FOSSIL ENERGY

MASTER

LONG TERM MATERIALS TEST PROGRAM

Preliminary Operations Plan

March 1980

Work Performed Under Contract No. AC01-79ET15457

General Electric Company
Energy Systems Programs Department
Schenectady, New York

U. S. DEPARTMENT OF ENERGY

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PRELIMINARY OPERATIONS PLAN

**PREPARED UNDER CONTRACT
DE-AC01-79ET15457**

**FOR THE
U. S. DEPARTMENT OF ENERGY**

MARCH 1980

**GENERAL ELECTRIC COMPANY
ENERGY SYSTEMS PROGRAMS DEPARTMENT
SCHENECTADY, NEW YORK**

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I. INTRODUCTION AND SUMMARY

A. Introduction

The General Electric Company has identified the Pressurized Fluidized Bed Coal Fired Combined Cycle (PFBC) as one of the coal utilization schemes which will provide improved thermodynamic efficiency and reduced electric power costs while meeting present and proposed environmental standards. Tests at the National Coal Board's Coal Utilization Research Laboratory and Exxon's Miniplant have proven the PFBC to be a viable cycle. During these tests short term (1000 hour) tests were performed on candidate materials for "in-bed" and gas turbine use. However, one of the key issues remaining in the commercialization of the PFBC concept is the accumulation of corrosion/erosion data from long term (10,000+ hours) exposure of candidate materials to the PFB combustor exhaust gas in order to qualify these materials for gas turbine manufacture.

To accumulate this data the General Electric Company (GE) has been awarded a contract by the U.S. Department of Energy (DOE) to test selected turbine materials for up to 14,000 hours of exposure in a test rig furnished by GE at no cost to DOE. The test rig will be designed to provide an environment representative of current PFBC technology and meet all current environmental considerations. The test rig design is adapted from the 12" test rigs at NCB/CURL and Exxon to assure simplicity in design, operation, maintenance and low operating cost.

This Preliminary Operations Plan delineates the objectives of the program, the preliminary test rig design, the preliminary test plan and projected operating costs. The Preliminary Operations Plan is an extension of the February 28 and 29 Review Meeting attended by DOE and EPRI and considers suggestions recommended during the review. One of the conclusions of the meeting was that Long Term Materials testing is essential to the development of the PFBCC.

B. Summary

The LTMT PFB facility has been designed to duplicate the design point condition of the CFCC reference commercial plant design developed by GE under contract to DOE,⁽¹⁾ including bed temperature (1750°F), pressure (10 atm), excess air (20%), and gas residence time (1.8 sec). The test rig has a one foot diameter bed and consumes about 1.6 tons/day of coal and 0.5 tons/day of dolomite sulphur sorbent.

Material specimens are contained in two test sections. The low velocity test section houses 132 pin specimens 1/4" dia., sixty of which can be cooled below the gas stream temperature. The nominal exposure environment of 1650°F, 10 atm, 27 fps should ensure representative corrosive conditions, without erosion. The high velocity test section is a rectangular gas duct containing four cascades of six airfoil shaped specimens which turn the flow through a 90° angle. These airfoils operate at intermediate velocities (800 - 1000 fps) common in industrial heavy duty gas turbines. In addition, three erosion pin specimens are exposed to gas velocity of 1400 fps, which represents the upper

(1)

"CFCC Development Program, Commercial Plant Design Definition (Task 1.2)," GE Report FE-2357-28, March 1978.

range of leading edge relative velocities likely to be encountered in practice.

The control system for the LTMT facility is designed to operate the rig in such a manner that the test specimens are subjected to constant, controlled conditions representative of the actual service environment. Operation of the rig is substantially automated to reduce operating costs. Provisions are made to bypass the test sections during start/stop transients. After steady-state conditions are achieved, the test cascades are brought on line at a controlled rate representative of the actual operating conditions.

The Preliminary Test Plan presented in Section V outlines three phases of PFB testing, plus screening tests for candidate materials. The first phase encompasses six months and includes rig qualification tests to establish the operational capabilities of the facility. The second phase, lasting for three months, comprises operation of the rig for corrosion testing validation. For this test period, corrosion-prone specimens will be installed in the test sections, and the corrosion rates will be examined for uniformity and correspondence with rates observed in previous cascade experiments. The final testing phase of four years will comprise long term steady-state exposure of materials and various protection schemes.

Operating costs have been updated to reflect the preliminary rig design data and current raw material quotes. The projected operating costs have been effected by raw material costs since the time of the original estimate, but the overall cost per hour of test is still very low: \$122/test hour. Manpower estimates are unchanged and projected rates have increased only slightly. The combination of labor and raw material escalation have increased the overall projection by approximately \$300K over the six year life of the project.

II. PROGRAM OBJECTIVES

A. Objective of Test

The objective of the Long-Term Materials Test Program is to assess materials' corrosion life through realistic PFB environmental exposure of candidate turbine materials for significant periods of time at a reasonable cost. Specifically, the primary objective of the test is to identify promising corrosion resistant materials through evaluation of candidate alloys in a low velocity test section designed to provide an actual PFB exhaust of uniform and known conditions which is representative of the CFCC commercial plant. The test will expose these candidate alloys to the uniform PFB conditions so that resistance to long term accelerated corrosion attack, "break away" corrosion, can be assessed in each of the candidate alloys.

The facility is designed with multiple specimen capability (132 specimens) to provide low unit specimen testing cost. Simple specimen shape promotes the ease of coating and/or cladding application, the reliability of corrosion penetration measurements and the accuracy and meaningfulness of weight gain/loss determination.

The environment must be representative of that expected in the PFB-powered gas turbine with respect to high temperature corrosion. Therefore, the key operating variables of the projected commercial facility will be faithfully reproduced in this small scale test unit as follows:

- A high sulphur coal typical of that best suited for economical operation in a fluidized combustor will be utilized. A high chlorine and alkali content will be desirable to produce a large release of alkali vapor to simulate the most aggressive commercial operation conditions.
- The bed conditions shall be consistent with those of a commercial power plant providing maximum thermal efficiency. The conditions will be a 1750°F bed temperature and a 10 atm operating pressure.
- Dolomite will be utilized as the sulphur sorbent, being supplied at the rate required to ensure that EPA standards, with respect to sulphur, are fully met.
- Fluidizing velocity and bed height will be controlled to provide a residence time identical to that in the reference plant design. This will provide the same alkali release as the commercial plant operating at the same temperature, pressure and on the same coal and dolomite, and will thus ensure the proper corrosive environment.
- Excess air, in the range of 20 percent or greater, will be maintained in the combustor and test section to prevent sub-stoichiometric conditions and the reduction of normally protective metal oxides.

- The control philosophy will maintain the uniformity and validity of the materials testing by isolation of test specimens from unrealistic transient exhaust conditions during start-up, shut-down and abnormal operating conditions. The specimen thermal transient during start-up and shut-down will be controlled to be representative of the actual service environment.

A second objective is to evaluate the influence of lowered specimen temperature on corrosion attack. Previous oil fired gas turbine experience at reduced power, operating in the temperature range of 1350°-1475° has indicated that this reduced temperature of operation may exhibit accelerated corrosion attack. The long term materials test will establish whether corrosion is inhibited at this temperature or whether the period of incubation prior to accelerated corrosion is extended.

The third objective of the test is to evaluate selected candidate materials of high promise under actual PFB exhaust conditions which are both corrosive and erosive. The erosion/corrosion environment should be representative of those expected in large industrial PFB-powered gas turbines. This environment is provided by the high velocity test section which will contain airfoil shaped specimens. To accurately simulate conditions in the PFB powered turbine, the temperature, gas velocity, particle size and distribution will be representative of conditions expected in the commercial reference plant.

III. TEST RIG DESIGN

The Long Term Materials Test Facility is a specialized rig in which candidate gas turbine materials will be exposed to the pressurized fluidized bed combustor effluent to determine long term corrosion effects. The facility will be an adaptation of an existing facility at the National Coal Board/Coal Utilization Research Laboratory in the United Kingdom.

A. Process Conditions

Process conditions for the test rig have been selected to duplicate, insofar as possible, the design point conditions of the coal-fired combined cycle (CFCC) which is the particular version of the Pressurized Fluidized Bed Steam and Gas Turbine Power Plant cycle currently under development by the General Electric Company. Figure III.1 illustrates the essential features of the CFCC power plant, and Table III.1 lists the CFCC combustor design conditions. A bed temperature of 1750°F was selected, which is high enough to provide good combustion and cycle efficiency and low enough to avoid ash fusion. Tradeoff studies have shown that the overall CFCC plant efficiency is fairly insensitive to pressure ratio over the range from 8 to 16 and a pressure ratio of 10 was selected. Excess air must, on the one hand, be kept low to minimize the gas volume flow and associated cost of hot gas cleanup equipment and, on the other hand, be high enough to avoid local reducing zones in the bed which could cause corrosion of the in-bed heat exchanger tubes. The design-point value of excess air for the CFCC combustor

FIGURE III.1 CFCC POWER PLANT FLOW SHEET

NOTE: UNDESIGNATED NUMBERS
ARE POUNDS/HOUR

TABLE III.1
CFCC COMBUSTOR CONDITIONS

Bed Temperature	=	1750°F	
Provides High Combustion Efficiency			
Provides High Cycle Efficiency			
Avoids Ash Fusion			
Bed Pressure	=	10 atm	
Excess Air	=	20%	
Low to Minimize Gas Volume Flow			
High Enough to Avoid Local Reducing Zones			
Bed Height	=	8.0 Ft	= 1.8 Sec
Fluidizing Velocity	=	4.5 Ft/Sec	
Combustion Efficiency Achievable			
High To Minimize Combustor Cost			
Ca/S Molar Ratio	=	1.5	
Provides 90% Sulfur Retention			

which we believe will meet these conditions is 20%. A bed height of 8 ft. was selected to provide the necessary bed volume for the cooling tubes and to provide for an adequate gas residence time for the reactions (principally, SO_2 capture) to occur at the design point fluidizing velocity of 4.5 ft/Sec. Considerations in selecting the fluidizing velocity include combustion efficiency, combustor size and cost, and particulate concentration in the gas which influences the hot gas cleanup requirements. Finally, for the CFCC combustor, a Ca/S molar ratio of 1.5 was selected to provide a 90% sulfur retention.

Table III.2 summarizes the design requirements for the Long Term Materials Test Facility derived from the CFCC design conditions. In the combustor, the design requirements are identical to the CFCC conditions with the exceptions of bed height and fluidizing velocity. Experience at the CURL* indicates that, for a 1 ft chamber bed operating at 6 atm. pressure, the onset of bed slugging occurs at a bed height of about 5 ft. The 1 ft diameter bed at the Exxon "miniplant" was operated without apparent slugging with a bed height of about 10 ft at a pressure of 10 atm. Since the Long Term Materials Test Facility will be operated at 10 atm. pressure, it appears conservative to increase the CURL bed height to 5.3 ft. A 3.0 ft/Sec fluidizing velocity was selected to duplicate the 1.8 sec gas residence time in the CFCC combustor. Included in the facility are a low velocity test section which will be used to determine long term corrosion effects on candidate gas turbine materials, and a high velocity test section to study erosion effects.

B. System Description

Figure III.2 is a simplified flow diagram showing the essential features and components of the Long Term Materials Test Facility. A compressor delivers air at 165 psia to a receiver. The major portion of the air is delivered

* Personal communications with the staff at CURL.

TABLE III.2
TEST FACILITY DESIGN REQUIREMENTS

COMBUSTOR

- Bed Temperature = 1750°F
- Bed Pressure = 150 psia
- Excess Air = 20%
- Ca/S Mole Ratio = 1.5
- Bed Height = 5.3 Ft
- Fluidizing Velocity = 3.0 Ft/Sec = 1.8 sec
- Bed Diameter = 1.0 Ft

LOW VELOCITY TEST SECTION

- Gas Velocity Less Than 200 Ft/Sec
- Gas Temperature = 1650°F
- Gas Pressure = 145 psia
- Cooled and Uncooled Materials Specimens
- Specimens Easily Removed for Inspection

HIGH VELOCITY TEST SECTION

- Modify Flow Channel Used in CURL 1000 Hr Test
- Three Cascades of Impulse Vane Specimens
- One Cascade of Reaction Vane Specimens
- Erosion Pin Specimens Exposed to 1400 Ft/Sec

FIGURE III.2 LONG TERM MATERIALS TEST FACILITY SCHEMATIC

directly to the combustor to be used as fluidizing air, and the remainder is used as the transport medium for the solids as illustrated in Figure III.2. Within the combustor, the coal is burned in a pressurized fluidized bed (PFB) of dolomite which reacts with the SO_2 to limit the sulfur in the effluent. Water flowing inside the tubes of an in-bed heat exchanger absorbs over half of the heat of the coal combustion to limit the bed temperature to 1750°F . Heat absorbed by the water is rejected to ambient in a water-to-air radiator.

The hot combustion products leave the combustor and flow through three stages of cyclones before entering the materials test sections. Exiting the high velocity test section, the gas is cooled in the exhaust gas cooler before being exhausted to the stack. A bypass line around the test sections and the cooler is provided for starting purposes as explained in Section IV.

Test rig operating conditions at the design point are summarized in Table III.3. At these operating conditions the rig consumes about 1.57 tons/day of coal and about 0.49 tons/day of dolomite. Figure III.3 is an isometric drawing of the test rig. The combustor, cyclones, and test sections are closely coupled to minimize both the reduction in gas temperature due to heat loss and the problem of thermal expansion. The principal test rig subsystems are as follows:

- Combustor
- Solids Handling and Feed
- Hot Gas Cleanup
- Heat Rejection
- Low Velocity Test Section
- High Velocity Test Section
- Instrumentation & Controls
- Air Supply

TABLE III.3
TEST RIG OPERATING CONDITIONS

Coal Flow Rate	131 lb/hr
Total Air Flow	1459 lb/hr (324 scfm)
Dolomite Flow	41 lb/hr
Combustion Products Flow	.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	700°F
In-Bed Heat Exchanger Duty	801,000 BTU/hr (52% of Coal Heating Value)

FIGURE III.3 LONG TERM MATERIALS
TEST FACILITY

C. Component Description

Combustor

Figure III.4 shows a cross-section drawing of the combustor pressure vessel. The combustor has a 12-inch inside diameter and is insulated with 1 1/2 inches of abrasion resistant refractory backed by 4 1/2 inches of insulating refractory. As shown, the vessel is made up of three segments bolted together at two flanges and has an overall height of 14 feet. An ignition port located about 17 inches above the air distributor holes will be used to ignite the propane during startup. Two pressure taps are located 2 feet apart (vertically) in the bed to determine the bed pressure gradient. A third pressure tap above the bed is used to determine the overall bed ΔP which is compared with the in-bed pressure gradient to determine the overall bed height. Excess bed material is removed through a refractory lined pipe leading to a cooling tank and then to a lockhopper. Thermocouples are located at one-foot vertical intervals to monitor the combustor temperature profile.

Figure III.5 shows the design of the combustor fluidizing grid patterned after the successful design used in the CURL 12" combustor. Fluidizing air enters the plenum, passes up through the air nozzles, and into the combustion chamber. During startup, propane enters the upper plenum and mixes with the fluidizing air in the nozzles. The propane is ignited from above by the ignitor described previously. Coal, dolomite and solids transport air is admitted through the center tube capped by a tee in the combustor. The length of the air admission nozzles has been extended to provide 3 inches of "dead" bed material which insulates the distributor plate from the high temperature bed material.

Table III.4 is a summary of parameters for the in-bed heat exchanger. The bed will be cooled with low pressure water entering at 113°F and exiting at 185°F.

FIGURE III.4 PFB COMBUSTOR

FIGURE III.5 FLUIDIZING GRID

TABLE III.4
IN-BED HEAT EXCHANGER PARAMETERS

Heat Load	801,000 BTU/hr
Water Inlet Temperature	113°F
Water Outlet Temperature	185°F
Water Flow	22 GPM
Bed-Side H.T. Coefficient	50 BTU/hr Ft ² °F
Log-Mean ΔT	1601°F
Heat Exchanger Surface Area	10 Ft ²

Since the combustor is to operate at 10 atm., the in-bed heat exchanger duty is quite high requiring a relatively large heat transfer surface area to be distributed in the limited bed volume. Figure III.6 shows the design of the in-bed heat exchanger. A staggered tube arrangement was selected to break up the bubbles and suppress bed slugging.

Solids Feed

Figure III.7 shows the solids feed arrangement to be used in the rig. Premixed coal and dolomite are stored in the storage hopper which is sized to hold enough solids for one-to-two days of operation. The lockhopper and feed hopper are suspended by the load cell which weighs the solids. A bellows between the storage hopper and lockhopper along with the flexible solids transport pipe at the bottom effectively isolate the lockhopper/feed hopper weight. Solids flow from the feed hopper to the solids transport pipe is controlled with a rotary feeder driven by a variable-speed DC motor. Figure III.8 shows more details of the rotary feeder and solids transport line. Solids are discharged from the feeder into a 1 1/2-inch tee where they are entrained by the transport air. The 1 1/2-inch line is reduced to 3/4-inch through a pair of eccentric reducers. Gas velocity in the 3/4-inch line is maintained at 45 ft/Sec.

Hot Gas Cleanup

Figure III.9 shows the design of the cyclone dust separators. A conventional cyclone with a tangential gas inlet is enclosed in a refractory-lined pressure vessel eliminating the pressure difference across the metallic walls of the cyclone. Differential thermal expansion is accommodated with a bellows. The primary cyclone is 8 inches in diameter and will remove most of the larger particles. The secondary and tertiary cyclones are 6 inches in diameter for higher

FIGURE III.6 IN BED HEAT EXCHANGER DESIGN

FIGURE III.7 SOLIDS FEED ARRANGEMENT

FIGURE III.3 ROTARY FEEDER ARRANGEMENT

FIGURE III.9 CYCLONE CONCEPT

velocity and removal of the smaller particles.

Predicted performance of the hot gas cleanup system is shown in Figure III.10. The upper curve shows the dust loading of the combustor efflux. Also shown are the dust loadings after the primary, secondary, and tertiary cyclones. The shaded areas show the range of loading experienced in previous cascade tests at CURL and Exxon along with projected gas turbine tolerance limits. During the qualification testing, the dust loading will be measured and a decision will be made whether to remove the tertiary cyclone.

Bed Heat Rejection System

Heat absorbed by the water flowing through the tube of the in-bed heat exchanger is rejected to ambient air in a water-to-air radiator. The closed loop water system is illustrated in Figure III.11. A three-way thermostatic valve will bypass a fraction of the water around the radiator when the ambient temperature decreases and lowers the water temperature. The bed temperature, for a fixed in-bed heat exchanger area, is a function of the coal to air ratio and the average water temperature. Some bed temperature trim capability is available through control of the water coolant temperature. Additional adjustment to increase bed temperature can be achieved by raising the heat exchanger until a fraction of the tubes are out of the bed. During the qualification tests, the bed cooling system will be adjusted to achieve the proper bed temperature.

D. Low Velocity Test Section

Figure III.12 shows the general arrangement of the high and low velocity test sections. The units are mounted vertically to avoid accumulation of dust which would occur in a horizontal unit. Hot gas from the tertiary cyclone enters the low velocity test section at 1650°F and 145 psia, flows over the materials specimens in the test section, and exits the low velocity test section through a

FIGURE III.10 CYCLONE PERFORMANCE

FIGURE III.11 BED HEAT REJECTION SYSTEM

REV. SYMBOLS AC - COMPLETE FOR P - PRELIMINARY R - RECORD	REVISION NO. DATE 1 11/1/70 2 11/1/70 3 11/1/70	DRAWN BY J. M. HALL 20-190	CHECKED BY REVIEW ENGR MECH	ENG. APPROVALS ELEC CIVIL	SCALE 1" = 1'-0"	TITLE INTERFACE CONTROL LOW VEL. TO HIGH VEL. TEST SECTIONS	GENERAL ELECTRIC ENERGY SYSTEMS PROGRAMS DEPT. SCHENECTADY, N.Y. 12301 DRAWING NO. C-016 CONT. ON 31

FIGURE III.12 INTERFACE CONTROL LOW VELOCITY TO HIGH VELOCITY TEST SECTIONS

choked orifice which controls the pressure/flow in the low velocity test section. At the design flow and temperature, the pressure entering the high velocity test section is about 41 psia. After flowing over four cascades of airfoil-shaped materials specimens, the gas exits the high velocity test section and is cooled in a heat exchanger before being exhausted up the stack.

The design of the low velocity test section is an extension of a successful design used at the National Coal Board Coal Research Establishment (CRE), Stoke Orchard, England.* Figure III.13 shows the turbine materials test sections which consisted of pipe sections with material specimen holders welded to the surface. The material specimens were solid cylindrical pins protruding into and perpendicular to the gas flow stream.

In the Long Term Materials Test Facility, the low velocity test section will be used to study long term corrosion of candidate gas turbine materials exposed to the effluent of a pressurized fluidized bed combustor. Both cooled and uncooled materials specimens will be employed. Figure III.14 shows the conceptual design of the low velocity test section. In order to simplify the insertion and removal of materials specimens, the metallic flow duct will also be the pressure containment in lieu of refractory lined piping operating at low temperature. The pressure containment material will be a high temperature creep-resistant material such as Hastelloy X. Gas velocity in the low velocity test section will be 27 ft/sec which is low enough that erosion is not a factor. As illustrated, four uncooled specimens will be positioned in the gas stream at each axial location. The specimens will be cylindrical shaped pins ($\frac{1}{4}$ " dia.) for ease of fabrication and measurement of corrosion. The cooled specimens will consist of hollow pins ($\frac{1}{4}$ " dia.) passing through the gas stream. Cooling air will flow through the center of the pin to maintain the required metal temperature.

*Investigation of Performance of Boiler and Turbine Alloys in Fluidized Bed Combustion Systems, GESP762.

FIGURE III.13 HOT GAS DUCT OF HIGH VELOCITY TEST SECTION

FIGURE III.14 LOW VELOCITY TEST SECTION CONCEPT

E. High Velocity Test Section

The high velocity test section is a rectangular gas duct containing four cascades of airfoil shaped materials specimens as illustrated in Figure III.15. Each cascade, consisting of six airfoil shaped materials specimens, turns the flow through a 90° angle exposing the materials specimens to erosion conditions similar to those in a heavy-duty industrial gas turbine. The first three cascades are made up of impulse type airfoils which turn the flow without a change in velocity (except for small velocity increases due to loss of pressure). Reaction type airfoils, which accelerate the flow as well as turning it, make up the fourth cascade. The gas velocity leaving the fourth cascade is 1400 ft/Sec. Three erosion pins are located in this high velocity gas stream downstream of the fourth cascade. Due to the high velocity, these pins are expected to experience the most severe erosion. Table III.5 is a summary of the temperatures, pressures, mach number, and velocities at key stations through the high velocity test section. Velocities upstream of the cascades range from 825 to 969 ft/Sec and increase to over 1400 ft/Sec downstream of the reaction vanes.

Figure III.16 is a photograph of the hot gas duct of a high velocity test section design used in tests at Exxon and at the CURL. The entire duct is fabricated from Hastelloy X and is enclosed in a refractory lined pressure vessel to minimize the pressure difference across the flat plate walls of the hot gas duct.

Figure III.17 shows the arrangement of the hot gas duct within the pressure vessel. Differential thermal expansion between the duct and the pressure vessel is accommodated with a piston seal design at the bottom.

FIGURE III.15 CASCADE LAYOUT IN THE HIGH VELOCITY TEST SECTION

FIGURE III.16 TURBINE MATERIAL TEST SECTION USED AT CRE

FIGURE III.17 HIGH VELOCITY TEST
SECTION AND PRESSURE
VESSEL.

TABLE III.5
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	.392	.412	.43	.462	.715	.695	1.0
Velocity, Ft/Sec	825	867	904	969	1470	1432	1995

IV. INSTRUMENTATION AND CONTROL

A. Design Criteria

General Control & Instrumentation Requirements

The control system is required to operate the LTMTF in such a manner that the metallurgical test specimens are subjected to a constant, controlled, known environment which is representative of conditions anticipated in a coal-fired PFB power plant application. In addition, control of the rig should be sufficiently automated that, eventually, a single technician can operate the facility under routine conditions.

The materials test specimens are mounted in a low velocity and a high velocity test section which are described in Sections III.D and III.E respectively. The low velocity cascade contains specimens of simple geometry (rods or bars) and has as its test objective the identification of promising corrosion resistant materials in the absence of erosion. The major flue gas parameters to be controlled consistent with these objectives are flue gas chemistry, temperature and pressure. The effect of blade cooling is examined with some specimens operating at the flue gas temperature and other specimens internally cooled to maintain metal temperatures in the order of 1450°F. The initial operating requirements for the low velocity test section are shown in Table IV.1.

The high velocity test section contains airfoil shaped specimens and has as its test objective the evaluation of selected materials under actual PFB

conditions which are both corrosive and erosive. The major flue gas parameters to be controlled consistent with the high velocity cascade test objective are flue gas temperature, chemistry, particulate loading and velocity. The initial operating requirements for the high velocity test section are shown in Table IV.2.

As the testing progresses it is conceivable that the operating requirements in Tables IV.1 and IV.2 may be respecified as metallurgical data becomes available. Thus some flexibility in the set points for the various subsystems is required.

Overall Control Criteria and Concept

The test section arrangement selected for the LTMTF ducts the flue gas sequentially thru the low and high velocity test sections. Consistent with the operating requirements specified for the Low Velocity Cascade (Table IV.1) the flue gas is controlled to the required chemical species and temperature by maintaining the PFB conditions at 20% excess air, bed temperature at 1750°F, bed pressure at 10 atmospheres and the residence time at 1.8 seconds. A bed height of 5.3 ft with a superficial fluidizing velocity of 3 ft/Sec provides the 1.8 second residence time.

Chemical control of the flue gas is achieved by burning coal containing representative levels of alkali, sulphur and other impurities in a controlled manner typical of a PFB power plant. The philosophy is to be as representative of a power station as possible. Elaborate coal analysis with chemical control and/or fuel doping is not employed.

No propane reheating of the gas stream external to the PFB is used to maintain gas temperature. The 1750°F bed temperature, 1650°F cascade entrance temperature represents a 100°F drop which is achieved by proper design of ducting geometry, length and insulation. Active temperature control elements maintain the bed temperature at a constant set value which can be manually

TABLE IV.1

INITIAL OPERATING REQUIREMENTS FOR LOW VELOCITY TEST SECTIONCorrosion Related (Primary Objective)

Flue Gas Chemical Species	Controlled by Burning Typical Coal-Dolomite with 20% Excess Air & 1.8 Sec. Residence Time (No Propane Reheat)
Temp., Flue Gas, Inlet	1650 ⁰ F
Temp., Uncooled Specimens	1650 ⁰ F
Temp., Cooled Specimens	1450 ⁰ F
Press, Flue Gas, Inlet	10 Atmospheres Approx.

Erosion Related (Secondary)

Dust Loading	Within Limits Marked Cascade Tests on Figure III.10
Velocity, Flue Gas	= < 200 Ft/Sec

selected. However, no active control is used for the cascade entrance temperature.

The PFB pressure is automatically controlled (at 10 atmospheres nominal) and the low velocity cascade entrance pressure is established by the pressure drop - flow characteristics of the ducting, cyclones and other gas clean-up accessories.

Two approaches toward controlling the coal feed rate to the PFB have been studied. The selected approach controls the coal feed on the basis of the combustion bed temperature. An alternate approach varies the coal feed on the basis of the fuel/air ratio required to achieve 20% excess air. The anticipated sensitivity of the metallurgical specimens to small changes in temperature dictates control of bed temperature rather than excess air which has a larger allowable control band and reduced impact upon the specimens. The selected steady state operating control criteria is to establish the design air flow rate based upon the fluidizing velocity and other design point parameters. The coal feed rate is then controlled to maintain the bed temperature. By proper design of the bed cooling heat exchanger, the excess air will be at the desired 20% excess air level. Manual trimming (or variation) of the in-bed heat exchanger cooling rate is accomplished as required to achieve these simultaneous objectives.

The dust loading at the cascade entrance cannot be independently controlled. Direct real time measurement of dust levels is not practical nor are means of varying the effectiveness of the cyclone stage. However, the performance of the gas clean up equipment will be measured during the facility qualification checkout phase, and the cyclones will be removed or altered as required to achieve a dust loading characteristic typical of that shown in Figure III.10. In addition, during material evaluation testing the pressure drop across

the various cyclone stages is continuously monitored with alarm indications for any malfunctioning of the gas clean-up equipment.

The high velocity test cascade immediately downstream of the low velocity cascade sees the identical flue gas with identical dust loading and chemical species. An insignificant temperature drop occurs in the upstream cascade and no flue gas reheat mechanism between the cascades is used. The erosion test objective as indicated in Table IV.2 requires that flue gas velocity be increased to approximately 800 to 1400 ft/Sec. This is accomplished by design of the test cascade as discussed in Section III and necessitates no specific control functions. The exit of the high velocity cascade contains a choked orifice to control the flow rate and to reduce the pressure of the gas stream to approximately atmospheric levels before entering the exhaust stack.

In both of the cascades some of the metallurgical specimens require special cooling to reduce the metal temperatures below that of the gas stream. This is accomplished with a feedback control which varies the flow of auxiliary cooling air to maintain a set temperature.

Transient Requirements

Test plans call for 100 hour duration test periods with weekend shutdowns. The numerous starting transients impact the control system design as discussed in the following paragraphs.

To allow meaningful metallurgical comparisons of results all start-stop transients must be repeatable and non-deleterious. The latter specifically means that reducing conditions, large temperature excursions and unrealistically rapid temperature variations which could spall deposits must not be allowed.

A by-pass line around the test cascades is utilized during start-stop transients since it provides the most reliable means of safeguarding the

TABLE IV.2

INITIAL OPERATING REQUIREMENTS FOR HIGH VELOCITY TEST SECTION

Corrosion Related

Temp., Flue Gas Inlet	1650°F
Temp., Uncooled Specimens	1650°F
Chemical Species	Controlled by Burning Typical Coal-Dolomite with 20% Excess Air and 1.8 Sec Residence Time (No Propane Reheat)

Erosion Related

Flue Gas Velocity	800 - 1400 Ft/Sec
Dust Loading	Within Limits Marked Cascade Tests on Figure III.10

metallurgical integrity of the test specimens. A valve arrangement which prevents flue gas from passing through the test section until steady state conditions consistent with the requirements of Tables IV.1 and IV.2 have been achieved is used. The temperature transient associated with the initial in-rush of the flue gas into the cascade is controlled by valve switch-over rate.

Instrumentation

Instrumentation is required (1) to enable control and operation of the PFB and (2) to provide metallurgical data related to the test specimens. Table IV.3 identifies a list of instrumentation parameters associated with the operation and control of the PFB LTMTF. Table IV.4 identifies metallurgical data which will be recorded.

Automatic - Manual Operation Modes

The steady state operation of the LTMTF is accomplished primarily by automatic control subsystems. The fluidizing air is regulated by an automatic pressure control system. The coal-dolomite feed rate control is an automatic servo system where the speed of the rotary feed valve is the final control element. The actual feed rate is controlled automatically to provide the bed temperature set by the operator. Bed height control is a manual operation.

The control systems philosophy is to make as many functions fully automatic as possible consistent with maximum reliability and economy. In general, automatic control subsystems have the capability for manual operation with the test operator controlling the specific function. For example, the main fluidizing air is controlled with a throttle valve which is part of the bed pressure control subsystem. The operator has the capability of manually controlling the position of this valve if he so chooses. The manual-automatic option increases the flexibility of the system by turning the control over to the test operator. In addition, it provides a back up mode of operation if

TABLE IV.3

INSTRUMENTATION REQUIRED FOR PFB LTMTF OPERATION & CONTROL

General

Time of Day, Date
Ambient Temp., Barometer, Humidity
Running Hrs, Total, This Period, At Test Point
Compressor Press. Temp.

Solids Handling

Conveying Air Velocity (2 Systems)
Totalized Fuel Feed, Total This Run
Load All Feed Hoppers
Valve Status
Hopper Pressures
Coal Rotary Valve Speed
Coal Batch No., Wt.
Dolomite Batch No., Wt.
Dolomite Rotary Valve Speed

PFB Combustion

Fluidizing Air Flow Rate
Receiver Air Temperature
Air Temperature at Baffle Plate
Bed (Profile) Temp., Press.

TABLE IV.3 (Continued)

INSTRUMENTATION REQUIRED FOR PFB LTMTF OPERATION & CONTROL

PFB Combustion (Continued)

Bed ΔP Gradient, ΔP Freeboard

Calc. Bed Height, Velocity

Valve Status

Flue Gas Analysis Results

Gas Clean-Up

Cyclone ΔP 's

Hopper Pressures

Valve Status

Heat Rejection

H₂O Pressure, Flow ΔT

TABLE IV.4

LTMTF METALLURGICAL SPECIMEN INSTRUMENTATION

General

Bed Operating Temperature & Pressure

Exposure Time

Low Velocity Cascade

Flue Gas Inlet Temperature, Pressure

Specimen Metal Temperature

Cascade Flow Rate

Dust Sampling Results and Time

High Velocity Cascade

Flue Gas Inlet Temperature & Pressure

Cascade Pressure Profile

Specimen Metal Temperature

Exhaust Orifice ΔP

there is a failure of the automatic system.

Limits, Alarms, Automatic Shutdowns

Very nearly all the instrumented parameters should be maintained within a reasonably small operating band during normal operations of the facility. High and low alarm limits are used to alert the test operators to an unsafe or unusual test condition. Key parameters directly associated with the safe operation of the facility have automatic shutdown or other appropriate control actions accomplished independent of the test operators.

Redundant Equipment

Redundant equipment to enable the operation to continue in the presence of a breakdown is limited to: (1) items felt absolutely necessary for safe operation and (2) items which based upon CURL experience have shown a propensity for frequent failure. A backup solid handling system and an emergency source of electrical power are provided. Dual air compressors are also tentatively included, but in any event the air receiver is of sufficient volume to enable full combustion of resident fuel contained in the PFB.

B. System Description

This section presents an overall description of the LTMTF primary control system shown schematically in Figure IV.1.

Compressor - Receiver

The fluidizing air is supplied to the receiver by a 200 HP electric motor driven air compressor. The receiver pressure is regulated to 165 psig by (PC1) which is part of the compressor control package. Compressor cooling equipment maintains the air delivered to the receiver to approximately 15°F above ambient.

FIGURE IV.1 LTMF MAIN CONTROL AND INSTRUMENTATION SCHEMATIC

System Pressure

Air leaving the receiver enters the PFB by 3 flow paths. Two of these paths are solids fuel injection circuits with continuous flow of conveying air. The 3rd path from the receiver to the PFB carries the main combustion air. The system pressure during normal operation is controlled by (PRC1) throttling the inlet flow on the basis of the feedback system pressure.

Dual Solids Injection

The two fuel lines continually feed conveying air into the PFB chamber so as to maintain a constant velocity in each line with (VRC1) and (VRC2) regulating the flow based on a sensed velocity head. Each feed line can be used to inject powdered coal-dolomite premix into the PFB but only one at a time is utilized. A plugged feed line is sensed by loss of the conveying air velocity and initiates fuel feed switch-over to the backup system.

Measured Total Air

The total air entering the PFB is measured at (FR1) and enables calculation of the reference fuel feed rate.

Fuel Feed Servo

The fuel feed rate control is accomplished via rotary valves entering pre-mixed coal-dolomite into the conveying lines. Load cell suspension of the lock hoppers enables the actual feed rate to be continuously monitored and compared to the reference feed rate with any resultant error used to bias the rotary valve speed. A switch-over of the fuel feed line automatically activates the appropriate rotary valve control.

Coal-Dolomite Ratio

The blending hopper enables the coal-dolomite ratio to be varied as required based upon SO₂ content monitored in the flue gas. The blend hopper is manually loaded with known weights of coal and dolomite.

Bed Height Control

The differential pressure between two fixed points within the bed ($\Delta PR 4$) is used to calculate the bed pressure gradient. A number of pressure tappings on the combustor casings at distances of 1, 3, 5 and 7 ft. above the distributor are available. The tappings are 3/8 inch tubes ending flush with the inside refractory surface of the combustor and fitted with a small continuous nitrogen purge. Any two levels can be used at any one time.

The differential pressure between a point in the bed (usually 1 ft. above the distributor) and the freeboard ($\Delta PR 5$), together with the bed pressure gradient, is used to calculate the bed height.

The differential pressure between the underside of the distributor and the freeboard ($\Delta PR 6$) is also monitored. All the differential pressures are continuously recorded.

Bed Temperature Control

Heat must be removed from the PFB by an auxiliary loop to maintain the bed temperature at the desired 1750°F level. The bed cooling loop as described in Section III.C circulates water at a constant rate through the bed heat exchanger tubes with a nominal 113 to 185°F temperature increase. The design-heat removed-load of 801,000 BTU/Hr will cool the combustion bed to the desired 1750°F temperature under maximum operating conditions (93°F ambient and zero bed losses).

If an error exists in the bed temperature, the normal control action is to vary the coal feed rate. Specifically if the temperature is too low, the coal feed rate is increased. This coal feed rate increase, however, may reduce the excess air ratio below the desired 15 to 25% band. To maintain excess air within the desired range, the rate of heat removed from the bed is adjusted by by-passing flow at the liquid-to-air heat rejection heat exchanger. This lowers

the bed temperature without altering the fuel-air ratio and the dependent excess air.

The heat rejection control is a manually commanded loop designed to maintain a constant rate of heat removal independent of ambient temperature changes. The bed coolant flow rate and ΔT is measured by (FR-3) and ($\Delta TR-1$) respectively. The actual heat rejection rate is calculated from $MC_p \Delta T$ and compared with the desired removal rate. Any error alters the rejection heat exchanger by-pass flow appropriately (within the 212°F limitation). A constant bed heat removal rate can thus be commanded.

The test operator decides, based upon flue gas analysis, when to alter the heat removal rate. Thus the excess air control will be slow, non-automatic and can be intermittent consistent with flue gas instrumentation results. By contrast the bed temperature control is fast and automatic. This approach is consistent with the specification/criteria which requires relatively tight temperature control with a fairly broad excess air allowance.

Gas Clean-Up

Gas clean-up employs 3 cyclones in series. The ΔP across each stage is instrumented and recorded. Limit alarms immediately warn the operator when an unusual pressure drop situation exists at a cyclone.

Flue Gas Analysis

The dust loading and flue gas analysis is sampled and evaluated on a periodic basis as has been previously accomplished at CURL. No active control action is based on flue gas analysis due to unavailability of real time instrumentation. The determination of the excess air is based upon flue gas analysis for O_2 , CO_2 and CO since the levels of these constituents have a direct relationship to the excess air available. The test operators use this assessment to manually adjust the heat rejection rate from the PFB and

indirectly control the excess air.

SO₂ in the flue gas is also monitored, and the SO₂ capture is manually controlled by varying the coal/dolomite (Ca/S) ratio. Automation of this function is theoretically possible, but would require instantaneous measurement of the sulphur entering the PFB so that the sorbent feed can be controlled based on feedforward rather than feedback information. Since instantaneous sulphur measurement is not state-of-the-art it was concluded that a separate variable dolomite feed system was not practical for this LTMTF program and that use of pre-mixed fuel would be the primary SO₂ control mode. The pre-mix ratios of the coal and dolomite are manually varied by the test operators based upon averaged flue gas analysis results.

Start-Up

Figure IV.1 shows two by-pass lines in parallel with the test cascades. By-pass A is a direct line from the gas clean-up equipment to the exhaust stack. Its purpose is to provide an unrestricted exhaust path to be used during starting to enable the light-off transient to be accomplished at atmospheric pressure. The initial start-up burns propane to heat the bed material to the point where spontaneous ignition of powdered coal will occur. (This temperature is approximately 1000°F). At this temperature coal feed is initiated and propane is discontinued. The bed temperature continues to rise during light-off and will approach 1200° - 1500°F temperature with the bed pressure essentially atmospheric.

By-pass B contains an orifice restriction which simulates the pressure-flow characteristic of the cascade sections and enables complete steady state stabilization of flue gas temperature and pressure prior to initiation of gas flow into the cascades. By-pass switch over from A to B to the test sections is accomplished during start-up. The temperature drop from the bed to these

valves lowers the actual gas temperature to about 1200°F so that readily available valves can be used. In general only "on - off" action of these valves is required.

Normal & Emergency Shut-Down

Abnormal operating conditions which could affect the metallurgical specimens are sensed and immediately revert the gas flow path into the by-pass and stop the gas flow in the cascades. The out of spec condition (e.g., excessive bed temperature) can then be corrected by whatever action is necessary without subjecting the cascade specimens to any unwanted conditions.

C. Component Description

This section presents detailed descriptions of the major subsystems involved in the control of the LTMTF. The bed pressure, temperature, height and start-up systems are discussed.

Bed Pressure Control

The PFB pressure is the intermediate pressure in an equivalent two orifice system and is dependent upon both the upstream and downstream orifice. As illustrated in Figure IV.2 the cascade outlet restriction essentially establishes a pressure-flow load line which is intersected by the family of inlet valve position. Continuity of flow enables a simultaneous solution.

The downstream orifice, in addition to establishing a pressure-flow load line, also controls the bed fluidizing velocity as shown in the analyses presented in Figure IV.3.

The inlet throttling valve sets the fluidizing flow to the amount necessary to pressurize the bed to the desired level. The cascade orifice simultaneously restricts this flow and achieves the desired fluidizing velocity. If erosion increases the area of the cascade orifice, the pressure control system

- IN A 2 ORIFICE SYSTEM, THE INTERMEDIATE PRESSURE IS DEPENDENT UPON BOTH THE UPSTREAM AND THE DOWNSTREAM ORIFICE

- SOLUTION APPROACH – CONTINUITY OF MASS FLOW

$$W = \frac{K P_{up} A N (P_u/P_d)}{\sqrt{T_{up}}}$$

INLET FLOW

OUTLET FLOW

COMPOSITE

FIGURE IV.2 SOLUTION OF INTERMEDIATE PRESSURE IN A 2 ORIFICE SYSTEM

• ANALYSIS

$$w_b = \left(\frac{P_2}{RT_2} \right) A_b v$$

$$w_b = w_{23} = \frac{K P_2 A_{23} N_{23}}{\sqrt{T_2}}$$

$$v = K \frac{A_{23}}{A_b} R \sqrt{T_2}$$

$$\left(\frac{KR}{A_b} = \text{constant} \right)$$

FIGURE IV.3 FLUIDIZING VELOCITY DEPENDENCE UPON CASCADE ORIFICE

will increase the flow to whatever value is required to achieve the commanded bed pressure. The increased flow and fluidizing velocity are monitored with alarm limits to ensure that sustained excessive conditions are not allowed.

Figure IV.4 shows a block diagram schematic of the pressure control sub-system and indicates that a stable system is readily achieved by appropriate choice of the gain at the valve position controller.

Bed Temperature Control

Figure IV.5 presents a block diagram of the bed temperature control with the associated coal feed servo system and the bed cooling heat rejection loop.

The heat balance at the PFB involves the 4 primary elements indicated in Figure IV.5. The input heat rate is the product of the coal feed rate and the coal lower heating value. The output heat rate is the sum of the heat removed by the flue gas, the heat removed by the bed cooling heat exchanger loop and the heat lost to the ambient by conduction and convection. The actual bed temperature results from this balance and can be regulated or controlled by either varying the input heat rate associated with the coal feed or by varying the heat removed from the bed by the bed cooling heat exchanger. Both control modes will be utilized as discussed previously.

As shown on the sketch, with normal control mode A active, the actual bed temperature is compared with the reference set point (1750°F) and any deviation supplements the coal feed command. Reset action at the temperature controller is required to prevent a steady state temperature error. In this control mode the coal feed rate is responding to bed temperature error and there is no direct control of the fuel/air ratio and the resultant excess air.

• CONTROL SCHEMATIC

FIGURE IV.4 BLOCK DIAGRAM OF BED PRESSURE CONTROL

FIGURE IV.5 BLOCK DIAGRAM OF BED TEMPERATURE CONTROL

Two alternative control modes are provided. In control mode C, the calculated coal feed rate commands the coal feed servo to deliver the fuel at the rate required to maintain the desired F/A ratio. In the manual operation mode (Mode B) the test operator selects the desired delivery rate (i.e., 130 lbs/hr) and this is the command for the coal feed delivery servo. With manual operation the F/A ratio is not automatically maintained.

During checkout and possibly at each start-up the "manual trim" adjustment of the bed cooling system is accomplished by the test operator with the F/A ratio automatically controlled (Mode C). The water by-passing the liquid-to-air heat exchanger is adjusted until the bed temperature is brought reasonably close to the desired value. At this point the automatic bed temperature control mode is selected. Thereafter coal feed modulation controls the bed temperature automatically. The excess air is approximately correct because of the previously established heat rejection rate at the design point condition. The dashed line feedback path shown in the schematic portrays the operator readjusting the heat rejection trim as necessary based upon randomly determined excess air status.

In any control mode the solids handling servo is operated closed loop so that perturbations in the delivery characteristics of the rotary valve are offset by speed variation as required to maintain a constant flow. A rotary valve jam-up causes the servo to attempt to increase the drive speed by increasing the driving torque. An SCR variable speed D.C. motor drive system is planned and thus torque data (and control) is available by measuring (and limiting) the average armature current. A sustained high torque, no delivery situation is immediately recognized by the process controller as a jam condition and effects immediate switch-over to the stand-by rotary valve feed system.

A coal-dolomite blockage in the feed lines between the rotary valve and the PFB stops the flow of the conveying air and is detected by a severe reduction or complete loss of conveying air velocity head instrumented upstream from the rotary valve. Automatic switch-over to the stand-by system is initiated by loss of conveying air velocity or a sustained zero delivery condition sensed at the hopper load cells.

Bed Height Control

The nominal coal and dolomite feed rates are 130 and 41 lbs/hr respectively. Based upon CURL data, 20% of the coal weight and 80% of the dolomite weight are retained in the bed which typically causes the bed height to increase at approximately 1.8 ft/hr or 0.36 in./min.

It is desired to maintain the bed height at 5.3 ft. $\pm$ 10% so as to control the residence time within a reasonable band. Accordingly in the steady state condition bed material must be removed approximately every 40 minutes.

Figure IV.6 shows a schematic of the bed off-take lock hopper system and control logic. Height is measured by two Δp sensors and compared to the reference figure. Lock hopper removal action is automatic with manual override. The two lock hopper valves are interlocked so that it is impossible to simultaneously open both valves. During the 40 minute interval between actuation, the upper hopper A would be full and the lower B hopper empty. This allows cooling of the bed material about to be removed and eases the temperature requirement of the lock hopper valves. By sizing hopper B smaller than A, a holding period for cool down is assured.

Start-Up Control

Start-up is accomplished without flue gas flow through the test cascades. After steady state operating conditions are established the flow is diverted from the by-pass to the test cascades.

CONTROL LOOP SCHEMATIC

FIGURE IV.6 BED OFFTAKE LOCKHOPPER SYSTEM

Start-up is achieved as follows:

1. Prior to initial light-off, bed material is removed to achieve a bed height low enough to prevent bed material contact with the coils of the coolant heat exchanger.
2. Fluidizing air thru the bed is set at the desired 3.0 ft/sec by opening the main throttle valve (A_{12}) to approximately 20%. The bed pressure is atmospheric since the cascade by-pass lines are open max. Propane gas is ignited to initiate the bed heat-up.
3. As the bed and fluidizing air increase in temperature the fluidizing velocity tends to increase due to the reduced gas density. Constant velocity is maintained by closing the main throttle valve as the temperature increases such that the product of the valve throat area and the bed temperature (absolute degrees) remains constant.
4. At an approximate bed temperature of 1000°F the coal-dolomite injection into the PFB is initiated. Spontaneous ignition of the coal particles occurs. The 3 ft/sec fluidizing velocity at the "Coal On" point requires that the air flow be reduced to approximately 15% of the design point value.
5. Bed heat-up raises the bed temperature to approximately 1500°F. During the 1000 to 1500°F transition the propane fuel is gradually replaced by the coal. During this transition a constant fuel/air ratio is maintained approximately by controlling the total fuel injection rate relative to the air. At a constant air flow rate, the fluidizing velocity increases from 3 to 3.7 ft/sec due to the reduced density associated with the temperature increase.

6. With the transition to coal fuel completed, the by-pass lines around the cascades is switched so that an orifice is introduced in the exhaust gas stream. This orifice will have the same pressure-flow characteristics (at choked flow) as the total cascade system and will allow the bed pressure to be raised to the design value prior to introduction of gas to the specimens. The switch over to by-pass line B will produce small changes in the bed pressure and velocity due to the low flow level involved. (Pressure 15 to 21.4 psia, velocity 3.7 to 2.6 ft/sec.)
7. The start-up transient continues with the temperature and pressure increasing to the design levels. The temperature transient is completed prior to the pressure transient. With the temperature at the design point (1750°F) the fluidizing velocity is essentially correct even with considerably reduced bed pressure.
8. The pressure transient is completed by increasing the air flow rate with the by-pass orifice restricting the flow. As flow increases the coal feed rate is also increased with a constant F/A ratio.
9. After complete stabilization of pressure, temperature, excess air, and residence time the flue gas will be diverted from the orifice containing by-pass (line B) to the cascade. A gradual switch over is used to prevent a violent thermal shock from occurring at the test specimens.

V. PRELIMINARY TEST PLAN

The Long Term Materials Test will be conducted in three phases. The first phase encompasses six months and includes rig qualification tests to establish the operational capabilities of the facility. The second phase, lasting for three months, comprises operation of the rig for corrosion testing validation. For this test period, corrosion-prone specimens will be installed in the test sections, and the corrosion rates will be examined for uniformity and correspondence with rates observed in previous cascade experiments. The final testing phase of four years will comprise long term steady-state exposure of materials and various protection schemes.

The LTMT facility qualification tests (Phase I) are discussed in Section A, and the corrosion validation test plan (Phase II) is discussed in Section B. These Preliminary Qualification Test Plans will be expanded and elaborated in a comprehensive Qualification Test Plan, to be submitted to DOE in month 12 of the contract.

Section C outlines a preliminary test plan for the Phase III long term testing program, as well as the criteria for selecting materials and protection schemes for long term exposure. The preliminary plan presented in Section C will be expanded and documented in a separate comprehensive Materials Exposure Test Plan for submittal to DOE in September, 1981. Finally, the plan for conducting improved screening tests of various candidate materials is discussed in Section D.

A. Preliminary Qualification Test Plan - Phase I

Long Term Materials corrosion, erosion and deposition experiments require the control of test parameters within precise limits so the metallurgical results will not be adversely affected. The qualification test program presents a sequence of tests which will establish these limits and prove the test rig.

Calibration Tests

In order to evaluate test conditions critical instrumentation will be calibrated to 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.

Compressor Tests

Compressor tests will be made to determine startup and shutdown characteristics and to determine the quantity of oil carryover. This test is critical to determine the startup and shutdown operating envelopes and prevent adverse test conditions during these periods.

Coal and Dolomite Test

The coal and dolomite test will calibrate the coal/dolomite feed systems and determine the coal/dolomite feed rate over the operating range of the rotary valves. Additionally, the range of Ca/S ratios of the coal/dolomite blending system will be determined.

Bed Pressure Drop Test

A bed pressure drop test will be performed to check out the pressure drop measurement system and determine the range of nitrogen purge flows used to keep pressure lines clear, which can be tolerated without affecting pressure measurements. The test will be performed by injecting 12" of bed material into the

combustor and operating over a range of superficial velocities. Subsequent 12" layers will be added until the design bed height is reached.

Ignition Tests

The ignition test will be performed by injecting a 9" to 12" startup bed into the combustor. The bed coolant system will be placed into operation and the propane ignition system will be tested over a range of superficial velocities to determine stable flame limits. Then the propane preheat system will be activated and tests performed at various superficial velocities to determine suitable air/fuel ratios for light off and bed preheating. During this period gas analysis equipment will be on line to assess the combustion gas conditions and determine the light off conditions which will meet test objectives and bed temperature control.

Combustor Tests

The startup bed will be preheated to the auto ignition point of coal $\approx 1000^{\circ}\text{F}$ and coal/dolomite injected. The combustor will be brought to the maximum operating temperature at atmospheric pressure in a series of 10% steady state steps. At each steady state point a complete set of data will be taken. The system will then be pressurized to design pressure in 20 psi steps but maintaining the bed temperature at 1750°F . At each step, steady state conditions will be achieved and data taken. The slow startup will limit the increase in refractory temperature to $50^{\circ}\text{F}/\text{hour}$ to cure the refractory and determine "off design" characteristics of the test rig. As the combustor approaches design conditions, data will be obtained to determine the combustor performance. However, several startups and shutdowns will be required such that the "in-bed" coolant heat exchanger immersion depth can be adjusted to maintain bed temperature at nominal design

conditions and Ca/S ratio can be altered to reach 90% sulphur capture. This test will tune the test rig to design operating conditions.

Shutdown Tests

Shutdown tests will be performed to determine the effect of power or coal loss and to test the effectiveness of the safety control system. Additionally, normal shutdown tests will be performed to determine shutdown procedures compatible with test objectives.

Cyclone Tests

Cold flow tests will be performed over a range of air flows to determine cyclone pressure drop. Additional data will be obtained during hot tests to locate cold spots and determine frequency and procedures for lockhopper operation as well as some preliminary performance data.

Preliminary Qualification Test

A preliminary 100 hour qualification test at design conditions will be performed to fine tune the test rig control system and establish the "dead band" control limits for compliance with test objectives. At the completion of this test the facility will be secured for installation of qualifying specimens. Additionally, the number of hot gas cleanup stages may be changed.

Qualification Test

A 13 week qualification test will be performed utilizing the startup and shutdown procedures established during the pre-qualification test program. Additionally, the test program will test emergency shutdown procedures, including inspection of the specimens to determine the effects of such shutdown on deposits and oxide film continuity. At the satisfactory conclusion of this and the preceding tests, the facility will be deemed ready to proceed with the Phase II Qualification Tests.

B. Preliminary Qualification Test Plan - Phase II

Up to 500 hours of corrosion validation testing will be performed to establish the corrosive conditions throughout the low velocity and high velocity test sections. A set of materials selected for their wide range of corrosion response in the PFB will be installed in the two test sections. This set of specimens will be reproduced throughout the low velocity test section at specific intervals to establish the uniformity of corrosion conditions through this section. The materials utilized will consist of the following:

- IN 671 - A nickel-chromium alloy highly susceptible to corrosion in the PFB environment. Generally this material will be destroyed (10 mils of attack) in less than 500 hours.
- IN 738 - A bare, cast superalloy utilized as bucket material in heavy duty industrial turbines. IN 738 is moderately resistant to corrosion in the PFB, suffering internal sulfidation in less than 250 hours.
- Fe-Cr-Al-Y - An overlay quite resistant to sulfidation attack in the PFB. Generally only surface attack will occur after 500 hours in the PFB at a 1575°F exposure temperature or lower.
- Co-Cr-Al-Y - an overlay also resistant to sulfidizing environments especially at high temperatures ($> 1600^{\circ}\text{F}$). Generally only oxidation will occur in 500 hours of exposure to PFB exhaust at 1575°F or lower.

Although all four materials will be tested, the emphasis will be on placing the two corrosion prone materials, IN 671 and IN 738, in many locations to ensure the validity of the corrosion in the test section.

Prior to exposure in the test facility, all specimens will be characterized by (1) metallographic examination of selected samples from each alloy lot to

establish the pre-test quality of each protective system, (2) documentation of the general surface condition of each specimen noting specific abnormalities, (3) diametrical measurements of the pin specimens and contour traces of the airfoil specimens to establish the original dimensions of each specimen and (4) weight measurements of all specimens.

After 250 hours of testing, all specimens will be removed from the facility and non-destructively inspected. This inspection will consist of weight gain/loss determinations and photographic documentation of the general surface condition of all specimens.

A representative sampling of each alloy system will be selected and evaluated by both dimensional analysis and metallographic means. The metallographic condition of these specimens will be compared to the same alloys after 250 hours of testing in the Exxon/Fireside II program and the CURL 10x100 hour test.

Based on this analysis and the ability to control the test conditions up to this point, the test will be continued for an additional 250 hours or else terminated, having verified the conditions in the facility.

C. Preliminary Long Term Test Plan - Phase III

Selection of Materials

The objective of the materials selection task (6.0) is to identify promising materials and candidate protection schemes for both nozzle and bucket use. These selected materials, coatings and claddings will be evaluated in both the long term materials test and the improved simulation test (Section D). The selection of materials will be based on the anticipated conditions in the PFB-powered gas turbine, applicable experience in coal burning and particulate laden environments, the fundamental understanding of the degradation processes of corrosion and erosion and the applicability of coatings and coating processes to commercial-scale PFB-powered gas turbines.

The anticipated conditions in the PFB-powered gas turbine are based on the CFCC reference plant design, combusting a high sulphur coal with moderate-to-high chlorine and alkali levels. The reference system employs a bed temperature of 1750°F and the turbine inlet temperature is approximately 1650°F. Cooling of nozzle and buckets is employed reducing the maximum metal operating temperature to approximately 1450°F. The exhaust particulate loading and size distribution will be controlled by a series of hot gas clean-up devices to achieve a dust loading within the range labeled "Cascade Tests" in Figure III.10. Approach velocities to the turbine components will be in the range of 800-1400 feet per second. Total alkali volatilized from the bed is calculated to be 1-10 ppm depending on the exact coal, dolomite, temperature of operation, and superficial fluidizing velocity.

As the result of these conditions in the turbines, the potential for erosion, corrosion and deposition are judged to be significant. The candidate material systems considered should therefore possess good resistance to both erosion and corrosion.

Published applicable experience in particle laden corrosive environments and coal burning turbine has been thoroughly reviewed to identify promising materials. Among the more significant experience surveyed has been (1) the early coal-burning turbine efforts by the Australian Aeronautical Laboratory, the Locomotive Development Committee and the U.S. Bureau of Mines, (2) gas turbine experience in sandy terrain and as expander turbines in fluidized cat-cracker units, (3) erosion-corrosion experiments performed by Curtiss-Wright, Westinghouse, United Technologies, NASA, and General Electric, and (4) recent fluidized bed corrosion/erosion tests performed by the General Electric Company and Curtiss Wright. In addition, the understanding of oil-fired erosion and

corrosion mechanisms will be used as a basis for establishing the relationship between this related experience and the contemplated PFB powered gas turbine.

The fundamental understanding of the PFB degradation processes will be utilized in an attempt to predict which systems will perform best in the erosive and corrosive exhaust of the PFB. The key variables determining both erosion and corrosion will be evaluated with respect to the candidate systems. Specifically, the release of alkali from the system, the melting points of the sulphates, the gettering action of the kaolins and feldspars in the coal and the composition of the protective alloy system and its ability to form protective oxides will be considered in predicting the corrosion/erosion resistance of the candidate systems.

Consideration of erosion resistance in the selection of materials must take into account the many theories of erosion which currently exist. These theories incorporate fatigue damage accumulation, particle fragmentation, impact angle, local melting, time of incubation and Hertzian cracking. Even though no existing erosion theory can comprehensively model the erosion process there are several phenomena which should be considered in the selection of materials or in the evaluation of their apparent performance in similar environments:

- Erosion generally increases to the second through the fifth power of velocity.
- Reduction in the leading edge diameter of an airfoil results in an increase in the number of particles impacting the surface. In other words, smaller parts are more prone to erosion than larger parts.
- Corrosion and erosion act together in a synergistic manner, producing a total degradation greater than the sum of the two processes acting independently.

- Angle of particle impact determines to some extent the degree of erosion that occurs. High impingement angle (90°) is conducive to rapid erosion of ceramics (oxides) while angles between 20-30 degrees maximize erosion of ductile materials.

The formation and maintenance of a continuous oxide film is mandatory for good resistance to corrosion. However, the influence of this oxide film on erosion resistance is unknown. In addition, the influence of the erosion process on the maintenance of the oxide scale is also unknown. The experience, to date, indicates the superior corrosion resistance also increases erosion resistance in the PFB environment. The most resistant material tested to date have been alumina (Al_2O_3) formers. The emphasis will therefore be placed on Al_2O_3 forming systems and those which form Cr_2O_3 , which is well known for its resistance to corrosion, in considering alloy systems for testing.

Other coating/cladding compositional effects will also be considered, especially in overlay coating and cladding systems. Generally the major elements of these systems are:

- Nickel - Generally added for oxidation resistance. Nickel is not recommended for use in PFB - Turbine protection systems because of its susceptibility to sulfidation.
- Cobalt - Excellent corrosion resistance and thermal/diffusional stability. Cobalt is highly recommended for PFB protective systems.
- Iron- Excellent sulfidation resistance. Restricted to approximately $\leq 7\%$ aluminum contents due to phase instability. Not as diffusional stable as cobalt base systems.
- Aluminum - Provides excellent resistance to accelerated attack through the formation of protective Al_2O_3 films. Systems which contain

sufficient quantities of aluminum to form continuous films have demonstrated excellent resistance to the combined effects of erosion and corrosion.

- Chromium - Excellent resistance to corrosion attack. Limited information on the erosion resistance of Cr_2O_3 . Primarily used at intermediate temperatures to avoid the loss of chromium from the oxide via formation of CrO_3 (gas).
- Rare earth elements are on occasion added to protective overlay systems to increase oxide adherence, which reduces oxide loss and subsequent penetration of sulfidizing constituents into the base alloy.

There are several different types of protective systems and many different methods of application. From all the candidate processes of application six are best suited for use with PFB-powered gas turbines. These six, pack cementation, cladding, thermal spraying, physical vapor deposition, slurry and sputtering, will be primarily considered in selecting systems of application. A comparison of the strong and weak points of these six systems is shown in Table V.1. Regardless of the coating composition or application process chosen, all the characteristics of the coatings must be considered. In order to be truly protective for a given substrate material, a coating should satisfy as many of the following requirements as possible:

- It should form a thin, adherent oxide scale, free from defects such as cracks, blisters, etc., and exhibiting minimum mass transport coefficients. The oxide scale should not spall off, vaporize, undergo transformation, or react with salt deposits in any damaging manner.

TABLE V.1

APPLICABILITY OF COATING PROCESSES

<u>Materials Applied</u>	<u>Methods Of Application</u>	<u>Advantages</u>	<u>Disadvantages</u>
Metals	Pack Cementation	Complex Shapes Coatable	Thin, composition limitation
Ductile Metals	Cladding	Thick overlays - Some Compositional Flexibility	Complex Parts - Restricted to low Al ($\leq 5\%$)
Metals, Oxides, Carbides	Thermal Spraying	Cheap, fast, complex shapes coatable, compositional flexibility	Flaws, thickness control difficult
Metals	Physical Vapor Deposition	Complex shapes coatable, reliable	Expensive
Metals, Oxides	Slurry	Compositional flexibility, cheaply applied	Line of sight, flaws, thickness control difficult
Metals, Oxides	Sputtering	Compositional flexibility, complex shapes coatable	Slow, expensive

- The coating should remain metallurgically bonded to the substrate during both processing and service. Flaws such as cavities and holes should neither be present nor form later at the coating/substrate interface.
- The coating should exhibit diffusional stability with the substrate so that during service, the two do not undergo excessive reaction to lose the composite nature of the system.
- Coatings should not adversely affect the mechanical properties of the substrate.
- The substrate and the coating must have similar heat transfer and thermal expansion characteristics.
- The coating should be resistant to stress rupture, thermal fatigue, erosion, and foreign object damage.
- The coating should be ductile at all temperatures, or should undergo brittle-to-ductile transition at a temperature lower than the actual service temperature.
- Coatings should not promote liquid phase formation at or under the coating/substrate interface during high temperature exposure.
- The coating should be thin, uniform, free from flaws, and relatively easy to apply and repair if necessary.

It is probable that no coating can satisfy all these requirements as well as provide resistance to erosion. However, a reasonable balance of these requirements will be sought in selecting candidate alloy systems.

Material Exposure Strategy

Subsequent to rig qualification and materials selection, long term response of the candidate materials will be established. Although candidate materials have not been selected at this time, preliminary inspection and removal schedules

have been prepared for both the low velocity and high velocity test section based on a predetermined number of candidate alloys, the available space in the test sections, and the expected shape of the corrosion curve for the materials being considered. The typical corrosion curve illustrated in Figure V.1, shows a rapid initial corrosion rate, generally parabolic in nature, a reasonably flat intermediate time period where corrosion is reduced essentially to zero and finally "breakaway" corrosion. The preliminary low velocity inspection and removal schedule as shown in Figure V.2 is based on the expectation that corrosion will follow the general trends exhibited in Figure V.1. Duplicate specimens are removed after 250, 500, 1,000, and 2,500 hours of exposure to characterize the initial corrosion curve. Specimens will be withdrawn at 5,000, 7,500, and 9,000 hours to characterize the flat portion of the corrosion curve.

Concurrent with this removal schedule, cursory inspection of the specimens will be made approximately every 500 hours in order to identify the initiation of "breakaway" corrosion. For this reason three specimens, designated 4, 5, and 6, have been allocated for removal in the last phase of the program after breakaway corrosion may have been initiated. If no breakaway corrosion is observed, these three specimens will be removed at the termination of the program.

The low velocity test section has been designed for 132 test specimens, 50 of which are cooled. This design will permit the testing of 12 different materials in the uncooled configuration and 10 different materials in the cooled configuration.

The same rationale has been used to develop the schedules for the high velocity test cascades. Six specimen locations will be utilized to generate the desired exposure times, Figure V.2. Cooling of these air foil shaped specimens is not planned. Three high potential materials will be evaluated in this test unit, as shown in matrix form, Figure V.3. This matrix will simultaneously

FIGURE V.1 PHILOSOPHY OF LTMT - BREAKAWAY CORROSION

SPECIMEN POSITION

FIGURE V.2 SPECIMEN REPLACEMENT SCHEDULE

CASCADE \ POSITION	1	2	3	4	5	6
I	B*	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 V.3 PRELIMINARY MATERIALS TEST MATRIX
FOR HIGH VELOCITY TEST UNIT

permit evaluation of materials from the same cascade while permitting evaluation of the differences in conditions which may exist between the four cascades due to slight increases in velocity throughout the high velocity unit.

High velocity erosion pin specimens downstream of the fourth cascade will be inspected at intervals and replaced as required based on the condition of the specimens.

D. Screening Tests

The value of small-burner rig screening tests has been amply proven in the selection of materials for oil-fired gas turbines. This simple experiment provides long term exposure data, at low cost, which can be directly correlated with actual service experience. However, efforts to simulate the PFB environment utilizing the small burner rig have been generally unsuccessful. Contaminant levels (Na, K, Cl) achieved through the addition of various dopants to the fuel or combustion air have produced corrosion rates and/or morphologies in several gas turbine alloys which are atypical of results from the actual PFB environment. These differences in hot corrosion behavior may be related to the presence of significant levels of various elements, such as Ca and Mg, in the actual PFB environment which interact with the corrosive alkali sulfates.

Under the LTMT Program, an improved simulation of the PFB environment will be attempted by including the influence of flyash in the small burner rig experiments. To incorporate the effects of flyash, a slurry of the third stage cyclone catch from either the CURL 10x100 hour test or the Fireside II (Exxon) test will be sprayed on specimens prior to exposure. Initial experiments will identify the effects of exposure on the composition of the flyash with and without the addition of alkali dopants to the fuel.

The information from these first tests will then be used to design small burner rig testing conditions which are more simulative of the actual PFB environment. Candidate alloy systems will be evaluated at the established conditions. The corrosion rates and morphologies will be compared to both previous PFB testing and small burner rig testing to determine the degree of correlation.

The first experiment (Table V.2) will determine the compositional change occurring in flyash deposit applied to small burner rig exposure at 1575°F. Sulphur dioxide, SO_2 , will be injected to increase the partial pressure of sulphur and so reduce the loss of sulphur from the deposit.

The second test series (II and III) 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 MgSO_4 which, together with Na_2SO_4 and K_2SO_4 , form constituents which melt around 1200°F. These low melting phases may dramatically (and unrealistically) increase corrosion rates. Analysis of PFB deposits reveal that only trace quantities of MgSO_4 appear on tested airfoils, as MgSO_4 is generally unstable at the temperature of operation. However, large quantities of CaSO_4 are present in PFB deposit. Therefore, calcium chloride will be substituted for magnesium chloride in the fuel dopant. The three major sulfates (Na_2SO_4 , K_2SO_4 , CaSO_4) 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: 79ppm Na, 112ppm K, 116ppm 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.

TABLE V.2
SMALL BURNER RIG TESTS

<u>Test</u>	<u>Dopant</u>	<u>Air Dopant</u>	<u>Flyash Slurry</u>	<u>Hours</u>
I	None	SO ₂	Yes	≤ 250
II	112 ppm K, 79 ppm Na, 16 ppm Ca, Cl, 1% S	None	Yes	≤ 250
III	"	None	No	≤ 250
IV	"	~15 ppm HCL	Yes	≤ 250

Materials

IN-671 clad/IN-738
Bare IN-738
GE-2541 clad/IN-738

The third preliminary test series (IV) 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 for additional testing. In these further tests, Table V.2, a wide range of alloy systems, which have been previously tested in PFB exhausts, will be evaluated for both corrosion rate and morphology.

In conjunction with the small burner rig testing, additional analysis of the Exxon and CURL tests will be performed to evaluate the effect of differences in operating conditions on the performance of the gas turbine alloys. This analysis will include the effects of bed operating conditions including coal and dolomite compositions, temperature variations through the hot gas path, temperature of the specimens in the turbine test section, and chemical composition of the particulate capture in the cyclones. Thermochemical calculations will be made to adjust conditions observed in the PFB for one atmosphere small burner rig operation.

In addition to corrosion testing in the small burner rig, the suspected synergism of erosion and corrosion will be investigated using the General Electric erosion/corrosion simulator (ECS) facility. The simulator, Figure V.4, 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 V.4 GENERAL ELECTRIC 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.

VI. PROJECTED OPERATING COSTS

Operating costs for the LTMT facility were examined in considerable detail during the preparation of the proposal leading to the present contract. All material costs such as coal, dolomite, shipping and waste disposal were substantiated by written quotations, and were escalated at 8% per year to project operating costs through 1985. Labor costs were determined using provisional rates approved for forward pricing by the Defense Contracts Audit Agency (DCAA). These projected cost estimates were examined and approved by the local DCAA representative during the negotiation of the present contract.

The original projections of operating cost have now been updated to reflect current design requirements and new quotations received from various suppliers. Some cost growth has occurred, principally because of altered requirements for coal type and quantity as discussed below. Nevertheless, the projected operating cost of \$122 per hour is substantially lower than any competing facility, by almost an order of magnitude.

Revised estimates of operating cost for each year are shown in Table VI.1, together with the initially quoted costs. The revised estimates in each category are discussed below:

Labor

Manpower estimates are unchanged from the initial estimates, and are based on the following assumptions:

TABLE VI.1
OPERATING COSTS*

CALENDAR YEAR	81	82	83	84	85	TOTAL	PREVIOUS QUOTE
Labor & OH	329.2	287.6	221.2	242.7	197.4	1,278.1	1,229.0
Coal	41.4	62.6	77.2	83.4	67.6	332.2	171.0
Dolomite	5.3	7.9	9.8	10.6	8.6	42.2	21.6
Waste Disposal	2.6	2.6	2.6	2.6	2.0	12.4	12.6
G&A, Fee	<u>92.8</u>	<u>88.4</u>	<u>76.2</u>	<u>83.2</u>	<u>67.6</u>	<u>408.2</u>	<u>343.0</u>
TOTAL COST	471.3	449.1	387.0	422.5	343.2	2,073.1	1,777.2
Test Hours	2500	3500	4000	4000	3000	17,000	17,000
\$/Test Hour	189	128	97	106	114	122	105

*Engineering Estimates, 1980 base costs, materials escalated at 8%, in thousands.

<u>FUNCTION</u>	<u>TIME PERIOD</u>	<u>MANPOWER</u>
Test Engineer	5th - 8th Quarter	1 1/2 Engr.
	9th - 23rd Quarter	1 Engr.
Test Technicians	5th - 11th Quarter	6 Tech.
	12th - 23rd Quarter	3 Tech.

Costs have been determined from these manpower requirements using updated forward pricing rates as approved by DCAA. It should be noted that these forward pricing rates are re-negotiated approximately annually, and are thus subject to future adjustments. Furthermore, they reflect average rates within each labor category, and not the actual rates charged to the contract.

As shown in Table VI.1, the current estimates of labor costs are greater than the initial estimate by a total of approximately \$50K over the five years of operations. This increase is entirely due to increased labor rates.

Coal

Coal costs have increased substantially due to the decision to change to a 4% sulphur, high chlorine coal and to recost on the basis of a 10 atmosphere PFB (vs. the original 6 atm.). Coal cost is up 52% and coal usage up 45% as shown in Table VI.2.

As related to us by Whitehead Brothers Company, the high coal processing cost is associated with the equipment cleanup required before and after our special high sulphur coal order. In addition, the coal and chemical analyses must now be purchased separately whereas they were originally included in the processing cost, based on supply of a local western Pennsylvania 2% sulphur coal. Alternate sources for coal processing have been sought without success. Generally, the quantity of coal required is too small to justify the special crushing requirements.

A Western Pennsylvania coal with 4% sulphur and 0.05% Chlorine will be used, provided a source can be located. The coal is estimated to cost \$30/ton. It will be crushed, dried and packaged by the Pennsylvania Rillton Division of Whitehead for \$145/ton (1/8 inch to 0, less than 3% moisture). Processing and shipment is in 20 ton lots. A final section of coal source has not yet been made so that the coal and transportation costs are still uncertain.

Dolomite

The dolomite is assumed to be an Agricultural Filler Number 6 (6x16 mesh) and shipped from Gibsonburg, Ohio in 22 ton lots consisting of 1 ton crates. Packaging was not previously considered, but is now considered necessary to facilitate handling and to maintain dryness. As with the coal, one chemical analysis per batch is felt to be adequate.

An alternate source of dolomite closer to the facility is being sought. A potential source in West Nyack, New York has been identified, but the dolomite has not yet been analyzed to determine its suitability. Dolomite from this source is quoted at about half the cost shown in Table VI.2, and transportation costs would also be substantially lower.

Other Costs

Waste disposal costs shown in Table VI.1 are unchanged from the initial estimate, and are based on a written quotation from a local firm. This quotation does not include any special landfill charges.

Utility costs have not been included in the operating costs, since their treatment under the GE accounting procedure has not been negotiated with DCAA. Should they be charged to the contract and not amortized in the overhead, approximately \$235K would be added over the life of the contract. The bulk of this cost is associated with the 200 hp. compressor drive motors.

TABLE VI.2
RAW MATERIAL COSTS

	<u>1979 Est.</u>	<u>1980 Projection</u>	<u>1980 Est.</u>
<u>COAL COST</u>			
Coal	93.75	101.20	30.00
Coal Analysis (1 per 20 Ton, \$88)			4.40
Transportation to P.R.			5.00
Processing (Penn Rillton)			145.00
Drums			4.60
Pallets/Strapping	15.00	16.20	10.00
Transportation	<u>45.40</u>	<u>49.03</u>	<u>35.00</u>
	\$154.15/T	\$166.43/T	\$234.00/T

<u>DOLOMITE COST</u>			
Dolomite (Pfizer, #6, 6x16 mesh)	8.25	9.62	8.75
Packaging			28.50
Transportation	51.19	59.71	57.84
Analysis (1 per 20 ton, \$100)	<u> </u>	<u> </u>	<u>5.00</u>
	\$ 59.44/T	\$69.33/T	\$ 95.09/T

COAL & DOLOMITE CONSUMPTION RATE

Coal (Tons/Hour)	.045	.0655
Dolomite (Tons/Hour)	.0155	.0205