down and all test specimens inserted in the low and high velocity test sections. Following a pressurization check and expansion check on the first heatup, the 250-hour corrosion validation test will begin.

The result of the qualification test plan will be a set of operating procedures and operator familiarity with the facility.

Figure 6-1. LTMT Operating Map

Section 7

SYSTEM DESIGN (TASK 1.2)

7.1 OVERALL SYSTEM DESIGN

The overall dimensions of the long-term materials test facility are 27 feet high, 24 feet long, and 12 feet deep. The component arrangement is shown in Figure 7-1. Not shown are the compressors, the control room, air/water heat exchanger and the dust collector.

The overall system design philosophy used to configure the rig is as follows:

- One-man operation
- Automatic alarm, then shutdown on parameters that could cause injury or test specimen damage
- Simple and straight-forward controls (hard-wired)
- Lockhopper and equipment interlocked for safe operation
- Emergency power for control room
- 24 hours/day, 5 days/week operation
- 17,000-hour minimum component lives
- Standard off-the-shelf equipment where possible

7.2 COAL AND DOLOMITE FEED

A Kelley Duplex vertical mixer and bucket elevator has been selected. The mixer has a 1-1/2 day capacity (150 ft³) while the bucket elevator has a 2 tph capacity. The mixer will operate during the filling operation. Pre-dried and crushed coal (1/8 inch to 0) and dolomite are poured in the inlet bin and mixed via an elevating screw feed.

The bucket elevator is gravity-fed from the bottom of the mixer and is operated once every 1-1/2 hours. The combustor will be fed from one coal/dolomite feed train while the other is being filled. A diverter gate at the elevator exits will direct the coal to the desired storage train.

Figure 7-1. Long Term Materials Test Facility

The fill sequence is as follows (see Figure 7-1):

- Close FCV 104 to separate the storage and feed hoppers
- Vent the upper storage hopper
- Open FCV 103 and fill the upper hopper using the bucket elevator
- Close FCV 103
- Repressurize with nitrogen
- Equalize the two vessel pressures
- Open FCV 104

The upper lockhopper has a 1-1/2 hour capacity while the lower lockhopper has a 1/2 hour capacity. The 1/2 hour capacity in the lower lockhopper allows continuous operation from one feed train should the other fail. These lockhopper vessels will be ASME Code stamped, nitrogen purged and rupture disk protected. The dust is controlled by venting the equipment to a Flex-Kleen dust collector (3500 cfm, 100 lb/day).

The major instrumentation on the lockhoppers are load cells for weighing, level detectors as a backup full/empty indicator, and TCs for fire detection.

Approximately 30% of the combustion air is required to transport the coal and dolomite from the rotary feed valve (FV 105) to the PFB. The rotary valve speed is used to control the coal flow rate while the rate requirement is based on bed temperature. The air velocity in the transport lines will be kept below 45 ft/sec to avoid erosion.

The air is being supplied by four single-stage screw-type compressors (one spare). The overall requirement is for 500 cfm at 160 psig; see Figure 7-2.

Figure 7-2. Screw Compressors (180 SCFM each)

7.3 COMBUSTOR DESIGN

Figure 7-3 shows the design of the PFB combustor with a bed diameter of 12 inches. The pressure containment vessel is made up of two 24-inch diameter pipe sections and a 24-inch tee, all fabricated from carbon steel. The pressure vessel is closed at the upper end with a blind flange and at the lower end with the fluidizing grid. Overall height of the combustor from the fluidizing air inlet holes to the centerline of the gas outlet pipe is about 14 feet.

Insulation of the cylindrical walls and the top flange is provided by a dual layer of castable refractory insulation. A two-inch thick inner layer of insulation is formed from a hard refractory $\left(K \approx 4.9 \frac{\text{Btu-in}}{\text{HrFt}^2\text{°F}}\right)$ chosen to withstand the abrasive action of the fluidized bed and particulate-laden flue gases. A four-inch thick outer layer is formed from an insulating refractory $\left(K \approx 1.8 \frac{\text{Btu-in}}{\text{HrFt}^2\text{°F}}\right)$ to minimize heat losses. Castable refractories are readily available from A.P. Green, Plibrico, etc. The design point bed height is 5.2 feet, which corresponds to a freeboard height of about 9 feet. Calculated heat losses through the combustor walls in the freeboard are shown in Figure 7-4 as a function of combustor OD (insulation thickness). Heat losses are expressed in terms of the flue gas temperature drop due to the heat losses at the design flue gas flow rate. Also plotted in Figure 7-4 is the outer surface temperature of the combustor vessel. At a combustor diameter of 24 inches, the flue gas ΔT is 52°F and the vessel surface temperature is 246°F. A substantial increase in combustor OD would be required to achieve modest reductions in the heat loss.

Figure 7-5 shows the design of the fluidizing grid. It has been patterned after a design used by the National Coal Board (NCB) at Leatherhead, England. Fluidizing air enters the large plenum, flows into the individual nozzles and discharges into the combustion chamber through holes in the nozzles which are designed for a 2 psi pressure drop. The air holes are positioned 3 inches above the plate, providing 3 inches of "dead bed" material which acts as a thermal insulation. Coal and dolomite are conveyed by transport air up the central tube and are discharged into the combustion chamber through the tee. During startup, the bed is heated by burning propane, which enters the small plenum in the fluidizing grid and flows into nozzles where it mixes with the fluidizing air and enters the combustion chamber. The propane is ignited by a pilot burner located in the combustor wall 18 inches above the fluidizing air inlet holes.

Figure 7-4. Heat Loss Through Combustor Wall in Freeboard

Figure 7-5. Fluidizing Grid Design

In addition to instrumentation ports, the major penetrations of the combustor vessel shown in Figure 7-3 are the relief valve connection near the top, a connection for adding bed material during startup, and the spent bed material offtake port near the bottom. As coal and dolomite enter the combustor, the bed height builds up at an estimated rate of 10.5 inches/hr. The bed height will be allowed to increase about 6 inches (10% of the 5-ft bed height) before removing the excess, resulting in a bed removal frequency of once per 34 minutes, or about every half hour. The spent bed material is discharged into a lockhopper where the pressure is let down to atmospheric. To avoid exposing the lockhopper inlet valve to material at 1750°F, the bed material is first discharged into a holdup volume where the material is cooled to about 700°F. A preliminary design of the cooling chamber is shown in Figure 7-6. The chamber consists of a 6-inch stainless steel pipe with four 1-inch cooling tubes positioned within the volume as shown. Air is the coolant flowing in the tubes. Design requirements on the cooling chamber are (1) that the average temperature of the bed material must be reduced from 1750°F to below 700°F over a 30-minute period; and (2) the temperature of the 6-inch steel containment pipe must be kept below a safe maximum, say 1000°F. During the 30-minute cooldown period, heat is lost from the bed material to the cooling tubes and to the containment pipe which rejects heat to the ambient by radiation and natural convection. Figure 7-7 shows the calculated transient temperatures in the cooling chamber over the 30-minute period. This indicates that the bed material temperature and the containment wall temperature will be below 700°F after 30 minutes. At the beginning of the transient, heat is transferred rapidly from the material in contact with the vessel to the steel vessel, resulting in a jump in the steel temperature and a corresponding cooling of a thin layer of material next to the wall. This thin layer of material then acts as an insulator which protects the wall (and slows the cooling process) during the remainder of the cooling process.

The function of the combustor in-bed heat exchanger is to remove heat from the bed such that with a bed temperature of 1750°F and a bed pressure of 150 psia, the excess air will be 20%. Figure 7-8 shows the bed cooling rate as a function of excess air with bed temperature, pressure, fluidizing velocity, and air inlet temperature constant at the combustor design conditions shown on the figure. At an excess air value of 20%, the in-bed heat exchanger duty is 801,000 Btu/hr.

The in-bed heat exchanger will consist of water-cooled tubes immersed in the bed. At the design point, the water inlet temperature to the combustor is 113°F

and the outlet is 185°F. The corresponding water flow rate is 3.056 lb/sec, or about 22 gpm.

Figure 7-6. Spent Material Cooling Chamber

Figure 7-7. Bed Off-Take System Temperatures

Based on a proprietary CURL correlation, the bed heat transfer coefficient is predicted to be between 65 and 70 Btu/hr ft² °F. Figure 7-9 is a plot of in-bed heat exchanger area as a function of excess air for various values of in-bed heat transfer coefficient. The philosophy in selecting a heat exchanger area is to maintain excess air above 20%. Examination of Figure 7-9 shows that the excess air will be equal to or greater than 20% if we select an area corresponding to $u = 70$ Btu/hr ft² °F (the highest expected value) and an excess air equal to 20%. The required area is then 7.15 ft². If it turns out that the actual bed heat transfer coefficient is 65 rather than 70 Btu/hr ft² °F, then, from Figure 7-9, the corresponding excess air will be 25%.

Figure 7-8. Bed Cooling Rate

Figure 7-9. In-Bed Heat Exchanger Area

Figure 7-10 shows the design of the in-bed heat exchanger. The interlaced helical coil arrangement was selected to break up the bubbles and suppress bed slugging. It is felt that this design offers the advantage of ease of fabrication. For ease of forming the coils, the tube diameter should be as small as possible. On the other hand, the water-side pressure drop increases rapidly as the tube diameter is decreased. Based on pressure drop limitations, the minimum tube diameter is about 0.75-inch OD with 0.065-wall (0.62" ID). For this size tubing, the total length required is 36.4-feet which provides 7.15 ft^2 of surface area.

Based on the configuration shown in Figure 7-10, three sets of coils, six rows deep, give the required tube length. The overall height of the heat exchanger is 2.0 ft. The water-side pressure drop in a straight 0.62" ID tube, 36.41 ft long is about 42 psi, but the total water pressure drop with bends is estimated to be 80 psi. Water velocity in the tube is 23.4 ft/sec.

The water inlet and outlet pipes to the in-bed heat exchanger will pass vertically through the combustor feed board and penetrate the combustor at the top. If the freeboard height is 9 ft., then the hot flue gas is exposed to 18 ft. of water-cooled pipe causing a substantial drop in flue gas temperature before it gets out of the combustor. Figure 7-11 is a plot of flue gas temperature loss due to heat transfer to the water inlet and outlet pipes as a function of insulation thickness for three values of insulation thermal conductivity. The lower curve is representative of "MIN-K" which is a Johns-Manville product having outstanding insulating properties. An uninsulated pipe results in a 46°F drop in flue gas temperature which is unacceptable. One-half inch of MIN-K insulation will reduce this to about 11°F , which is acceptable.

The general arrangement of the bed heat rejection system is shown in Figure 7-1. Water from the pump flows through the in-bed heat exchanger, exits at the top of the combustor and flows through an air-cooled radiator where the heat removed from the bed is rejected to ambient. The radiator is sized assuming an air inlet temperature of 93°F . When the inlet air temperature changes, there will be a corresponding change in the water temperature at the combustor inlet and outlet. The plan is to monitor the water temperature at the combustor outlet. When the water temperature drops, a portion of the hot water will be bypassed around the radiator to avoid overcooling the water. A water conditioning system is planned for the make-up water.

FIGURE 10. Pg. 1-14

RFA-3493

Figure 7-10. Design of In-Bed Heat Exchanger

Figure 7-11. Insulation Thickness vs. Flue Gas Delta Temperature

7.4 HOT GAS CLEANUP

The task of the hot gas cleanup system is to simulate the particle size and distribution which will be available in the eventual commercial PFB power plant. Both will use three stages of cyclones.

The primary cyclone will be 8 inches in diameter, and the next two will be 6 inches in diameter. The cyclone dimensions shown in Figure 7-12 are representative of high efficiency cyclones now in industrial use. Their performance has been predicted to reduce the cumulative dust load from 10 gr/scf to 0.2 gr/scf with a maximum particle size of 8 microns, see Figure 7-13. This compares favorably with the projected gas turbine tolerance where maximum size is thought to be the most critical parameter in preventing gas turbine erosion. The prior experience of Exxon and CURL cascade tests is also shown. A cyclone arrangement has been chosen in which one 6-inch cyclone could be eliminated.

The cyclones will be constructed from 310 stainless steel with the dip legs heat traced to prevent condensation and clogging. Thermal expansions are accommodated with a stainless steel bellows. Particulates are removed through a manually operated lockhopper. The particulate loading will be evaluated using a system comprised of an isokinetic probe, Balston total filter and a Coulter counter.

The cyclones have been located in a single 4-foot diameter containment vessel to minimize heat loss. The vessel will be ASME code stamped and capable of with-

Technical drawing of a mechanical part, likely a piston or a similar component, showing dimensions and a list of values.

Dimensions and values:

- $D_c = 3"$
- $D_e = 4"$
- $l = 22"$
- $a = 4"$
- $b = 1.6"$
- $h = 12"$
- $H = 32"$
- $s = 3"$
- $s = 6"$

The drawing includes a side view of the part, a cross-section view, and a list of dimensions and values. The side view shows a tapered shape with a central vertical line and a horizontal line. The cross-section view shows a rectangular shape with dimensions D_c and D_e . The list of values includes $D_c = 3"$, $D_e = 4"$, $l = 22"$, $a = 4"$, $b = 1.6"$, $h = 12"$, $H = 32"$, $s = 3"$, and $s = 6"$.

7-13

Figure 7-13. Cumulative Dust Load vs. Particle Size

7.5 HEAT LOSS SUMMARY

A design requirement for the test facility is that the flue test temperature drop from the surface of the combustor bed to the inlet of the low velocity test section shall be less than 100°F. The following tabulation is a summary of the calculated losses:

<u>COMPONENT</u>	<u>FLUE GAS T, °F</u>
Loss through combustor wall in freeboard	52
Loss to water lines in combustor feedboard	10
Loss in cyclone vessel	4
Connecting line loss (estimated)	<u>10</u>
	76

The estimated 76°F total loss adds reassurance that the 100°F limit can be met without propane injection to reheat the gas.

7.6 LOW VELOCITY TEST SECTION

The low velocity test section will be used to study long-term corrosion effects on candidate gas turbine materials exposed to high temperature combustion products from a pressurized fluidized bed combustor. Materials test specimens will have a

simple cylindrical shape and these will be both uncooled and cooled (metal temperature cooled to 1450°F average) specimens. Design requirements for the low velocity test section are as follows:

Gas inlet temperature	1650°F
Gas inlet pressure	145 psia
Gas velocity in test section	< 200 ft/sec
Number of uncooled specimens	120
Number of cooled specimens	60
Specimens easily removed for inspection	
Life	14,000 hrs
Thermal cycles	200

Figures 7-14a and b show the design of the low velocity test section which consists of a 4-inch ID pipe, the materials test specimens, and the specimens, and the specimen holders. The materials specimens are 1/4-inch OD cylinders which extend radially into the gas stream from the 4-inch pipe. At each of 60 specimen locations, two uncooled specimens extend to near the center of the 4-inch pipe, and one cooled specimen passes through the 4-inch pipe. Thus, there are 120 uncooled specimens and 60 cooled specimens. The specimens are supported by tubes which penetrate the thermal insulation as shown. Each set of three specimens (two uncooled, one cooled) is rotated 45° relative to the preceding set to break up wakes in the gas stream. Design of the uncooled and cooled materials specimens are shown in Figures 7-15 and 7-16, respectively. Details of an air-cooled specimen assembly are shown in Figure 7-17.

The design requirement for the cooled specimens is that specimen metal temperature at the midpoint of the specimen be held at 1450°F, which is 200°F below the temperature of the hot gas stream. Figure 7-18 shows the arrangement of the specimen cooling air system. Air from the compressor passes through a control valve which will hold the pressure in the inlet manifold constant at 50 psia. An electric heater will be used to control the cooling air inlet temperature to the required value. A choked orifice at the inlet cooled specimen will determine the cooling air flow which is a function of the upstream pressure and temperature.

During the course of the experiment, it is anticipated that a layer of dust will build up on the surface of the specimens exposed to the combustor flue gas. If no action were taken (cooling air flow and inlet temperature unchanged) the specimens would be overcooled as shown in Figure 7-19. The objective is to maintain a constant metal surface temperature (on the cooled specimens) of 1450°F. This requires that the cooling air inlet temperature be increased with increasing

Figure 7-14a. Assembly of Low Velocity Test Section Concept #1

Figure 7-14b. Interface Control for Low Velocity to High Velocity Test Sections

dust thickness as shown in Figure 7-20. Note that the cooling air temperature rise decreases with increasing dust thickness -- that is, the cooled specimen becomes a less effective heat exchanger as the thermal resistance increases due to dust buildup.

Figure 7-15. Uncooled Specimen Design

Figure 7-16. Cooled Specimen Design

Figure 7-17. Cooled Specimen Assembly

Figure 7-18. Specimen Cooling Arrangements

Figure 7-19. Effect of Dust Thickness on Specimen Surface Temperature if No Control Action Taken

Figure 7-20. Specimen Cooling Air Requirements

The cooling air temperature rise, then, is a measure of the dust buildup and will be used as the basis of controlling the cooling air. Figure 7-21 shows the cooling air inlet temperature required to maintain a 1450°F metal surface temperature as a function of cooling air ΔT . The control scheme will be as follows:

- Measure the cooling air ΔT
- Determine the required cooling air inlet temperature from Figure 7-21
- Adjust the electrical heater power to give the required cooling air inlet temperature

Figure 7-21. Cooling Air Inlet Temperature Requirements

In this approach, the metal temperature is inferred from measurements of the cooling air inlet and outlet temperatures. We are also looking at the possibility of attaching thermocouples to the outer surface of about five of the cooled specimens to assure that the proper specimen metal temperature is being maintained. Specimen failure will be detected by monitoring individual cooling air exhaust temperatures.

7.7 HIGH VELOCITY TEST SECTION

The function of the high velocity test section is to study long-term erosion effects on candidate gas turbine materials exposed to high temperature PFB flue gasses at velocities in the 800 to 900 ft/sec range. The plan is to refurbish and use the high velocity test section which was used in the NCB's CURL 10 x 100 hour test. Figure 7-22 shows the conceptual design of the test section consisting of

three cascades of six impulse vanes and one cascade of six reaction vanes followed by three erosion pins. The impulse vanes turn the flow without a significant velocity change while the reaction vanes accelerate and turn the flow.

Figure 7-22. High Velocity Test Section Cascade

Table 7-1 is a summary of design conditions in the high velocity test section. Velocities entering the airfoil specimens range from 825 to 969 ft/sec, and the velocity just upstream of the erosion pins is 1432 ft/sec. The hot gas duct of the high velocity test section is rectangular in cross section with flat plate walls which cannot withstand a large ΔP . In order to minimize this ΔP , the test section is contained within a pressure vessel as shown in Figure 7-23. Pressure equalization holes are drilled through the gas duct near the inlet. Differential thermal expansion between the hot gas duct and the pressure vessel is accommodated with the piston seal arrangement shown in Figure 7-23.

Figure 7-23. High Velocity Test Section Pressure Vessel

Table 7-1
CASCADE TEST CONDITIONS

	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>Throat</u>	<u>5</u>	<u>Orifice</u>
Total Temperature, °F	1650	1650	1650	1650	1650	1650	1650
Static Temperature, °F	1606	1602	1598	1590	1511	1518	1395
Total Pressure, psia	40.9	39.6	38.3	36.9	36.9	34.1	34.1
Static Pressure, psia	37.1	35.6	34.1	32.2	26.9	25.3	18.8
Mach Number	0.392	0.412	0.43	0.462	0.715	0.695	1.0
Velocity, ft/sec	825	867	904	969	1470	1432	1995

The high velocity test section has been used previously by GE for the CURL 10 x 100 hour test. The cascade channel is being modified to include bolt-on cover-plates to hold the vanes instead of the welded design.

The mechanism for holding the oblong erosion pins is shown in Figure 7-24. The pins will not be cooled for the LTMT test. Also shown is the orifice plate which will maintain the HVTS at 41 psi.

Figure 7-24. HVTS Erosion Pin and Orifice

7.8 GAS SAMPLING PROBE

A cross section of the insulated tees and gas sampling probe is shown in Figure 7-25. The isokinetic probe will be utilized for both dust and alkali sampling (not concurrently). Also shown is the extraction point leading to the gas analysis equipment for on-line monitoring of O_2 , SO_2 and CO_2 .

Figure 7-25. Insulated Tees and Gas Sampling Schematic

7.9 INSTRUMENTATION AND CONTROLS

The LTMT control philosophy is as follows:

- Keep the design simple and easy to troubleshoot
- All controls will operate on a 4-20 mA signal with 3-15 psi conversion for actuator control at the end point
- Any condition which could become a hazard or damage the test section will create an alarm and an automatic shutdown if the control parameters exceed preset limits
- Controls are interlocked to prevent accidents that may arise from improper operating commands

The conditions requiring automatic shutdown have been limited to those listed below:

Shell over-temperature on containment vessels
 Fuel transport line over-temperature
 Over-temperature of exhaust gas at control valve inlet
 Combustor temperature high
 Test section inlet temperature high
 Control air supply pressure low
 Cyclone ΔP high/low
 Bed heat exchanger ΔP

O₂ level below 20% excess
Fire in equipment or building
Operator activation of shutdown sequence

Conditions are sensed by data logger and where possible, analog switches.

Briefly, the PFB steady-state operation is accomplished by maintaining bed temperature, bed pressure, Ca/S mole ratio and bed height. By doing so, the levels of excess air, fluidizing velocity, and gas chemistry will be sustained.

Bed temperature and pressure are controlled automatically by adjusting coal and air flow. Bed height is controlled manually by periodically removing bed material through the bed off-take cooler and lockhopper. The Ca/S mole ratio is obtained by premixing the coal and dolomite in proper proportions.

Since there is a choked orifice at the exit of the low velocity test section, system pressure is maintained simply by controlling the flow of air into the combustor. This pressurizing air is the sum of the fluidizing air and transport air. A control scheme is incorporated to maintain transport air velocity at around 30 ft/sec independent of system pressure. In no case is transport air more than 30% of the total pressurizing air flow.

To control combustion temperature, the output voltage of one of the five bed thermocouples is selected and provided to a transducer. The transducer output signal, 4 to 20 mA, is linearly proportional to the input temperature signal. This transducer's output, which can be adjusted in span, is the input to the SCR motor controller. As the 4 to 20 mA signal increases, the motor rotary valve speed decreases. A failure of the control thermocouple would stop the coal supply. An over-torque situation in the coal feeder will create an alarm, plus a switchover to the standby coal feed train.

The normal startup and shutdown is manual and outlined in Tables 7-2 and 7-3 respectively. Note that the bypass loop does not operate at pressure. Coordinating the valves to transfer the flow at full pressure was felt to be too difficult.

The automatic shutdown consists of shutting off the coal flow and main fluidizing air while opening a small bypass air valve. See Figure 7-1 for the valve arrangement. The bypass air will provide bed cooldown and carbon burnout during shutdown. The in-bed heat exchanger coolant flow is shut off manually after bed cooldown.

A complete instrumentation list will not be attempted. However, the major process instrumentation is worth summarizing (also see Figure 7-26 for the LVTS instrumentation):

- In-bed thermocouples (5)
- Bed pressure (3)
- LVTS and HVTS inlet pressure and temperature
- Gas sampling at LVTS inlet (O_2 , CO_2 , and SO_2)
- Dust sampling at LVTS inlet
 - isokinetic probe
 - Balston filter
 - Coulter counter
- Air flow orifices
- Coal lockhopper load cells
- Bed coolant orifice and inlet and exit temperature
- Cooled materials sample surface TCs (5)

Table 7-2

GENERAL STARTUP PROCEDURE

1. Trace heating on cyclones and LVTS
2. Water to in-bed heat exchanger
3. Bypass valve open - main exhaust closed
4. One foot of bed material in combustor
5. Fluidize bed material ~ 2 ft/sec
6. Start cooling air to bypass line
7. Light pilot flame
8. Inject main propane
9. Turn off and withdraw ignitor
10. When bed reaches 1300°F, start coal feed with excess inert
11. Turn off main propane when bed temperature is about 1500°F
12. Start specimen cooling air
13. Begin opening main exhaust slowly; start blower
14. Continue opening main exhaust such that test section temperature increases uniformly over 20 minutes
15. After opening main exhaust, close bypass and bypass cooling air valves simultaneously. Bed pressure will rise to about 6 psig.
16. Increase air flow to increase bed pressure and simultaneously increase coal flow to maintain constant bed pressure; bring bed pressure to 140 psia
17. Bring bed temperature to 1750°F

Figure 7-26. Process and Instrumentation Diagram for Long Term Materials Test Facility

Table 7-3
NORMAL SHUTDOWN

1. Cutback on air flow to reduce bed pressure while maintaining bed temperature
2. When bed pressure is about 10 psig, open bypass and bypass cooling valves
3. Stop blower, close main exhaust valve, and stop specimen cooling air
4. Allow coal feed hopper to go empty
5. Continue air flow until bed temperature is below 1000°F
6. Stop air flow
7. Remove spent bed material

A data logger will monitor approximately 240 channels and produce an alarm whenever a channel is out of limits. The logger will also give a paper tape print-out in engineering units for selected channels.

In parallel to the data logger, two 24-point strip chart recorders will monitor transducers and other data requiring continuous data output.

Section 8

TEST OPERATIONS (TASK 2.0)

No activities planned for this task during this reporting period.

Section 9

MATERIALS EVALUATION (TASK 3.0)

Orders have been placed for the cast pin specimens and the cascade airfoils. Quoting reluctance was encountered due to the difficulty in casting a 6-inch long, 1/4-inch OD, 1/8-inch ID pin. The vendor is permitted to increase the OD if required.

The low velocity test section will be constructed from RA333 due to the unavailability of Hasteloy-X. RA333 has slightly more chrome and like Hasteloy-X, it is suitable for high temperature and pressure applications.

A high chromium ferritic stainless steel, Type 444 (UNS S444000), will be used for the in-bed heat exchanger. Type 444 stainless will provide short-term high temperature corrosion resistance and high resistance to stress corrosion cracking. It is carbide stabilized with Nb and Ti to prevent intergranular attack.

Section 10

PROGRAM MANAGEMENT (TASK 4.0)

Overall, the LTMT program is on schedule and on budget. The technical progress was first offered at the February PFB Materials Program Review, held to summarize General Electric's experience with gas turbine protective materials in the PFB environment and to solicit opinions on the rig configuration. At the conclusion of the preliminary design phase, April 4, the Preliminary Operations Plan was presented at Morgantown and accepted.

The detail design phase took place from late March through mid-August with a design review of the major components on June 19. The quotation process started in mid-May and orders were placed starting June 19 following the design review go ahead. As of October 1, 1980, 95% of the equipment has been ordered. The exceptions are the dust and alkali analysis equipment and the high velocity test section modifications. These are short lead time items.

Substantial rig completion is expected in December and qualification testing by the end of March. The official DOE light-off milestone is April 1.

The New York State supplied facilities renovations have begun and will be completed for the LTMT by March 1981. New York State is supplying improvements in the form of a road, landscaping fences and storage areas. Internally, the building is being redecorated and control rooms, laboratory, cranes and a LTMT exhaust stack are being added.

The LTMT program is on schedule. Referring to Figure 10-1, the Master Schedule, deliverables 1 (Management Plan) and 1A (Preliminary Operations Plan) were delivered on time. Due to technical difficulties in completing the EPRI sponsored Simulation Rig, deliverable number 9 has been delayed until April 1981. Presentation of the Qualification Review was also delayed until mid-December to allow us to concentrate our efforts on the rig construction. The combined Yearly Report and Qualification Plan is presented here:

Figure 10-1. Program Master Schedule, Long Term Materials Test Program

The required permits are:

<u>Permit</u>	<u>Approval Date</u>
Permit to Construct - NYS ENCON	August 18, 1980
Order of Consent (4% S) - NYS ENCON	August 18, 1980
Permit to Operate - NYS ENCON	60 days after light-off
DOE Environmental Go Ahead	Required by light-off

The LTMT is on budget; see Figure 10-2. The actual costs reported to DOE plus the commitments to vendors and nonESPD departments is projected to be \$1.1 million, which is what was provided in the contract. The forward funding has kept pace with the cost plan.

Hardware costs are also expected to be within budget as shown in Table 10-1.

Table 10-1
DOE COST PERFORMANCE: PURCHASED PARTS ESTIMATES
(\$ x 1000)

	<u>Contract</u>	<u>Current*</u>
Low Velocity Test Sections and Mock-Up	30.0	39.9
Cooling Manifolds		7.5
Miscellaneous Instrumentation and Materials		11.3
Air Heated		4.8
High Velocity Test Section	45.0	16.7 ⁽¹⁾
Pressure Vessel		2.5
Particulate Analysis	61.2	16.0 ⁽²⁾
Alkali Sample Probes and Dust Sample System	6.7	2.9
Heated Vessel (Est.)		3.0
Test Specimens - LVTS/HVTS	73.0	
TRW		53.4
Howmet		3.4
Coatings/Claddings	<u>51.8</u>	<u>71.3</u>
	267.3	232.4

*Dollars Represent Actual Expenditures, Purchase Orders Placed, or Firm Quotes for which P.O.'s will be Placed.

(1) Modify CURL HVTS (2) GE owns Coulter Counter - Save \$45K

Figure 10-2. Cost Performance of LTMT

Section 11

MATERIALS SCREENING TESTS (TASK 5.0)

11.1 SMALL BURNER RIG

The small burner rig (SBR) is used to obtain corrosion penetrant data to allow prediction of the behavior of materials in combustion (propane, fuel oil) atmosphere containing various amounts of injected contaminants (sodium, potassium, sulfur, vanadium, chlorine and lead).

The test stands consist, in part, of a combustion zone in which the fuel is burned, Figure 11-1. The combustion products pass over a rack holding up to 21 disc specimens nominally 1-inch (25 mm) in diameter and 0.060-inch (1.5 mm) thick. The combustion tube is contained in an electric furnace having two sections; the forward section controls the temperature of the primary combustion air at about 500°F (260°C) and the aft section is used as a ballast heater to minimize temperature variations between the specimens.

Figure 11-1. Schematic Cross Section of Small Burner Test Stand

Propane enters the combustion chamber at slightly higher than atmospheric pressure. Liquid fuels are supplied by a gear pump through a hypodermic needle that has a small concentric clearance around it through which atomizing air can pass.

Corrosion disc specimens are sliced from investment cast and heat treated bars of 1-inch diameter x 6-inch length (25 mm x 150 mm). The specimens are machined to a diameter of 0.95-inch (24 mm) and carefully ground to a nominal 0.060-inch (1.5 mm) thickness with a tolerance of ± 0.0005 inch (0.001 mm) so that the two sides are parallel.

To date, several programs^(1,2,3) have attempted to develop small burner rig test parameters which faithfully duplicate the corrosion accompanying coal combustion processes; none has been notably successful. The attempts in this program are directed at improving the simulation by directly incorporating the influence of flyash in the experiment. The first series of tests, in which the stability of the flyash and its ability to cause corrosion without the injection of additional corrosive media has been completed.

Initial tests indicate the flyash could be effectively applied to the surfaces of specimens and retained through drying and subsequent burner rig exposure. Ten percent of the deposit was lost after 24 hours, and 15% was lost after 90 hours of testing. Chemical analysis of the deposit after 90 hours of testing at 1575°F revealed that approximately 1% of the total alkali concentration (Na and K) has been lost. The analysis did reveal a shift in the proportions of Na to K, Table 11-1.

Table 11-1
ALKALI AND SULFATE CONCENTRATIONS
(Weight Percent)

	<u>CURL Flyash</u>	<u>Deposit</u>
Na	0.18	0.86
K	0.95	0.10
SO ₄	13.0	9.9

¹Fireside I

²Fireside II

³CFCC

In the final test of this series, flyash coated specimens of GE-2541, IN-738, IN-671 and IN-100 were exposed to 1575°F in the burner rig with an SO₂ overpressure to maintain sulfate concentration. Specimens were removed from the test after 250 hours and evaluated. Generally, only mild surface oxidation was observed on the IN-738, IN-671 and GE-2541 specimens. No hot corrosion was detected. The IN-100 specimen did suffer hot corrosion, which was attributed to the presence in the alloy of vanadium, which reduces the melting point of the oxide films to below the rig operating temperature.

Deposits taken from specimens in this test are being analyzed for sulfate, sodium, and potassium.

The second test series will evaluate the effects of different levels of alkali dopants on the composition of flyash. The alkali dopants to be used will be based on the PFB simulation composition developed in the Fireside I program. The constituents of this test are: Na, K, S, Cl and Mg. The chloride and magnesium are generally included in small burner rig tests together as MgCl. The resultant deposit contains a substantial quantity of MgSO₄ which, together with Na₂SO₄ and K₂SO₄, form constituents which melt around 1200°F. These low melting phases may dramatically (and unrealistically) increase corrosion rates. Analysis of PFB deposits reveals that only trace quantities of MgSO₄ appear on tested airfoils, as MgSO₄ is generally unstable at the temperature of operation. However, large quantities of CaSO₄ are present in PFB deposit. Therefore, calcium chloride will be substituted for magnesium chloride in the fuel dopant. The three major sulfates (Na₂SO₄, K₂SO₄, CaSO₄) of PFB flyash will thus be present in the deposit of the small burner rig. Initial composition of the fuel dopant will be as follows: 79 ppm Na, 112 ppm K, 116 ppm CaCl and 1% S. Modification of this input will be made, if necessary, based on comparison of the resultant deposit in the burner rig to that obtained in the PFB.

The third preliminary test series will establish the influence of additional chlorine on the composition of the deposit on the specimens. In this test, 15 ppm of HCl will be added directly to the combustion air to increase the volatility of the alkali species in the one atmosphere pressure test.

From these four tests the conditions producing deposits on the specimens most simulative of the actual PFB deposits will be chosen.

11.2 EROSION/CORROSION SIMULATOR

In addition to corrosion testing in the small burner rig, the suspected synergism of erosion and corrosion is being investigated using the General Electric erosion/corrosion simulator (ECS) facility. The simulator, Figure 11-2, is capable of exposing airfoil specimens (identical in geometry to those in the high velocity test section) to simultaneous erosion and corrosion under precisely controlled conditions. The erosion rate is easily varied by adjusting the dust concentration and size distribution. The corrosion rate is varied by adjusting the dopant level.

Figure 11-2. Erosion/Corrosion Simulator

Since this rig operates at one atmosphere, it can exactly duplicate the corrosive environment in the improved small burner rig simulation. Using this corrosive simulation, the effect of various dust levels can be readily explored, ranging from little or no erosivity (as in the LTMT low velocity test section) to highly erosive conditions (as in the high velocity test section).

Experiments in the ECS facility will be analyzed to determine empirical relationships between erosion and corrosion. The data thus obtained will be used to relate the small burner rig experiments to the observed phenomena in both the low velocity and high velocity test sections of the LTMT facility.

Currently five tests are planned in the simulator, Table 11-2. To date, two tests have been successfully completed, Test I and II.

The results of Test I indicate surface oxidation and some slight hot corrosion has occurred on the bare materials IN-738 and FSX-414. Slight erosion of the leading edges and pressure surfaces of these materials was also noted. The FeCrAlY and CoCrAlY clad materials resisted both corrosion, oxidation, and erosion much better than the bare alloys. Essentially no hot corrosion or erosion was noted. Apparent internal oxidation of area experiencing particle impaction was noted possibly due to breakage of the oxide film and subsequent selective oxidation of the high yttrium-phases.

Contour traces of FSX-414 and FeCrAlY before and after test are shown in Figures 11-3 and 11-4. The erosion at the leading edge of FSX-414 is easily noted. Conversely the profile of the FeCrAlY clad airfoil shows very little erosion. Areas of deposition can be noted on both posttest airfoils.

The second test (Test II) has been completed. No analysis of these airfoils has been made. Detailed metallography of both these and specimens from Test I are underway.

Table 11-2
EROSION-CORROSION TEST MATRIX

Test	I	II	III	IV	V
	(250 Hr)	(250 Hr)	(250 Hr)	(250 Hr)	(1000 Hr)
Specimen	CoCrAlY (Lo Al)	CoCrAlY (Lo Al)	CoCrAlY (Lo Al)	CoCrAlY (Lo Al)	CoCrAlY (Lo Al)
	CoCrAlY (Hi Al)	CoCrAlY (Hi Al)	CoCrAlY (Hi Al)	CoCrAlY (Hi Al)	CoCrAlY (Hi Al)
	IN-738	IN-738	IN-738	IN-738	IN-738
	FeCrAlY (Lo Al)	FeCrAlY (Lo Al)	FeCrAlY (Lo Al)	FeCrAlY (Lo Al)	FeCrAlY (Lo Al)
	FSX-414	FSX-414	FSX-414	FSX-414	FSX-414
Conditions	1600°F;	1600°F;	1600°F;	1600°F;	1600°F; (To Be
	1000 Ft/Sec;	1000 Ft/Sec;	1300 Ft/Sec;	1000 Ft/Sec;	Determined)
	72% of particles	98% of particles	98% of particles	98% of particles	
	< 10 µm at	< 10 µm at	< 10 µm at	< 10 µm at	
	100 ppm; 2x10 ⁻¹¹	100 ppm; 2x10 ⁻¹¹	100 ppm; 2 x 10 ⁻⁴	1869 ppm; 2x10 ⁻¹¹	
	moles/cc/sec	moles/cc/sec	moles/cc/sec	moles/cc/sec	
	corrosive media	corrosive media	corrosive media	corrosive media

Figure 11-3. Contour Traces of FSX-414 Before and After 250 Hours of Erosion/Corrosion Testing (Test #1) Leading Edges are Shown at Bottom of Page

Figure 11-4. Contour Traces of GE-2541 Clad IN-738 Before and After 250 Hours of Testing in the Erosion/Corrosion Simulator (Test #1). Leading Edge is at Bottom of Page

Section 12
MATERIAL SYSTEM SELECTION (TASK 6.0)

The preliminary selection of materials has been modified to reflect the perceived requirement to protect cast cobalt-base alloys, generally used as nozzle materials, in the PFB environment. This expansion also more completely utilizes the uncooled pin specimen slots in the low velocity test section. Twelve materials have been identified as promising candidates and will be used pending the results of the screening tests.

The expanded matrix results in the following total specimen requirements.

Alloy	Uncooled Pin	Cooled Pin	Impulse Airfoil	Reaction Airfoil	Erosion/Corrosion Pin	Total
IN-738	240	200	180	63	27	710
FSX-414	120	80	80	28	12	320
U-500	20	20	20	7	3	70
IN-739	20	20	20	7	3	70
TOTAL	400	320	300	105	45	1170

This expansion is also reflected in the planned utilization of these materials in the testing of protective systems which is as follows:

Base Alloy	Protective System	Identification	Process	USE ⁽¹⁾				
				Low Vel. UP	Vel. CP	High Velocity		
						IA	RA	E/C P
IN-738	FeCrAlY	GE-2541	Clad	20	20	20	7	3
IN-738	FeCrAlY	ATD-17	Coating	20	20	20	7	3
IN-738	CoCrAlY	PFB-6	Clad	20	20	20	7	3
IN-738	CoCrAlY	ATD-14	Coating	20	20	20	7	3
IN-738	CoCrAlY	ATD-2	Coating	20	20	20	7	3
IN-738	Aluminide +Pt	RT-22	Coating	20	20	20	7	3
IN-738	Aluminide	RT-19	Coating	20	20	20	7	3
IN-738	Thermal Barrier	PS-TBC	Plasma Spray	20	--	--	--	--
IN-738	CoCrAlY	GT-29	Plasma Spray	20	--	--	--	--
IN-738	Ni-48Cr	IN-671	Clad	20	20	--	--	--
IN-738	None ⁽²⁾	--	--	40	40	40	14	3
FSX-414	Aluminide +Rh	RT-44	Coating	20	20	20	7	3
FSX-414	CoCrAlY	ATD-2	Coating	20	20	20	7	3
FSX-414	FeCrAlY	ATD-17	Coating	20	--	--	--	--
FSX-414	CoCrAlY	ATD-14	Coating	20	--	--	--	--
FSX-414	None ⁽²⁾	--	--	40	40	40	14	3
U-500	None	--	--	20	20	20	7	3
IN-739	None	--	--	20	20	20	7	3

(1) UP-Uncooled pin; CP-Cooled pin; IA-Impulse airfoil; RA-Reaction airfoil; E/C P-Erosion/Corrosion pin.

(2) Includes 1 spare set plus one set for potential coating cladding system

Twelve of these materials will be evaluated cooled and uncooled in the low velocity test section. Each material will have six specimen positions of the uncooled type and five specimen positions of the cooled type in the rig at the same time. The planned replacement schedule is shown in Figure 12-1. Specimen position number 6 will be eliminated for cooled specimens to permit an increase in the number of materials tested.

The planned matrix for the high velocity test is shown in Figure 12-2. A series of four 1000-hour tests will screen 12 candidate materials (three at a time). At the end of these tests (total 4000 hours), three materials will be chosen and tested at the remaining 10,000 hours. Specimens of each material will be removed

at 2500 hours and replaced, thus producing erosion/corrosion data for each material at 1000, 2500, 7500 and 10,000 hours.

Figure 12-1. Specimen Replacement Schedule

POSITION CASCADE	1	2	3	4	5	6
I	R*	A	C	C	B	A
II	A	C	B	B	A	C
III	C	B	A	A	C	B
IV	C	B	A	A	C	B
V	B	A	C			

*ALLOYS A, B AND C

Figure 12-2. Preliminary Materials Test Matrix for High Velocity Test Unit

Although these plans are firm at this time, information from the small burner rig or erosion/corrosion simulator could influence the selection of these and other candidate materials.