DVORSCAK
Paralegal
Carla

DOE/PC/91154--T11

DEVELOPMENT OF A HIGH-PERFORMANCE COAL-FIRED POWER GENERATING SYSTEM WITH PYROLYSIS GAS AND CHAR-FIRED HIGH TEMPERATURE FURNACE (HITAF)

DE-AC22-91PC91154

FINAL REPORT
Volume I

We have no objection from a patent standpoint to the publication or dissemination of this material.
Mark Dvorscak 3-22-96
Office of Intellectual Property Counsel — Date
DOE Field Office, Chicago

Prepared for
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

FWDC Project 9-41-3492
February 1996

RECEIVED
96 MAR 14 A9:41
U.S.D.O.E.
I.P.C.

FOSTER WHEELER DEVELOPMENT CORPORATION
12 Peach Tree Hill Road, Livingston, New Jersey 07039

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

VOLUME 1
FINAL REPORT

TABLE OF CONTENTS

PAGE NO.

1.0 INTRODUCTION 1

2.0 PRELIMINARY COMMERCIAL GENERATING PLANT DESIGN 3

  2.1 PROCESS OVERVIEW 6

  2.2 PLANT DESIGN AND DESCRIPTION 9

    2.2.1 DESIGN BASES 9

    2.2.2 PROCESS FLOW DIAGRAM 10

    2.2.3 MASS AND ENERGY BALANCE 18

    2.2.4 COMPLETE PLANT DESCRIPTION 19

  2.3 SUBSYSTEM DESIGN 23

    2.3.1 SOLID FEEDING AND REMOVAL (PLANT SECTION 1) 23

    2.3.2 STREAM GENERATOR ISLAND (PLANT SECTION 2) 30

      2.3.2.1 HIGH TEMPERATURE ADVANCED FURNACE (SUBSECTION 2.1) 30

      2.3.2.2 CHAR COMBUSTOR (SUBSECTION 2.2) 33

      2.3.2.3 HEAT RECOVERY SYSTEMS (SUBSECTION 2.3) 43

      2.3.2.4 STACK AND LOW-TEMPERATURE DUCTING (PLANT SUBSECTION 2.4) 47

      2.3.2.5 INDUCED-DRAFT FAN (PLANT SECTION 2.5) 48

    2.3.3 HIGH TEMPERATURE EXCHANGER - RECUPERATOR (PLANT SECTION 3) 48

    2.3.4 HIGH TEMPERATURE PIPING AND DUCTING (PLANT SECTION 4) 51

    2.3.5 PROCESS SYSTEMS (PLANT SECTION 5) 51

VOLUME 1
FINAL REPORT

TABLE OF CONTENTS

PAGE NO.

2.3.6 GAS TURBINE/TOPPING COMBUSTOR (PLANT SECTION 6) 64

2.3.7 STEAM TURBINE/BFW (PLANT SECTION 7) 70

2.3.8 EMISSIONS CONTROL SYSTEMS (PLANT SECTION 8) 72

2.3.8.1 FUEL GAS PARTICULATE CONTROL 75

2.3.8.2 GAS TURBINE NO_x CONTROL BY SCR 77

2.3.8.3 FLUE GAS PARTICULATE AND NO_x CONTROL 78

2.3.8.4 SO_2 CONTROL 80

2.3.9 BALANCE OF PLANT 83

2.3.10 SOLIDS MATERIALS HANDLING (PLANT SECTION 10) 83

2.3.11 WATER SUPPLY AND TREATMENT (PLANT SECTION 11) 88

2.3.12 SUPPORT SYSTEMS (PLANT SECTION 12) 91

2.3.13 CIVIL WORKS AND STRUCTURES (PLANT SECTION 13) 92

2.4 PLANT PERFORMANCE AND EMISSIONS 94

2.5 PLANT OPERATING PROCEDURE AND MAINTENANCE 96

2.6 COST AND ECONOMICS 100

2.6.1 COST ESTIMATE BASIS 100

2.6.2 CAPITAL COST 100

2.6.3 OPERATING AND MAINTENANCE COSTS 103

2.6.4 ECONOMIC ANALYSIS 104

2.6.5 COST SENSITIVITY ANALYSIS 105

2.6.6 COMPARISON OF HIPPS AND PULVERIZED COAL PLANT 105

VOLUME 1
FINAL REPORT

TABLE OF CONTENTS

PAGE NO.

2.7 REPOWERING APPLICATION 108

2.8 BACKUP STRATEGIES AND ALTERNATIVE DESIGNS 112

2.9 COMMERCIAL ACCEPTABILITY OF DESIGN TO POWER PRODUCERS 124

3.0 TECHNICAL ISSUES 125

3.1 INTRODUCTION 125

3.2 PYROLYZER 127

3.3 CHAR SEPARATION AND TRANSPORT 130

3.4 CHAR COMBUSTOR DEVELOPMENT ISSUES 131

3.4.1 COMBUSTOR PERFORMANCE ISSUES 133

3.4.2 COMBUSTOR DESIGN ISSUES 135

3.4.3 COMBUSTOR OPERATIONAL ISSUES 136

3.5 HITAF 138

3.6 GAS TURBINE COMBUSTOR 139

3.7 EMISSIONS SYSTEMS 142

3.8 SYSTEM INTEGRATION AND CONTROL 143

3.9 CERAMIC AIR HEATER (ALTERNATIVE DESIGN) 144

3.9.1 EVALUATION OF MATERIALS 144

3.9.2 FABRICATION 145

3.9.3 DESIGN 146

4.0 RESEARCH, DEVELOPMENT AND TEST PLAN FOR PHASE 2 147

4.1 INTRODUCTION/OVERVIEW 147

4.2 PYROLYZER/CHAR TRANSPORT 149

VOLUME 1
FINAL REPORT

TABLE OF CONTENTS

PAGE NO.

4.2.1 CHAR DEPRESSURIZATION TEST 149

4.2.2 PYROLYZER/CHAR TRANSPORT TEST 152

4.3 CHAR COMBUSTOR RESEARCH, DEVELOPMENT AND TEST PLAN FOR PHASE 2 160

4.3.1 DATA REQUIREMENTS AND PRIORITIES 160

4.3.2 RATIONALE AND APPROACH 163

4.3.3 ENGINEERING ANALYSIS AND MODELING ACTIVITIES 166

4.3.4 EXPERIMENTAL RESEARCH AND TEST ACTIVITIES 171

4.3.4.1 EXPERIMENTAL RESEARCH ACTIVITIES 172

4.3.5 DATA UTILIZATION 180

4.4 HITAF 182

4.5 GAS TURBINE COMBUSTOR 184

4.6 INTEGRATED SYSTEM TEST 185

4.7 DYNAMIC MATHEMATICAL MODEL 195

4.8 RELIABILITY, AVAILABILITY AND MAINTAINABILITY MODEL 197

4.9 CALCIUM SULFIDE CONVERSION AND PARTICLE ATTRITION 199

4.10 COMPUTER MODELING OF PYROLYZER 201

4.11 CERAMIC AIR HEATER DEVELOPMENT (ALTERNATIVE DESIGN) 203

4.11.1 DESIGN AND ANALYSIS 203

4.11.2 CERAMIC AIR HEATER DEVELOPMENT 203

5.0 PHASE 2 AND 3 STATEMENT OF WORK 209

VOLUME 1
FINAL REPORT

LIST OF FIGURES

Figure No. **PAGE NO.**

1 SIMPLIFIED HIPPS PROCESS FLOW DIAGRAM 4

2 SIMPLIFIED HIPPS REPOWERING PROCESS FLOW DIAGRAM 5

3 HIPPS COMMERCIAL PLANT OVERALL BLOCK FLOW DIAGRAM 7

4 HIPPS COMMERCIAL PLANT PROCESS FLOW DIAGRAM 12

5 OVERALL SITE PLAN 20

6 GENERAL ARRANGEMENT PLAN 21

7 ELECTRICAL SINGLE LINE DIAGRAM 22

8 FLOW DIAGRAM: COAL PREPARATION AND FEEDING-PYROLYZER SECTION 24

9 FLOW DIAGRAM: COAL PREPARATION AND FEEDING-SLAGGING COMBUSTOR SECTION 24

10 FLOW DIAGRAM: SORBENT PREPARATION AND FEEDING 27

11 SECTIONAL SIDE VIEW OF THE HITAF 31

12 CHAR COMBUSTOR FUNCTIONAL SCHEMATIC 33

13 CHAR COMBUSTOR GENERAL ARRANGEMENT 34

14 CHAR COMBUSTOR PHYSICAL DIMENSIONS 36

15 CHAR COMBUSTOR CARBON BURNOUT CALCULATIONS AS A FUNCTION OF STOICHIOMETRY AND PARTICLE SIZE 38

16 CHAR COMBUSTOR NOx EMISSION CALCULATIONS AS A FUNCTION OF STOICHIOMETRY AND AMMONIA ADDITION 39

17 SLAGGING CHAR COMBUSTOR OPERATING ENVELOPE 40

18 TRW SLAGGING COMBUSTOR INTEGRATED INTO CLEVELAND DEMONSTRATION PLANT 42

19 HITAF ECONOMIZER 45

20 DIMENSIONS OF HITAF ECONOMIZER 45

VOLUME 1
FINAL REPORT

LIST OF FIGURES

Figure No. **PAGE NO.**

21 GAS TURBINE HRSG 46

22 DIMENSIONS OF GAS TURBINE HRSG 46

23 GAS TURBINE RECUPERATOR CONDITIONS 49

24 OVERALL MODULE DIMENSIONS 50

25 PYROLYZER/CHAR TRANSPORT SYSTEM 53

26 CIRCULATING FLUIDIZED BED PYROLYZER 59

27 SODIUM CONCENTRATION IN FUEL GAS VS. TEMPERATURE 61

28 CONCEPTUAL COMBUSTION TURBINE ARRANGEMENT 66

29 TOPPING COMBUSTION ASSEMBLY 66

30 TOPPING COMBUSTOR/COMBUSTION TURBINE ARRANGEMENT 67

31 TOPPING COMBUSTOR/COMBUSTION TURBINE INTERFACE 67

32 MASB ASSEMBLY 68

33 ALL COAL HIPPS EMISSION CONTROL FLOW SYSTEM 73

34 BARRIER FILTER ASSEMBLY 75

35 GAS FLOW THROUGH POROUS CELL WALLS 79

36 MAGNESIUM-ENHANCED LIME FGD SYSTEM 81

37 FLOW DIAGRAM: COAL RECEIVING AND HANDLING 84

38 FLOW DIAGRAM: SORBENT RECEIVING AND HANDLING 85

39 ASH AND SLAG HANDLING AND DISPOSAL 86

40 BLOCK FLOW DIAGRAM: RAW WATER SUPPLY AND TREATMENT 89

41 HIPPS SYSTEM CONTROL 97

42 SIMPLIFIED HIPPS REPOWERING PROCESS FLOW DIAGRAM 109

VOLUME 1
FINAL REPORT

LIST OF FIGURES

Figure No. **PAGE NO.**

43 PROCESS FLOW DIAGRAM OF THE HIPPS REPOWERING CYCLE 111

44 SYSTEM BLOCK DIAGRAM OF HIPPS REPOWERING 116

45 PYROLYZER COAL/SORBENT PREPARATION AND FEEDING 117

46 PYROLYZER SUBSYSTEM 118

47 COAL/CHAR FEED SYSTEM TO BOILER 119

48 CERAMIC AIR HEATER HIPPS 123

49 SLAGGING CHAR COMBUSTOR TECHNICAL ISSUES 131

50 TECHNOLOGY READINESS 132

51 CONCEPTUAL ARRANGEMENTS OF THE MULTI-ANNULAR SWIRL BURNER BASED ON J.M. BEER'S PATENT DESIGN (1989) 140

52 RECENT 14-IN. MASB DESIGN 140

53 PHASE 2 PROJECT OVERVIEW (BY TASK/SUBTASK) FOR PHASE 1 148

54 SCHEMATIC DRAWING OF CHAR SEPARATION AND TRANSPORT SYSTEM 150

55 SCHEMATIC DRAWING OF RPDS TEST UNIT 150

56 PYROLYZER/CHAR TRANSPORT PROCESS FLOW SCHEMATIC 154

57 PYROLYZER/CHAR TRANSPORT PILOT PLANT 155

58 APPROACH FOR RESOLVING PERFORMANCE, OPERATIONAL AND DESIGN ISSUES 164

59 CHAR COMBUSTOR ANALYTICAL MODEL GEOMETRY AND ZONE DEFINITION 168

60 OVERALL TEST PROGRAM LOGIC 173

61 SCHEMATIC OF TEST SET-UP FOR CHAR COMBUSTOR DEVELOPMENT TESTING AT TRW 176

VOLUME 1
FINAL REPORT

LIST OF FIGURES

Figure No. **PAGE NO.**

62 PHOTOGRAPH OF TEST CELLS AT FETS 177

63 TEST LOGIC FOR CHAR COMBUSTOR DEVELOPMENT TESTS AT TRW 179

64 SCHEMATIC OF INTEGRATED SYSTEM TEST 187

65 LAYOUT OF THE UTSI FACILITY -- CFFF SITE PLAN 194

66 LABORATORY CaS CONVERSION AND ATTRITION TEST RIG 200

67 CERAMIC AIR HEATER DEVELOPMENT ORGANIZATION 203

VOLUME 1
FINAL REPORT

LIST OF TABLES

Table No. **PAGE NO.**

1 DESIGN COAL ANALYSIS (PITTSBURGH NO. 8 BITUMINOUS) 10

2 COMMERCIAL PLANT FLOW STREAMS 13

3 OVERALL MASS AND ENERGY BALANCE (FULL LOAD - 60°F AMBIENT) 18

4 MAJOR EQUIPMENT LIST: SOLIDS FEEDING AND REMOVAL (PLANT SECTION 1) 25

5 KEY DESIGN PARAMETERS AND DATA: SOLIDS PREPARATION, FEEDING, AND REMOVAL (PLANT SECTION 1) 28

6 HITAF TUBE SPECIFICATIONS 31

7 CHAR COMBUSTOR OPERATION AND PERFORMANCE CHARACTERISTICS 36

8 HITAF ECONOMIZER SPECIFICATIONS 47

9 GAS TURBINE HRSG SPECIFICATIONS 47

10 STACK DESIGN PARAMETERS AND SPECIFICATIONS 47

11 DESIGN SPECIFICATIONS FOR PIPING AND DUCTING 52

12 PYROLYZER BALANCE AT 1700°F AND 16 ATMOSPHERES 56

13 SUMMARY OF SECOND-GENERATION PFB PILOT PLANT PYROLYZER TEST CONDITIONS 57

14 SIZE DISTRIBUTIONS AND FLOWRATES OF SOLIDS STREAMS 60

15 DESIGN SPECIFICATION AND FEATURES: STEAM TURBINE-GENERATOR SUBSYSTEM 71

16 DESIGN SPECIFICATION AND FEATURES: CONDENSATE BFW SUBSYSTEM 71

17 EMISSION SUMMARY 74

18 DESIGN SPECIFICATIONS AND FEATURES: COAL RECEIVING AND HANDLING 86

VOLUME 1
FINAL REPORT

LIST OF TABLES

Table No. **PAGE NO.**

19 DESIGN SPECIFICATIONS AND FEATURES: SORBENT RECEIVING AND HANDLING 87

20 DESIGN SPECIFICATIONS AND FEATURES: ASH AND SLAG HANDLING AND DISPOSAL 87

21 OVERALL WATER BALANCE FLOW RATES OF MAJOR STREAMS (GAL/MIN) 89

22 MAJOR PROCESS PARAMETERS: WATER TREATMENT AND SUPPLY SUBSYSTEM 90

23 DESIGN SPECIFICATIONS AND FEATURES: WATER TREATMENT AND SUPPLY SUBSYSTEM 90

24 OVERALL PROJECTED PLANT PERFORMANCE (60°F AMBIENT) 94

25 HIPPS TOTAL DIRECTED FIELD COST (MILLIONS OF DECEMBER 1993 DOLLARS) 101

26 TOTAL CAPITAL REQUIREMENTS (MILLIONS OF DECEMBER 1993 DOLLARS) 102

27 HIPPS OWNER'S COST SUMMARY (THOUSANDS OF DECEMBER 1993 DOLLARS) 103

28 HIPPS FIRST YEAR ANNUAL OPERATING AND MAINTENANCE COSTS (THOUSANDS OF DECEMBER 1993 DOLLARS PER YEAR)* 104

29 HIPPS ECONOMIC INPUTS AND RESULTS (UNLESS INDICATED, COST ARE THOUSANDS OF DECEMBER 1993 DOLLARS) 105

30 HIPPS SENSITIVITY ANALYSIS 105

31 CAPITAL COSTS COMPARISON BETWEEN PCF POWER PLANT AND HIPPS 106

32 COMPARISON OF PCF AND HIPPS ECONOMICS INPUTS AND RESULTS (UNLESS INDICATED, COSTS ARE THOUSANDS OF DECEMBER 1993 DOLLARS) 107

33 TYPICAL REPOWERING APPLICATION 110

34 REPOWERING PROCESS FLOW STREAMS 112

VOLUME 1
FINAL REPORT

LIST OF TABLES

Table No.		PAGE NO.
35	STATUS OF HIPPS TECHNOLOGIES	126
36	ORGANIZATION OF RD&T PLAN DISCUSSION	147
37	SUMMARY OF PYROLYZER/CHAR TRANSPORT TEST	153
38	PYROLYZER/CHAR TRANSPORT TEST FLOW PARAMETERS	156
39	PYROLYZER SCALE PROGRESSION	158
40	SUMMARY OF ISSUES AND TECHNICAL APPROACH	161
41	SUMMARY OF TRW-PROPRIETARY CODES	167
42	SEMIQUALITATIVE ASH ANALYSIS OF CHAR-SORBENT MIXTURE (WT%)	183
43	INTEGRATED PILOT PLANT PROCESS FLOW PARAMETERS	188
44	INTEGRATED SYSTEM TEST (IST) MEASUREMENTS	191

1.0 INTRODUCTION

Early in the twenty-first century it is anticipated that new electricity generating plants will be needed. These plants will be required to meet continuing increases in demand for electric power, and to replace generating stations that will have reached the end of their useful life. Because of its abundance and low cost, coal will be an important option for powering new plants; however, environmental concerns could suppress its use.

To address the entire spectrum of environmental concerns associated with coal use, the Pittsburgh Energy Technology Center (PETC) began a three-phase program for the development of Coal-Fired High Performance Power Systems (HIPPS). A major objective of the HIPPS program is to achieve significant increases in the thermodynamic efficiency of coal use for electric power generation. Through increased efficiency, all airborne emissions can be decreased, including emissions of carbon dioxide. Moreover, higher efficiency will provide environmental benefits throughout the entire fuel cycle, including coal mining and transportation, reduced solid wastes, reduced water requirements and reduced thermal loadings to rivers and other water bodies.

High Performance power systems as defined for this program are coal-fired, high efficiency systems where the combustion products from coal do not contact the gas turbine. Typically, this type of a system will involve some indirect heating of gas turbine inlet air and then topping combustion with a cleaner fuel. The topping combustion fuel can be natural gas or another relatively clean fuel. Fuel gas derived from coal is an acceptable fuel for the topping combustion. The ultimate goal for HIPPS is to have a system that has 95 percent of its heat input from coal. Interim systems that have at least 65 percent heat input from coal are acceptable, but these systems are required to have a clear development path to a system that is 95 percent coal-fired.

A HIPPS plant must have an efficiency of at least 47 percent on a higher heating value basis. It must also have very low emissions. SOx and NOx emissions must each be less than 0.06 lb/MMBtu and particulates must be less than 0.003 lb/MMBtu. The cost of electricity (COE) from a HIPPS plant must be 10 percent less than a modern coal-fired power plant conforming to current New Source Performance Standards (NSPS).

A three phase program has been planned for the development of HIPPS. Phase 1, reported herein, includes the development of a conceptual design for a commercial plant. Technical and economic feasibility have been analysed for this plant. Preliminary R&D on some aspects of the system were also done in Phase 1, and a Research, Development and Test plan was developed for Phase 2. Work in Phase 2 includes the testing and analysis that is required to develop the technology base for a prototype plant. This work includes pilot plant testing at a scale of around 50 MMBtu/hr heat input. The culmination of the Phase 2 effort will be a site-specific design and test plan for a prototype plant. Phase 3 is the construction and testing of this plant.

This report contains the results of Phase 1 of the HIPPS project that is being done by the Foster Wheeler Development Corporation (FWDC) team. The other team members for Phase 1 were:

- AlliedSignal
- Bechtel
- General Electric
- Research Cottrell
- TRW

Some of the testing done in Phase 1 was done by subcontract to other Institutions. Some of the laboratory testing on char combustion was done by Brigham Young University. Some pyrolyzer testing was done at Southern Illinois University.

Volume I of this report is the main body of the report. It fully describes our HIPPS plant and includes the technical and economic analysis of the plant. Volume II and III contain appendices that include more detail on specific tests and analyses that were done during Phase 1.

2.0 PRELIMINARY COMMERCIAL GENERATING PLANT DESIGN

INTRODUCTION/SUMMARY

The HIPPS concept presented in this report will achieve all the program objectives including 47 percent efficiency, 0.06 lb/MMBtu SO_x, 0.06 lb/MMBtu NO_x and 0.003 lb\MMBtu particulates. A plant of this design will fulfill the ultimate goal of having a system that uses only coal as fuel. This can be achieved within Phase 2 and Phase 3 of this project, eliminating the need for an intermediate, hybrid natural-gas/coal-fueled system.

The base case system will not depend on the successful development of ceramic heaters since we are confident of meeting the efficiency goals with our proposed design. Also, It is uncertain if the state of the art in ceramic technology development will support the development schedule stipulated for Phases 2 and 3. However, recognizing the enhancements ceramic heat exchangers can bring, we have included further ceramic heater development as part of our RD&T plan for Phase 2. Should this development succeed in time, ceramic heat exchangers can be incorporated into the demonstration unit. Such a design has been conceptually developed in Phase 1 and was shown to be feasible provided the ceramic air heater is sufficiently reliable.

In addition to the base case, a greenfields HIPPS plant, our concept can be used as a repowering option that will significantly increase the overall efficiency of U.S. power production—economically and in the short term. Unlike other coal-fired repowering options that involve scrapping the existing boiler, this concept will retain the existing pulverized coal-fired boiler while increasing capacity and efficiency. Because our approach can be economical, even with relatively new boilers, improvement in the nation's overall power generation efficiency can be greatly accelerated.

The simplified process flow diagram shown in Figure 1 illustrates the basic concept of the base-case HIPPS plant. The heart of the system is the high-temperature advanced furnace (HITAF), which is a combination boiler/air heater that transfers heat to the topping and bottoming cycles. A key component of the system is the pyrolyzer, which converts the coal into a low-Btu fuel gas and char. The HITAF and the pyrolyzer are combined to obtain a system that meets the project goals with coal as the only fuel.

Coal, sorbent, and air are fed to the pyrolyzer. It is operated at about 240 psia/1700°F under substoichiometric conditions that produce a low-Btu fuel gas and char. After leaving the pyrolyzer, the fuel gas is cooled to about 1100°F to remove alkalies, and the char is separated from the fuel gas. The char is burned in the HITAF, which contains both steam and air heat-transfer surface. In the HITAF, the gas turbine air is heated in metal alloy tubes to 1400°F. Evaporation and superheating for the steam cycle also take place in the HITAF.

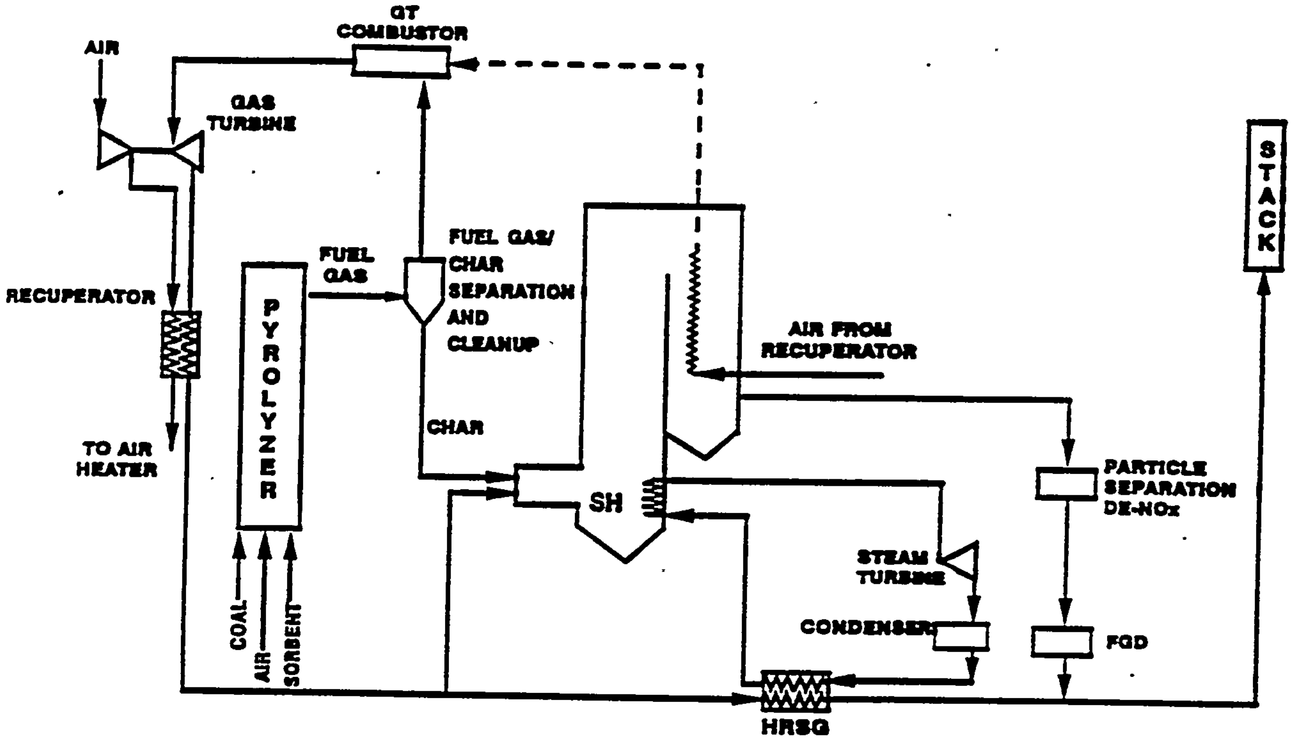


Figure 1 Simplified HIPPS Process Flow Diagram

The gas turbine air leaving the HITAF is heated further by firing the cleaned fuel gas in the topping combustor. The gas temperature entering the first stage of the gas turbine is 2350°F. The exhaust from the gas turbine goes through a recuperator, where heat is transferred to the compressor discharge air. A portion of the vitiated air from the gas turbine is used as combustion air for the HITAF. The unused vitiated air goes through a heat-recovery steam generator.

Emission control can be accomplished by a variety of methods, depending on the sulfur content of the fuel and the required emissions levels. For the high-sulfur coal and very low emissions levels specified for this project, cleanup systems will be required for NO_x, SO_x and particulates. The base-case HIPPS system uses a wet lime scrubber system to remove SO_x from the HITAF and gas turbine exhaust streams. NO_x will be controlled by low NO_x combustion and a selective catalytic reduction system.

The repowering application provides a means for rapidly changing the nature of power production in the U.S. It is applicable to a wide range of existing pulverized coal-fired boilers, and it should provide an economic incentive for increasing efficiency while maintaining coal as the fuel. A simplified process flow diagram of the repowering application is shown in Figure 2. The pyrolyzer subsystem is the same as the greenfields plant. The fuel gas is fired in a gas turbine. The char from the pyrolyzer and the gas turbine exhaust go to the existing boiler. The char and coal fuel the boiler, and the turbine exhaust is the combustion air. This system is similar in concept to "hot windbox" repowering schemes that have been used in Europe. The main difference is that HIPPS repowering will be applied to a coal fired boiler, and it will eliminate the need for oil or gas as a fuel for the gas turbine. With repowering, plant electrical output can be increased by up to 50 percent, and plant efficiency will increase by 4 to 6 percentage points. The repowering option can therefore be applied in a wide range of sizes encompassing the spectrum of existing pulverized coal-fired boilers.

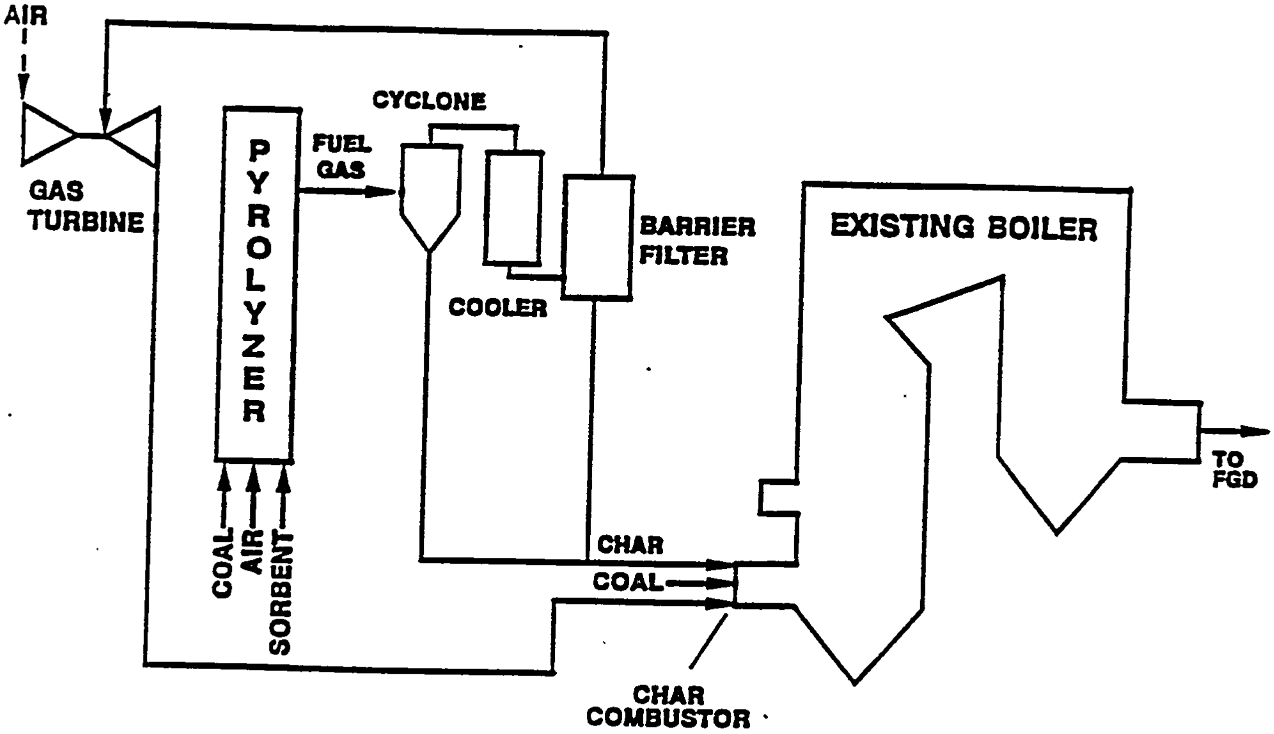


Figure 2 Simplified HIPPS Repowering Process Flow Diagram

The major development area for the HIPPS plants is the integrated operation of a pyrolyzer and char combustor. Both of these components have been tested separately in other projects; integrated operation requires both the physical transport of char and a matching of the process requirements of both components. This development work started during Phase 1. Laboratory testing determined the combustion characteristics of the char, and computer modeling of both the char combustor and pyrolyzer evaluated relevant parameters.

The Phase 2 development effort for these subsystems will essentially be done in two steps. First, the components will be tested separately in pilot plants. A pyrolyzer with a coal input of approximately 600 lb/h will be run in conjunction with a char transport system. Separately, a 40 MMBtu/h char combustor will be tested on both commercially generated char and then with char from the pyrolyzer pilot plant. These initial tests will allow us to develop the design and operation of these components and more accurately establish the required input and output parameters. Next, an integrated system will be tested where the pyrolyzer, char transport system, char combustor, and furnace are operated together. The coal input to the integrated system will be approximately 6500 lb/h. This pilot plant will be sufficiently complete and of a large enough scale to provide the necessary design information and to demonstrate the system.

The Commercial Plant HIPPS is based on a Westinghouse 501F gas turbine. The gas turbine research done as part of the second-generation Pressurized Fluidized Bed (PFB) project, is directly applicable to the HIPPS, so only minimal R&D is required in this project. Likewise, the emissions systems that are used are either commercial or being demonstrated as part of other projects.

2.1 PROCESS OVERVIEW

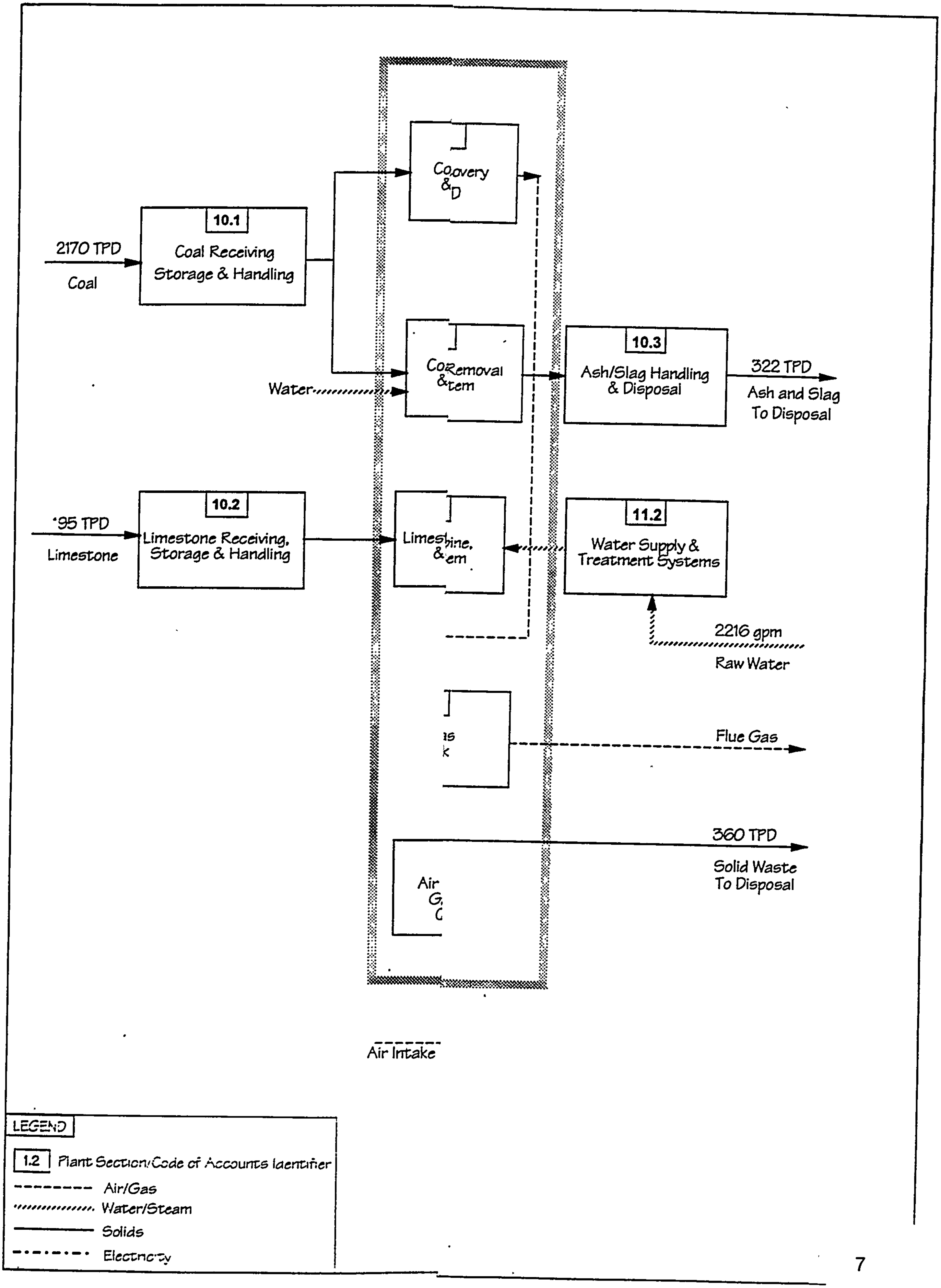
Our HIPPS concept is a combined-cycle system that is totally coal-fired. It is based on PC firing and is amenable to a variety of emissions systems. Because of the type of firing and the flexibility afforded by the conversion of coal into fuel gas and char, the system can be configured in a variety of arrangements. A block diagram of the base case HIPPS plant is shown in Figure 3. The block diagram includes the plant subsystem numbers that match the code of accounts. Other arrangements include repowering systems and operation without topping combustion when air heaters with sufficiently high outlet temperatures are developed. A general overview of the system follows. Each subsystem is described in more detail in Section 2.3.

Coal and sorbent are received at the site and stored with conventional equipment *(10.1 and 10.2)*. These feedstocks are then fed to the coal and sorbent preparation and feeding subsystems *(1.1 and 1.2)* where they are sized. Coal and sorbent for the pyrolyzer are processed in a commercial pulverizer/bin system and then combined with water to form a paste. This paste is pumped into the pyrolyzer. Coal for the char combustor precombustor is pulverized and direct fired like a conventional pulverized coal boiler.

The pyrolyzer *(5.1)* is a circulating fluidized bed that is operated under conditions that convert the coal into fuel gas and char. It is operated under pressure, and the fuel gas is fired in the gas turbine topping combustor *(6.0)*. Before the fuel gas is fired, it is cooled to 1100°F to remove alkalies by condensation, and the char is separated for use in the HITAF *(5.2/5.3/5.4)*. Sorbent in the pyrolyzer will remove over 90 percent of the sulfur that is released in the pyrolyzer. This removal efficiency combined with the HITAF back end cleanup, will be sufficient to meet emissions requirements well below current NSPS. For the SO_2 emissions required in this project, additional sulfur removal will be required in this stream. The fuel gas can be cleaned before it is fired in the gas turbine or in the gas turbine exhaust stream. Because a FGD system is required in the HITAF flue gas stream, the same type of system will be used in the gas turbine exhaust stream *(8.2)*.

The char that is separated from the fuel gas is fed to the HITAF with the char transport subsystem *(5.5)*. This subsystem lowers the char pressure to a level compatible with the atmospheric pressure char combustor/HITAF subsystems. It also meters and pneumatically transports the char. The char combustor *(2.2)* receives the char from the pyrolyzer *(5.1)* and coal from the coal preparation and feeding system *(1.1)*. These fuels are burned in the char combustor and the hot gas enters the HITAF furnace. Vitiated air from the gas turbine exhaust stream is used as combustion air in the char combustor and in the HITAF furnace where combustion is completed.

In the HITAF (2.1), the flue gas heats air and generates steam. The air and steam are contained in tube banks and tube walls. The design and construction of the HITAF is very similar to a conventional pulverized coal boiler. SO_2, NO_x and particulate removal are accomplished downstream of the HITAF in the HITAF emissions system (8.1/8.2). The cleaned flue gas then goes to the stack (2.4). The ash handling and disposal subsystem (10.3) removes the fly as and slag from the HITAF.


10.1
Coal Receiving Storage & Handling
2170 TPD
Coal
Co overy
& D
Co Removal
& tem
Water
10.3
Ash/Slag Handling & Disposal
322 TPD
Ash and Slag To Disposal
10.2
Limestone Receiving, Storage & Handling
'95 TPD
Limestone
Limes ine,
& em
11.2
Water Supply & Treatment Systems
2216 gpm
Raw Water
as
k
Flue Gas
Air
G
C
360 TPD
Solid Waste To Disposal
Air Intake
LEGEND
1.2 Plant Section/Code of Accounts Identifier
Air/Gas
Water/Steam
Solids
Electricity

The fuel gas from the pyrolyzer *(5.1)* is fired in the gas turbine topping combustor *(6.0)*. In the topping combustor, the hot air from the HITAF is heated up to the gas turbine inlet temperature. This vitiated air then goes through the gas turbine which is the prime mover for the combustion air. Part of the gas turbine exhaust goes through a recuperator *(3.0)* where heat is transferred to the compressor discharge air. Additional heat is extracted from the gas turbine exhaust stream in the gas turbine Heat Recovery Steam Generator (HRSG) *(2.3)*. This heat goes to the steam cycle. For the base case emissions requirements, NO_x reduction is required in the gas turbine exhaust stream. This cleaning is done in the gas turbine emissions subsystem *(8.3)* before the vitiated air is sent to the stack.

The steam turbine/Boiler Feed Water System (BFW) subsystem *(7.0)* operates in conjunction with the HITAF *(2.1)*, gas turbine HRSG *(2.3)* and the water supply and treatment subsystem *(11.2)* to form the Rankine bottoming cycle. The electrical switchyard and distribution system *(12.3)* performs all the required functions for the control of the generated power.

2.2 PLANT DESIGN AND DESCRIPTION

2.2.1 Design Bases

The major design criteria used for the commercial plant are described below:

- The plant is a grassroots facility designed for base-load operation.
- All systems are based on 60°F ambient temperature.
- All equipment is designed for a 30-year plant life.
- The entire plant is to be erected at one time, without consideration for phased construction.
- The HIPPS plant sizing is based on a single Westinghouse 501F gas turbine with a nominal output of 160 MW at ISO on natural gas; additional power generation capacity is provided by a single reheat steam turbine with a nominal output of 170 MW.
- The HIPPS boiler is designed to incorporate two TRW slagging combustors. The air heater is designed to achieve a minimum outlet air temperature of 1400°F.
- Fuel gas temperature is 1100°F.
- Plan efficiency must be 47 percent or greater based on HHV.
- Cost of electricity (COE) must be at least 10 percent lower than a comparable pulverized coal-fired plant.
- The plant uses a Pittsburgh No. 8 bituminous coal feedstock with the analysis shown in Table 1 and limestone feed with minimum of 95.5 percent calcium content.
- The plant air emissions must not exceed 0.06 lb/MM Btu for sulfur dioxide, 0.06 lb/MM Btu for NO_x, and 0.003 lb/MM Btu for particulates. Solids discharged from the plant are non-hazardous and are either disposed of off site or sold as byproducts. Wastewater discharged from the plant must meet the EPA Effluent Guidelines and Standards.

Other criteria, guidelines and data related to site, resources, and plant services include the following:

- Site location is assumed to be in Pennsylvania, and the site area is assumed to be clear and level with road and rail access and a nearby source of water.
- Design dry and wet bulb temperatures are 60°F and 52°F, respectively, with corresponding maximum of 95°F and 75°F, and atmospheric pressure is 14.7 psia.
- Coal is delivered by rail and limestone by truck.
- Mechanical draft cooling towers are used, with cooling water supplied at 63°F.
- Power voltages are assumed to be 230 kV to line, 13.8 kV to switchyard, 480 V to motors less than 250 hp, and 4.16 kV to motors larger than 250 hp.
- Coal and limestone preparation equipment, gas and steam turbines, and water treatment facilities are all located indoors.

The criteria and assumptions used in developing the plant cost estimates are given in Section 2.6 Plant Cost.

2.2.2 Process Flow Diagram

The envisioned HIPPS commercial plant will be a grassroots, coal base-load facility exporting 310 MWe of net power to the grid at full load. The plant size was set based on using one advanced heavy-frame industrial gas turbine train with a nominal output of 160 MW. Additional power generation capacity is provided by a single reheat steam turbine, with steam inlet temperature/pressure/reheat conditions of 1075°F/2615 psia/1075°F. At full load, the plant consumes about 2,170 tons per day of Pittsburgh No. 8 bituminous coal feedstock, 195 tons per day of limestone and about 2,216 gallons per minute of raw water. The plant is projected to achieve an overall thermal efficiency of 47.2 percent (HHV basis) at full load and to meet the emission limits of 0.06 lb/MMBtu for SO_2 and NO_2 and 0.003 lb/MMBtu for particulates. Two main gaseous streams are produced in the plant: one stream is a clean gas turbine exhaust that is mostly air, and the other stream is a dirty flue gas exhausted from the furnace. Separate emission control and heat recovery systems are used for the clean and dirty gas streams although they share a common FGD system. The solid waste from the plant consists mostly of slag, ash, and FGD waste. The liquid waste consists mainly of treated wastewater discharge.

Table 1 Design Coal Analysis (Pittsburgh No. 8 Bituminous)

Constituent	As Received Percent
Ultimate Analysis:	
Carbon	69.36
Hydrogen	5.18
Nitrogen	1.22
Sulfur	2.89
Ash	9.94
Oxygen	11.41
TOTAL	100.00
Proximate Analysis:	
Moisture	6.00
Ash	9.94
Volatile Matter	35.91
Fixed Carbon.	48.15
TOTAL	100.00

Higher Heating Value	12,450 Btu/lb

Table 1 Design Coal Analysis (continued)

Ash Analysis	
Description	**Percent**
Silica, SiO_2	48.1
Aluminum Oxide, Al_2O_3	22.3
Iron Oxide, Fe_2O_3	24.2
Titanium dioxide, TiO_2	1.3
Calcium Oxide, CaO	1.3
Magnesium Oxide, MgO	0.6
Sodium Oxide, Na_2O	0.3 (0.9% in Coal)
Potassium Oxide, K_2O	1.5 (0.15% in Coal)
Sulfur Trioxide, SO_3	0.8
Phosphorous Pentoxide, P_2O_5	0.1
TOTAL	100.00

Ash Fusion Temperature °F		
Description	**Reducing Atmosphere**	**Oxidizing Atmosphere**
Initial Deformation	2015	2570
Spherical	2135	2614
Hemispherical	2225	2628
Fluid	2450	2685

Figure 4 shows the process flow diagram for the HIPPS commercial plant, and Table 2 lists the flow rates, composition, and conditions for the major streams indicated on the flow diagram.

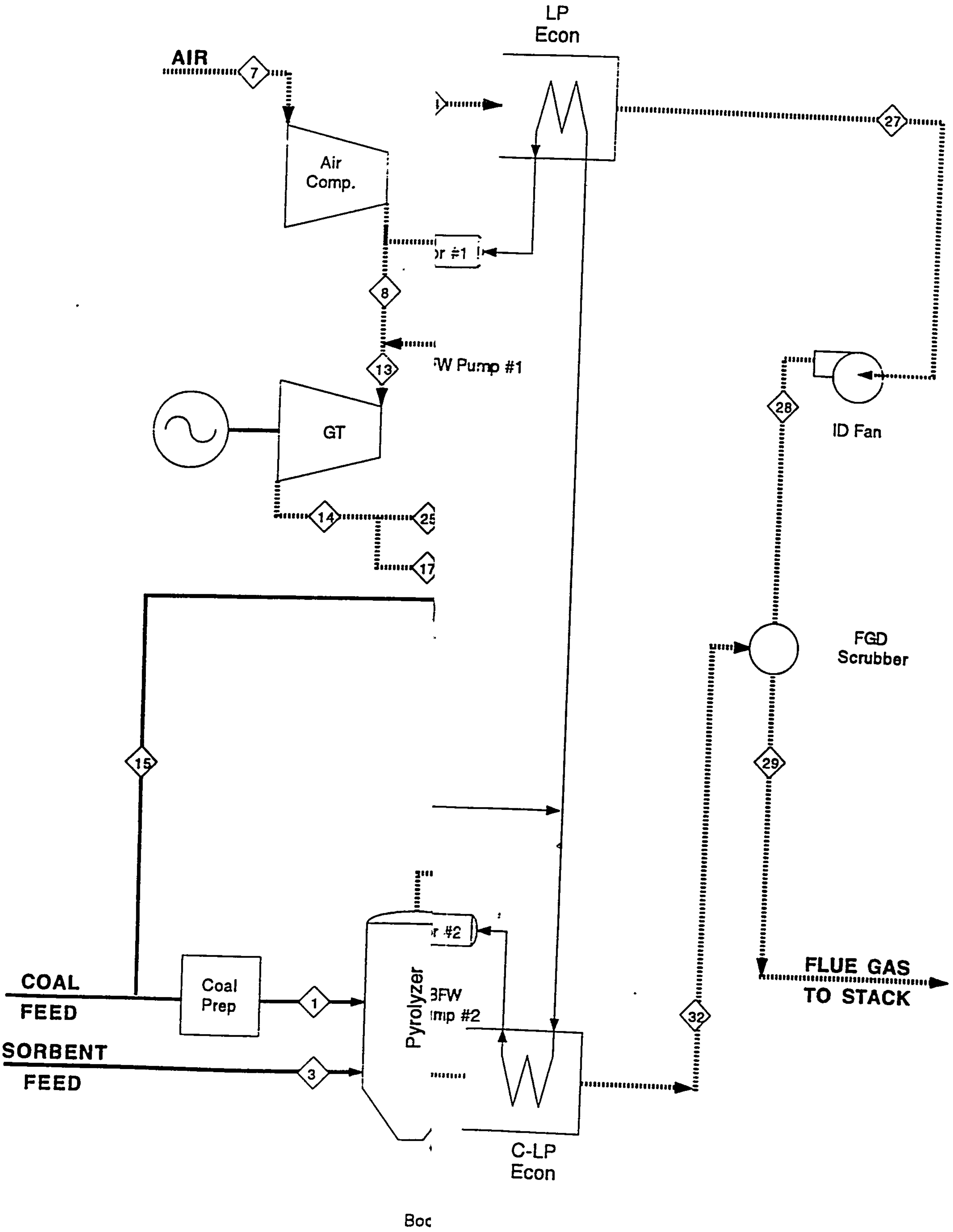

LP
Econ
AIR
7
27
Air
Comp.
r #1
8
W Pump #1
13
28
ID Fan
GT
14
25
17
FGD
Scrubber
15
29
r #2
COAL
FEED
Coal
Prep
1
Pyrolyzer
BFW
mp #2
FLUE GAS
TO STACK
32
SORBENT
FEED
3
C-LP
Econ
Boc

Table 2 Commercial Plant Flow Streams

	Stream No.	1		2		3		4		5		6		7	
		Coal to Pyrolyzer		Air to Pyrolyzer		Sorbent to Pyrolyzer		Char fm Pyrolyzer		Fuel Gas fm Pyrolyzer		Fuel Gas to GT Comb.		Air to Compressor	
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
Solids lb/h	Carbon	53.85%	113,970					55.21%	37,355	55.21%	2,909				
	Hydrogen	3.51%	7,431					0.35%	235	0.35%	18				
	Oxygen	4.74%	10,028												
	Nitrogen	0.94%	1,993					0.97%	654	0.97%	51				
	Sulfur	2.24%	4,743					0.92%	620	0.92%	48				
	Ash	7.72%	16,345			0.95%	155	24.39%	16,500	24.39%	1,285				
	Moisture	27.00%	57,144			2.00%	325								
	CaCO3					95.50%	15,533	5.22%	3,530	5.22%	275				
	MgCO3					1.55%	252								
	CaO														
	MgO							0.18%	120	0.18%	9				
	CaS							12.78%	8,649	12.78%	674				
	CaSO4														
Gases lb/h	CH4									1.06%	6,246	1.06%	6,202		
	C2H4														
	C2H6														
	C3H8														
	CO									19.62%	115,278	19.62%	114,480		
	H2									1.26%	7,397	1.26%	7,346		
	CO2			0.05%	202					14.95%	87,840	14.95%	87,231	0.05%	1,565
	H2O			0.82%	3,493					7.39%	43,391	7.39%	43,091	0.82%	27,039
	O2			22.95%	98,083									22.95%	759,147
	N2			74.90%	320,071					54.59%	320,770	54.59%	318,549	74.90%	2,477,293
	H2S									0.05%	297	0.05%	295		
	COS														
	SO2														
	C6H6+														
	Argon			1.28%	5,460					0.93%	5,460	0.93%	5,422	1.28%	42,256
	NH3									0.14%	849	0.14%	843		
	NO2														
Total Flow, lb/h		100.00%	211,644	100.00%	427,309	100.00%	16,265	100.00%	67,663	199.99%	587,555	100.00%	583,487	100.00%	3,307,300
					14,689						24,088		23,921		113,693
					29.09						24.39		24.39		29.09
Pressure, psia			258.20		265.00		258.20		239.32		239.32		229.70		14.60
Temperature, °F			70.00		410.10		70.00		1,700.00		1,700.00		1,100.00		60.00
Temperature, °C			21.11		210.06		21.11		926.67		926.67		593.33		15.56

Table 2 (Continued)

Stream No.		8		9		10		11		12		13		14	
Stream		Bypass Air		Air to Recuperator		Air to Furnace		Air to GT Combustor		FG fm GT Combustor		Total Gas to GT		Gas fm GT	
		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
	Carbon														
	Hydrogen														
	Oxygen														
	Nitrogen														
	Sulfur														
Solids	Ash														
lb/h	Moisture														
	CaCO3														
	MgCO3														
	CaO														
	MgO														
	CaS														
	CaSO4														
	CH4														
	C2H4														
	C2H6														
	C3H8														
	CO														
Gases	H2														
lb/h	CO2	0.05%	358	0.05%	1,005	0.05%	1,005	0.05%	1,005	10.53%	285,122	8.24%	285,480	8.24%	285,480
	H2O	0.82%	6,188	0.82%	17,357	0.82%	17,357	0.82%	17,357	5.23%	141,524	4.26%	147,712	4.26%	147,712
	O2	22.95%	173,732	22.95%	487,332	22.95%	487,332	22.95%	487,332	12.43%	336,467	14.73%	510,199	14.73%	510,199
	N2	74.90%	566,932	74.90%	1,590,291	74.90%	1,590,291	74.90%	1,590,291	70.54%	1,909,173	71.49%	2,476,105	71.49%	2,476,105
	H2S														
	COS														
	SO2									0.02%	555	0.02%	555	0.02%	555
	C6H6+														
	Argon	1.28%	9,670	1.28%	27,126	1.28%	27,126	1.28%	27,126	1.20%	32,548	1.22%	42,218	1.22%	42,218
	NH3														
	NO2									0.04%	1,181	0.03%	1,181	0.03%	1,181
Total Flow, lb/h		100.00%	756,880	100.00%	2,123,111	100.00%	2,123,111	100.00%	2,123,111	100.00%	2,706,570	100.00%	3,463,450	100.00%	3,463,450
			26,019		72,985		72,985		72,985		93,036		119,055		119,055
			29.09		29.09		29.09		29.09		29.09		29.09		29.09
Pressure, psia			223.10		223.10		222.40		221.70		208.70		208.70		16.10
Temperature, °F			740.00		740.00		1,053.00		1,400.00		2,560.70		2,200.60		1,121.00
Temperature, °C			393.33		393.33		567.22		760.00		1,404.83		1,204.78		605.00

Table 2 (Continued)

Stream No.		15		16		17		18		19		20		21	
		Coal to Precombustor		Char to Char Comb		Prim Air to Precomb		Secondary Air to Furn.		Slag fm Char Comb		Flue Gas to SH#3		Flue Gas to Fur. AH	
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
	Carbon	69.33%	11,402	52.08%	37,355										
	Hydrogen	4.52%	744	0.33%	235										
	Oxygen	6.10%	1,004												
	Nitrogen	1.21%	200	0.91%	654										
	Sulfur	2.88%	474	0.86%	620										
Solids	Ash	9.95%	1,636	23.00%	16,500					67.28%	14,509	0.30%	3,627	0.30%	3,627
lb/h	Moisture	6.00%	987												
	CaCO3			4.92%	3,530										
	MgCO3														
	CaO									32.28%	6,961	0.14%	1,740	0.14%	1,740
	MgO			0.17%	120					0.45%	96	0.00%	24	0.00%	24
	CaS			12.06%	8,649										
	CaSO4														
	CH4			0.06%	43										
	C2H4														
	C2H6														
	C3H8														
	CO			1.11%	798										
Gases	H2			0.07%	51										
lb/h	CO2			0.85%	608	8.24%	62,948	8.24%	27,787			22.70%	272,937	22.70%	272,937
	H2O			0.42%	300	4.26%	32,570	4.26%	14,378			4.81%	57,834	4.81%	57,834
	O2					14.73%	112,499	14.73%	49,660			2.14%	25,699	2.14%	25,699
	N2			3.10%	2,221	71.49%	545,981	71.49%	241,011			67.88%	816,315	67.88%	816,315
	H2S			0.00%	2										
	COS														
	SO2					0.02%	122	0.02%	54			0.84%	10,046	0.84%	10,046
	C6H6+														
	Argon			0.05%	38	1.22%	9,309	1.22%	4,109			1.16%	13,904	1.16%	13,904
	NH3			0.01%	6										
	NO2					0.03%	260	0.03%	115			0.03%	391	0.03%	391
	Total Flow, lb/h	100.00%	16,446	100.00%	71,731	100.00%	763,691	100.00%	337,114	100.00%	21,566	100.00%	1,202,516	100.00%	1,202,516
							26,252		11,588				39,521		39,521
							29.09		29.09				30.43		30.43
	Pressure, psia		25.00		25.00		16.10		15.40		14.70		14.50		14.20
	Temperature, °F		60.00		600.00		1,121.00		891.00		2,400.00		2,551.00		2,117.30
	Temperature, °C		15.56		315.56		605.00		477.22		1,315.56		1,399.44		1,158.50

Table 2 (Continued)

Stream No.		22		23		24		25		26		27		28	
		Flue Gas to RH		D Flue Gas to DENOX		D Flue Gas to LP Econ		Gas to Recuperator		Gas fm Recuperator		D Flue Gas to Fan		D FG to SO2 Scrub	
Stream		%wt	lb/hr	wt%	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
	Carbon														
	Hydrogen														
	Oxygen														
	Nitrogen														
	Sulfur														
Solids lb/h	Ash	0.30%	3,627	0.30%	3,627										
	Moisture														
	CaCO3														
	MgCO3														
	CaO	0.14%	1,740	0.14%	1,740										
	MgO	0.00%	24	0.00%	24										
	CaS														
	CaSO4														
	CH4														
	C2H4														
	C2H6														
	C3H8														
	CO														
Gases	H2														
lb/h	CO2	22.70%	272,937	22.70%	272,937	22.81%	272,937	8.24%	222,532	8.24%	222,532	22.81%	272,937	22.81%	272,937
	H2O	4.81%	57,834	4.81%	57,834	4.83%	57,834	4.26%	115,141	4.26%	115,141	4.83%	57,834	4.83%	57,834
	O2	2.14%	25,699	2.14%	25,699	2.15%	25,699	14.73%	397,700	14.73%	397,700	2.15%	25,699	2.15%	25,699
	N2	67.88%	816,315	67.88%	816,315	68.21%	816,315	71.49%	1,930,124	71.49%	1,930,124	68.21%	816,315	68.21%	816,315
	H2S														
	COS														
	SO2	0.84%	10,046	0.84%	10,046	0.84%	10,046	0.02%	433	0.02%	433	0.84%	10,046	0.84%	10,046
	C6H6+														
	Argon	1.16%	13,904	1.16%	13,904	1.16%	13,904	1.22%	32,909	1.22%	32,909	1.16%	13,904	1.16%	13,904
	NH3														
	NO2	0.03%	391	0.03%	391	0.00%	39	0.03%	920	0.03%	920	0.00%	39	0.00%	39
Total Flow, lb/h		100.00%	1,202,516	100.00%	1,202,516	100.00%	1,196,773	100.00%	2,699,759	100.00%	2,699,759	100.00%	1,196,773	100.00%	1,196,773
			39,521		39,521		39,513		92,803		92,803		39,513		39,513
			30.43		30.43		30.29		29.09		29.09		30.29		30.29
Pressure, psia			14.00		13.60		13.40		16.10		15.40		13.50		15.10
Temperature, °F			1,502.20		805.70		390.70		1,121.00		891.00		265.80		278.30
Temperature, °C			816.78		429.83		199.28		605.00		477.22		129.89		136.83

Table 2 (Continued)

	Stream No.	29		30		31		32	
		Flue Gas to Stack		C Flue Gas to Evap		C Flue Gas to LP Econ		C Flue Gas to Scrub	
Stream		%wt	lb/hr	wt%	lb/hr	wt%	lb/hr	wt%	lb/hr
	Carbon								
	Hydrogen								
	Oxygen								
	Nitrogen								
	Sulfur								
Solids	Ash								
lb/h	Moisture								
	CaCO3								
	MgCO3								
	CaO								
	MgO								
	CaS								
	CaSO4								
	CH4								
	C2H4								
	C2H6								
	C3H8								
	CO								
Gases	H2								
lb/h	CO2	12.63%	467,682	8.24%	194,745	8.25%	194,745	8.25%	194,745
	H2O	8.44%	312,598	4.26%	100,764	4.27%	100,764	4.27%	100,764
	O2	10.09%	373,739	14.73%	348,040	14.74%	348,040	14.74%	348,040
	N2	67.67%	2,505,427	71.49%	1,689,113	71.51%	1,689,113	71.51%	1,689,113
	H2S								
	COS								
	SO2	0.00%	133	0.02%	379	0.02%	379	0.02%	379
	C6H6+								
	Argon	1.15%	42,704	1.22%	28,800	1.22%	28,800	1.22%	28,800
	NH3								
	NO2	0.00%	116	0.03%	805	0.00%	77	0.00%	77
Total Flow, lb/h		100.00%	3,702,398	100.00%	2,362,645	100.00%	2,361,916	100.00%	2,361,916
			129,100		81,215		81,199		81,199
			28.68		29.09		29.09		29.09
Pressure, psia			14.70		15.40		15.10		15.00
Temperature, °F			126.00		891.00		318.00		210.30
Temperature, °C			52.22		477.22		158.89		99.06

2.2.3 Mass and Energy Balance

Table 3 shows the overall mass and energy balance for the HIPPS commercial plant for plant operation at full load and 60°F ambient.

Table 3 Overall Mass and Energy Balance (Full Load- 60°F Ambient)

Description	Mass Flow lb/h	Energy Flow, million Btu/h[1]			
		HHV	Latent & Sensible	Power	Total
Input					
Coal	180,807	2,251.1	—		2,251.1
Sorbent	16,265	—	0		0.0
FGD lime reagent	10,080	—	0		0.0
Raw water intake	1,107,874				
Air to GT Compressor	3,307,300				
Total Input	4,622,326	2,251.1	0.0	0.0	2,251.1
Output					
Net power output				1,059.4	1,059.4
Flue gas to stack	3,702,398		372.9		372.9
Ash/slag to disposal	26,957		0.9		0.9
FGD solid waste to disposal	30,000		1.2		1.2
Cooling tower evaporation & drift	647,500		789.0		789.0
Treated wastewater discharge	211,000		1.0		1.0
Water loss in ash wetting	4,471		0.0		0.0
Miscellaneous heat losses			26.7		26.7
Total Output	4,622,326	0	1,191.7	1,059.4	2,251.1

[1] Based on 60°F liquid water and 3413 Btu/kWh

2.2.4 Complete Plant Description

Plant Layout

The site is estimated to be on approximately 37 acres of clear and level land. Figure 5 shows a preliminary layout of the overall plant; Figure 6 shows a conceptual plan view of the major equipment in the plant. The location of the major equipment was based on minimizing the distances of those lines that have special process considerations like the hot char transfer lines, or lines that were relatively large and costly, like the hot gas lines running to and from the HITAF furnace. For ease of construction and to minimize the distances between equipment, a single main equipment train is used that includes the solids handling, pyrolyzers, HITAF furnace with char combustors and air heater, dirty economizer, FGD system, and stack. Many of the large hot gas lines will be located in trenches to allow better maintenance and access to major equipment during operation.

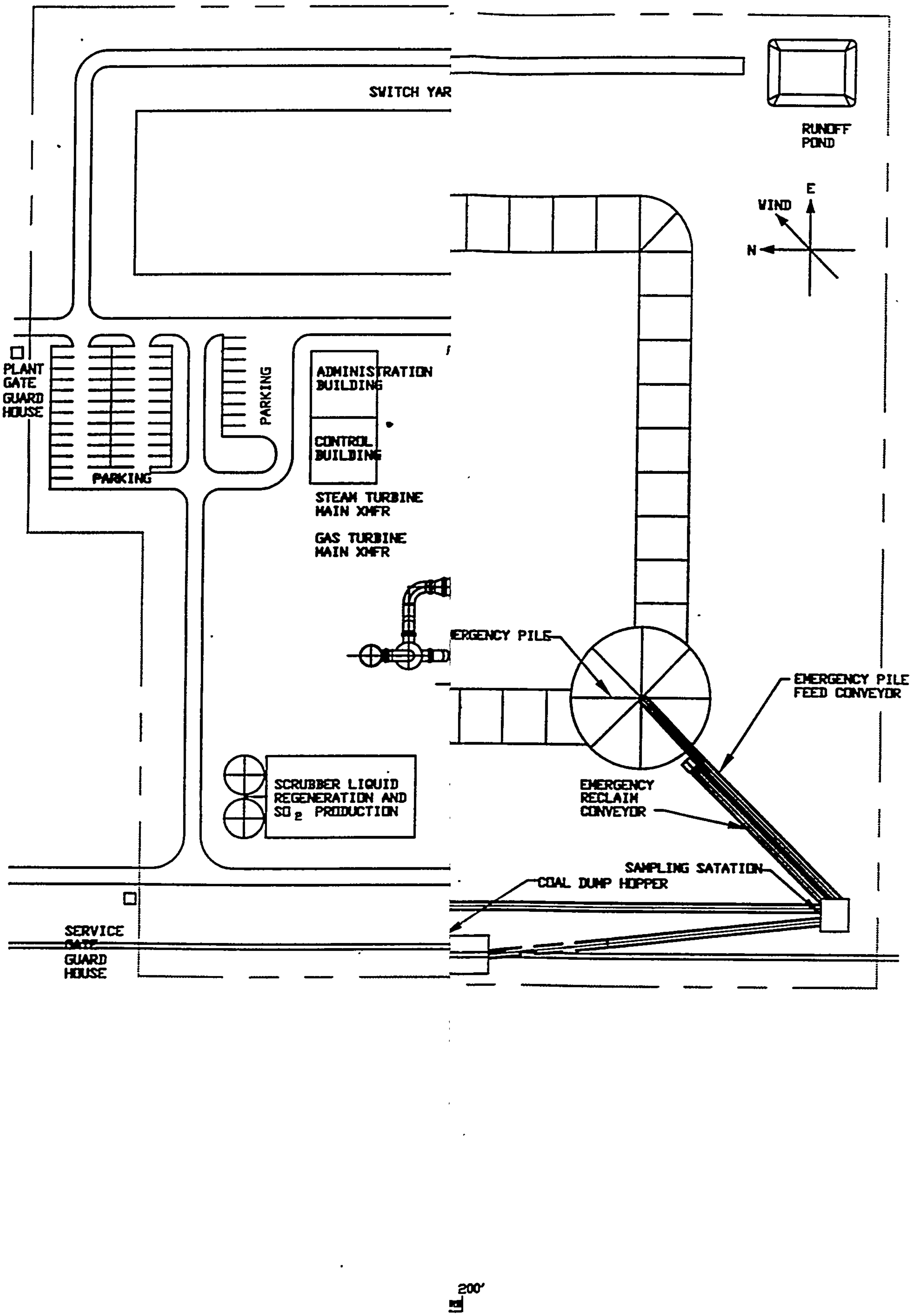
Plant Electrical Distribution

The plant-wide electrical distribution system controls and delivers the generated power to a 230 kV distribution grid and provides auxiliary power for the in-plant loads. Figure 7 shows an electrical single line diagram for the plant. A more detailed description of the electrical distribution system is given under section 2.3 Subsystem Design.

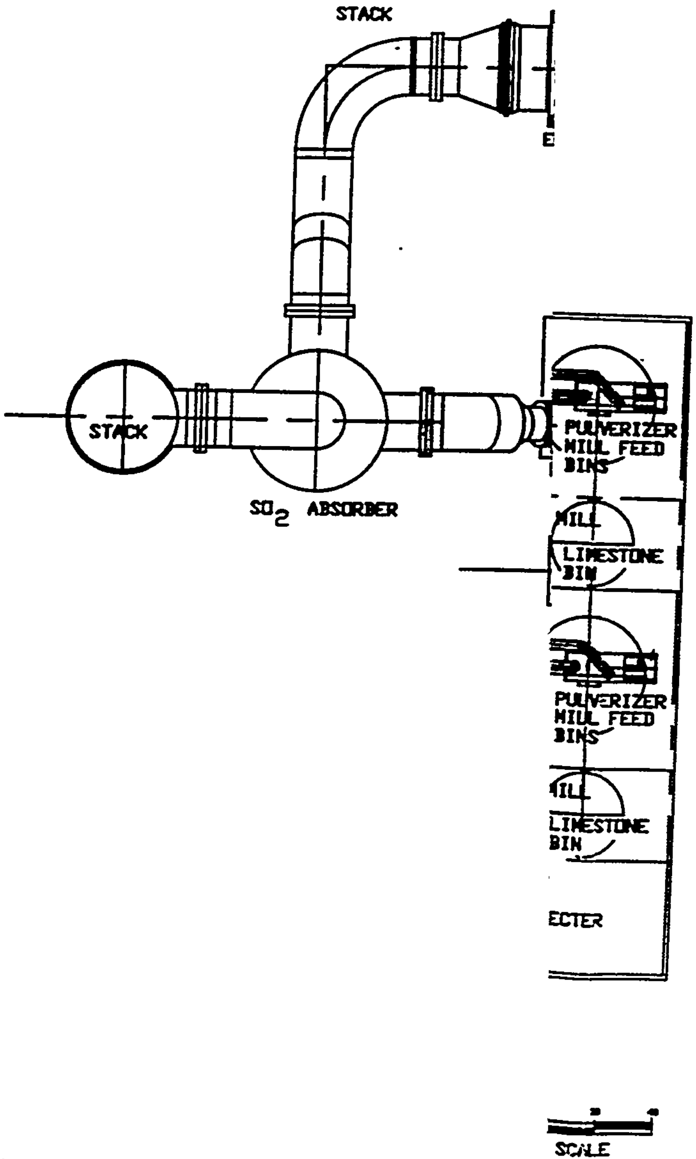
Offsites

The offsites consist of balance-of-plant components and systems that support the operation of the power island. The offsites include the facilities listed below; a detailed description of these facilities is given in section 2.3 Subsystem Design.

- Coal receiving and handling
- Sorbent receiving and handling
- Ash and slag handling and disposal
- Cooling water system
- Raw water supply and treatment
- Service and instrument air system
- Interconnecting piping
- Instrumentation and controls system
- Fire protection
- General services and mobile equipment
- Miscellaneous buildings



21840A29.DWG



21840a28.dwg

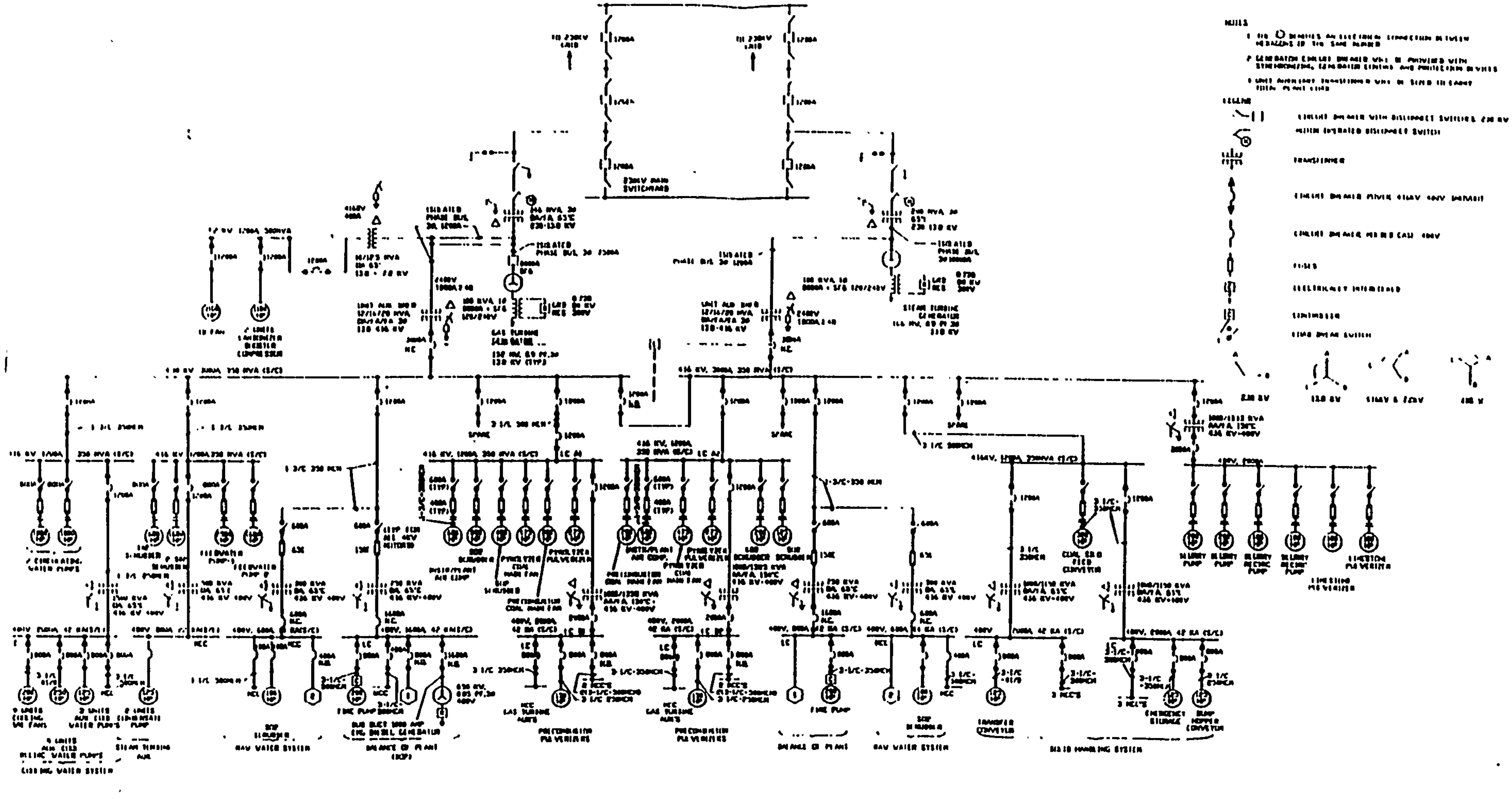


Figure 7 Electrical Single Line Diagram

2.3 SUBSYSTEM DESIGN

2.3.1 Solids Feeding and Removal (*Plant Section 1*)

This subsystem is part of the boiler island. It contains equipment in three process sections that: (1) Prepare and feed coal into the pyrolyzers and the slagging combustors; (2) Prepare and feed the sorbent into the pyrolyzers; and (3) Remove and cool the molten slag produced by the slagging combustors.

Coal Preparation and Feeding *(Plant Subsection 1.1)*. This subsection withdraws coal from the mill feed bins in the coal receiving and handling plant section *(Subsection 10.1)*, simultaneously dries and pulverizes the coal to specifications, and feeds the prepared fuel into the pyrolyzers and slagging combustors. The subsection comprises four trains, two serving the two pyrolyzers and the other two serving the two slagging combustors. Figures 8 and 9 are process flow diagrams of this subsection. Major equipment used in this plant is listed in Table 4.

The pyrolyzer coal preparation and feed subsection pulverizes and dries the coal in a gas stream, separates the coal from the gases, stores the pulverized coal, and injects it as a water paste into the pressurized pyrolyzer reactors. In the slagging combustor coal preparation and feed subsection, the pulverized coal is blown directly from the pulverizers into the combustor, avoiding the solids/gas separation and pulverized coal storage steps.

As shown in Figure 8, the pyrolyzer coal preparation subsection receives the coal from a feed bin in the coal receiving and handling plant. Two roller mills grind the coal to 2-in. x 0; the ground coal is then swept from the grinding chamber by a stream of hot gases delivered from a natural gas-fired heater. The gas-borne coal particles then pass through an adjustable motor-driven spinner separator. Coal particles that are smaller than the product size specification are carried by the gas stream leaving the spinner separator; oversize particles drop back into the grinding chamber for additional grinding. The exiting coal particles are separated from the gases in a cyclone and then fed to a surge bin, while the separated gases are split into two streams. One small stream is passed through a baghouse before venting to the atmosphere; a second larger gas stream is recycled to the roller mill along with hot combustion gases. Pulverized coal and limestone are withdrawn from their surge bins, weighed accurately, and mixed to form a water paste containing 75 percent solids. The paste is discharged to a holding tank with about 1.5 hours of storage capacity. An agitator and a circulating loop keep the solids in suspension. The paste is then fed by a high-pressure pump to the pyrolyzer.

As shown in Figure 9, the combustor coal preparation and feed subsection receives the coal from a feed bin in the coal receiving and handling plant and delivers it to a hammer mill-type crusher for processing to a top size of 1/2 in. The crushed coal is fed to the pulverizer. A roller mill with an integral spinner pulverizes and dries the coal; its design and operation are similar to that of the pyrolyzer coal preparation system. The mill uses preheated air to sweep the grinding chamber and pneumatically transports the ground coal to the slagging combustors.

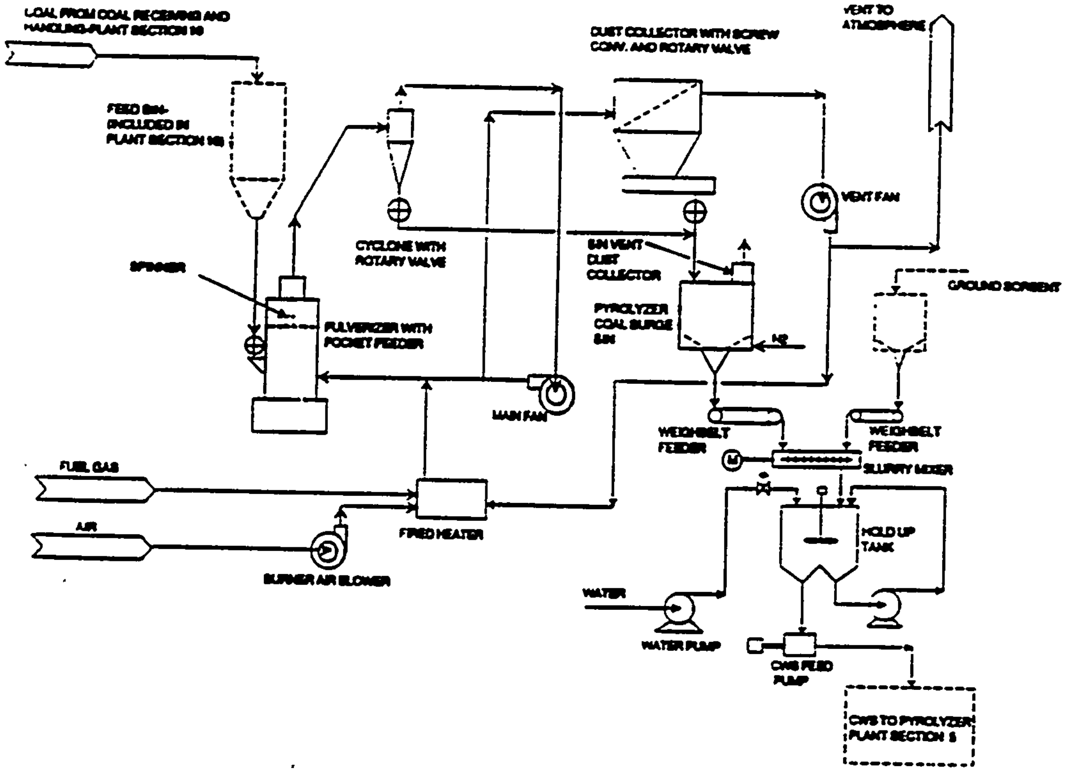


Figure 8 Flow Diagram: Coal Preparation and Feeding-Pyrolyzer Section

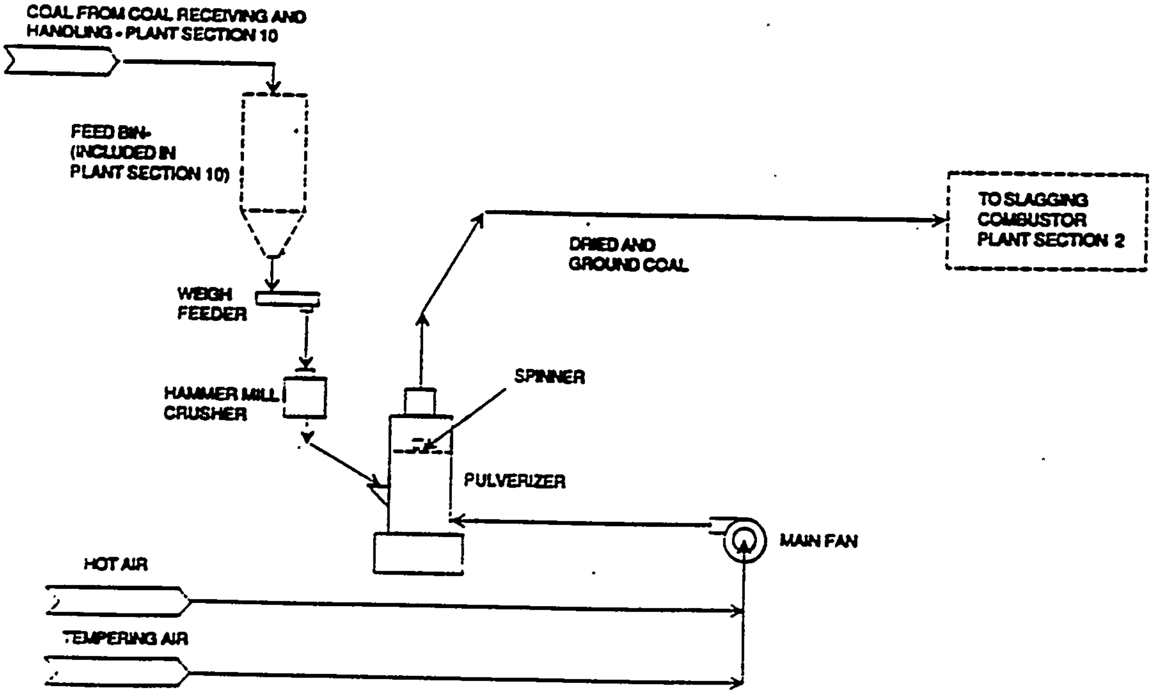


Figure 9 Flow Diagram: Coal Preparation and Feeding-Slagging Combustor Section

Table 4 Major Equipment List: Solids Feeding and Removal (Plant Section 1)

Equipment Name/ Quantity Required	Description	Unit	Value	Total HP
Subsection 1.1: Coal Preparation and Feeding				
Pyrolyzer Coal Surge Bin/2	Active Capacity	ton	90	
Paste Storage Tank/2	Capacity Size	gal	20,000 15' ID x 30'H	
Pyrolyzer Fired Heater Package (including Fan)/2	Capacity Motor	10 Btu/h HP	12 30	60
Pyrolyzer Paste Pump (High-Pressure Diaphragm Type)/ 2 operating/1 spare	Capacity Discharge Pressure Δ Pressure Motor	gpm psia psi HP	225 315 200 200	400
Paste Recirculation Pump (Progressive Cavity)/ 2 operating, 1 spare	Capacity Discharge Pressure Δ Pressure Motor	gpm psia psi HP	600 20 75 100	200
Pyrolyzer Coal Main Fan/2	Motor	HP	475	950
Pyrolyzer Vent Fan/2	Motor	HP	40	80
Burner Air Blower/2	Motor	HP	5	10
Precombustor Coal Main Fan/2	Motor	HP	200	400
Pyrolyzer Coal Weigh Feeder/2	Capacity Motor	t/h HP	50 15	30
Pyrolyzer Pulverizer With Spinner (20 HP) and Pocket Feeder (7.5 HP)/2	Motor	HP	275	550
Pyrolyzer Circuit Cyclone With Rotary Valve/2	Motor	HP	1.5	3
Pyrolyzer Circuit Baghouse With Screw Conveyor (3 HP) and Rotary Valve (1 HP)/2	Motor	HP	10	20
Precombustor Pulverizer With Spinner (5 HP)/2	Motor	HP	150	300
Coal Crusher With Screw Conveyor and Rotary Valve/2	Motor	HP	10	20

Table 4 (Cont) Major Equipment List: Solids Feeding and Removal (Plant Section 1)

Equipment Name/ Quantity Required	Description	Unit	Value	Total HP
Paste Mixer/2	Motor	HP	200	400
Subsection 1.2: Sorbent Preparation and Feedings				
Pulverized Limestone Surge Bin/2	Active Capacity	ton ft³ hours	20 665 4	
Limestone Main Fan/2	Motor	HP	75	150
Limestone Vent Fan/2	Motor	HP	10	20
Limestone Circuit Fluidizing Blower/2	Motor	HP	5	10
Pyrolyzer Limestone Weigh Feeder/2	Capacity Motor	t/h HP	5 5	 20
Limestone Pulverizer With Spinner (3 HP) and Pocket Feeder (3 HP)/2	Motor	HP	100	200
Limestone Circuit Cyclone With Rotary Valve/2	Motor	HP	0.75	1.5
Limestone Circuit Baghouse With Screw Conveyor (3 HP) and Rotary Valve (0.75 HP)/2 Spinner (20 HP) and Pocket Feeder (7.5 HP)/2	Motor	HP	3.75	7.5

Sorbent Preparation and Feeding ***(Plant Subsection 1.2)***. This subsystem receives limestone crushed to a 1/2-in. top size from the limestone mill feed bins in Plant Subsection 10.2. The limestone is pulverized, dried, stored, and then added to the coal/water paste before it is injected into the pressurized pyrolyzer reactors. Figure 10 is a flow diagram of this subsection. Major equipment specifications are listed in Table 4.

Roller mills are proposed to pulverize the limestone. The system configuration, similar to that for the pyrolyzer coal, has a surge storage bin for the pulverized product. Unlike the coal preparation system for the pyrolyzer, no hot gas/combustion gases are needed for drying; heat generated in the mill and fan is adequate for drying it from 2- to 1-percent moisture.

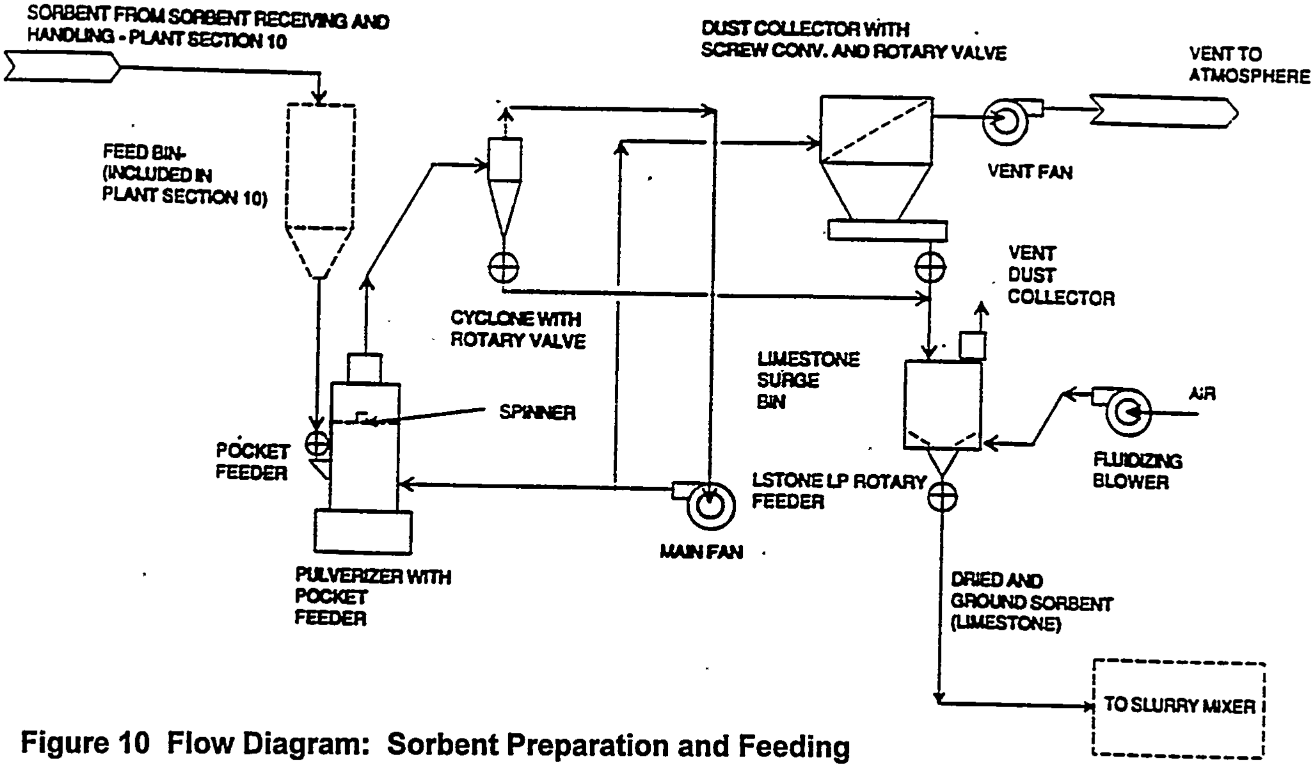


Figure 10 Flow Diagram: Sorbent Preparation and Feeding

Ash and Slag Removal ***(Plant Subsection 1.3)***. This subsection is designed to receive slag from the slagging combustors, cool it, crush the oversized lumps, and deliver it (partially dewatered) to the conventional solids material handling subsection in Plant Subsection 10.3 (ash handling and disposal). Molten slag from each of the two slagging combustors flows through lined transition chutes into pools of water for quenching. Each unit incorporates a partially submerged chain conveyor to dredge solidified slag from the bottom of the pool and bring it out and over an inclined "beach" area of the unit. The partially dewatered solids are deposited over an inclined grizzly. Lump-sized slag sliding over the bars of the grizzly are fed into a slag crusher. Fine-sized slag passes through the opening of the grizzly and lands in a fully enclosed slag-collecting conveyor, which also receives slag from the crushers. The conveyor delivers the dewatered slag to a storage bin in Plant Section 10 (solid materials handling). After sluice water moves the rejects from the pulverizers, they are collected in the submerged chain conveyors.

Design Specifications and Features

Two equal-capacity equipment trains prepare and feed coal to the two slagging combustors. Each train has adequate capacity for meeting the full demand of both combustors. Normally, both trains are operated—each at 50 percent of full capacity. With a partial or complete outage of one train, the output from the other is increased to meet the full demand of both combustors. Since this coal is only used for the precombustors, coal finess is not very critical. There should not be any problem in using commercial pulverizers over this range of operation.

Design and operation of the "storage system" in the pyrolyzer coal feed section calls for a greater degree of caution during both design and operation to minimize risks of coal fires and explosions. Although storage systems are not as common as those of the direct-firing type, several industrial plants use the storage system to meet their special needs. In addition to instruments for constantly monitoring oxygen content, the system has automatic fire detection and extinguishing systems. Two equal-capacity equipment trains prepare and feed limestone sorbent to the two pyrolyzers. As the design capacity of each train at 5 t/h is more than the maximum demand of each pyrolyzer (4.4 t/h), partial shortfall from one train can be made up by operating the second at full capacity. The submerged chain conveyor unit for solids removal is designed for a peak load of about 6 t/h per train.

Table 5 lists the key parameters and engineering data used in designing the solids preparation, feeding, and removal subsystem.

Table 5 Key Design Parameters and Data: Solids Preparation, Feeding, and Removal (Plant Section 1)

Coal Preparation	
Total Coal Consumption	
Pyrolyzer	77.5 t/h
Combustor	7.9 t/h
Number of Operating/Spare Trains	2/0
Feed Coal Size	2 in. x 0
Design Feed Rate/Train	
Pyrolyzer	46.3 t/h
Combustor	9.5 t/h
Hardgrove Grinding Index	57
Product Size	
Pyrolyzer	50% <100 microns
Combustor	50% <74 microns
Feed/product Moisture Content	6.0/1.0 wt%
Coal/Limestone/Water Paste Surge Storage Capacity	
Paste Solids Concentration	2 hours
Paste Pump Discharge Design Pressure	75 wt%
	315 psia
Sorbent Preparation	
Total Sorbent Consumption	8.0 t/h
Operating/Spare Trains	2/0
Limestone Feed Size	1/2 in. x 0
Product Size	50% <300 microns
Feed/Product Moisture Content	2.0/1.0 wt%
Slag and Ash Removal	
Slag Production Rate	13.5 t/h
Molten Slag/Cooled Slag Temperature	2400/180°F
Feed Slag Material Size	1/2 in. x 0

Operating Characteristics

The coal preparation and feeding plant subsection uses conventional procedures for start-up, shutdown, and emergency stops; they are generally similar to those used in commercial power plants. Instrumentation and sequence controls ensure safety for personnel and equipment. This subsection can be operated between 33 percent and full design load using variable-capacity feeders at the head end of each pulverizer train. Important requirements for start-up are:

- System inerting so that oxygen in the system is below the permitted level before fresh coal is introduced.
- Availability of combustion gases at the required temperature.
- Availability of nitrogen for blanketing.

These prime requirements must be met before coal is introduced. Thus, other than utility systems, the operating status of other systems in the power generation plant do not affect start-up and operation of this subsection. The pulverized coal surge bin and paste holding tank provide adequate on-line storage time, but a prolonged lack of demand for the product from the pyrolyzer will prompt subsection shutdown.

The sorbent receiving and handling subsection is similar in operation/turndown to that for coal preparation and handling except that operations are simpler because the sorbent subsection is smaller. It uses conventional procedures for start-up, shutdown, and emergency stops—generally similar to those for commercial power plants.

The ash and slag removal subsection is designed with adequate margins above calculated production rates for ash materials when the generating plant operates at the maximum burn rate. The subsection will operate satisfactorily at any rate below this maximum. Start-up, shut-down, and emergency plant stops are relatively simple, with no special requirements because the equipment used is conventional and commercially proven.

Maturity of Technology

The solids feeding and removal subsystem uses the largely conventional and commercially proven equipment common to coal-based power plants for similar duties. Conventional equipment, coupled with a careful selection of plant design parameters, should minimize operating uncertainties once an adequate level of scheduled and routine maintenance is ensured. A coal/limestone/water paste has been common practice in pressurized fluidized bed combustion systems, and the high pressure paste pumps used in the design have been used over the last 20 years for pumping pastes with solids concentration up to 75 wt percent. Industry experience indicates that the presence of limestone in the paste may reduce the paste viscosity and hence improve its pumping characteristics. Pilot-scale testing may still be needed, however, to confirm paste feed system performance and operation. Pulverized coal and limestone fed to the pyrolyzers will be coarser than what is normally used in PC-fired boilers. Phase 2 testing will determine what the size distribution needs to be, but the current estimate is about 50% less than 100 microns. Experience in large-scale pulverizing of coal at such coarse sizes is limited in industry. The capabilities of the pulverizer integral classifier at the required coarse product size must be confirmed in pilot-scale testing. The coal size distribution to the precombustors is the same as is generally used in PC boilers. The precombustor coal is pulverized in separate mills so there are no technology issues in that coal preparation.

Possible alternatives to the bin pulverizer system and paste feed system will be investigated in the Phase 2 review of the Commercial Plant design. High compression roller mills may be better suited for the HIPPS than pulverizers. These devices will not require a gas phase for classification of the particles which will significantly simplify the coal preparation system. They also may be better suited to achieve the required size distribution. The use of dry feed instead of paste feed will also be investigated. Paste feeding puts more constraints on particle size than dry feeding because the particle size effects for both the process and the feed system need to be considered. Dry feeding will significantly reduce particle size distribution restraints for the feed system. Lock-hopper systems are commercial, and a recently developed solids pump may offer a simplified, more reliable dry feed system.

2.3.2 Steam Generator Island (*Plant Section 2*)

2.3.2.1 High Temperature Advanced Furnace *(Subsection 2.1)*

The HITAF is a combined boiler/air heater that is the central feature of the HIPPS plant. This subsystem is designed and constructed very much like a conventional boiler. A sectional side view of the HITAF is shown in Figure 11.

Although most of the combustion is done in the char combustors, a furnace with overfire air is used to complete combustion and lower the gas temperature to a reasonable level for the subsequent tube banks. The furnace is constructed of both evaporator surface and superheater surface. The rear wall and screen tubes are evaporator surface. Of the four furnace walls, the rear wall is subject to the highest and most uneven heat transfer. The very good inside heat transfer coefficient of evaporation is therefore used to advantage in the rear wall. The thermodynamic efficiency of the cycle is enhanced if some superheating is done in the furnace walls. The first stage of superheating is done in the side walls and front wall of the furnace. These tube walls are coated with Blu-Ram HS plastic refractory on the inside of the furnace, and three passes in series are provided with mixing between the passes. The steam outlet temperature from the furnace enclosure is 800°F at full load.

The pendant superheater surface is located in the upper furnace. This tube bank provides the final superheating for the steam cycle by heating the steam to 1075°F. After passing through the final superheater and the rear wall screen tubes, the flue gas enters the air heater tube bank. In this tube bank, the gas turbine inlet air from the recuperator is heated from 1053°F to 1400°F. Because the air outlet temperature is relatively high as compared with boiler steam temperatures, the air heater tube bank is located immediately downstream of the furnace. This surface is not located in the furnace, however, because the high and uneven heat fluxes could more easily overheat these tubes. Reheater and economizer tube banks are located downstream of the air heater tube bank.

Design Specifications and Features

The design of the HITAF is, for the most part, based on proprietary Foster Wheeler models and standards for pulverized coal boilers. The main areas of difference are the air heater tube bank and the superheater enclosure wall of the radiant furnace, but these components were incorporated into existing models.

A summary of the HITAF tube specifications is included in Table 6. The steam circuit material selection is typical of a utility steam boiler and is governed by the high-temperature strength and the steam side and fireside metal wastage considerations. The use of materials and allowable stresses are covered by proven FW and ASME design standards. They incorporate the consideration of tensile, yield, and creep strength. The ASME Code does not address corrosion. Therefore, FW has performed its own research on steam side and fireside wastage. These tests have included laboratory and field exposures using air-cooled, retractable corrosion probes of multiple alloys for multiple years of exposure. We have studied the pyrosulfated and alkali-iron-trisulfate corrosion mechanism and developed the materials selection guidelines for where to use carbon steel, Cr-Mo, and stainless steel alloys.

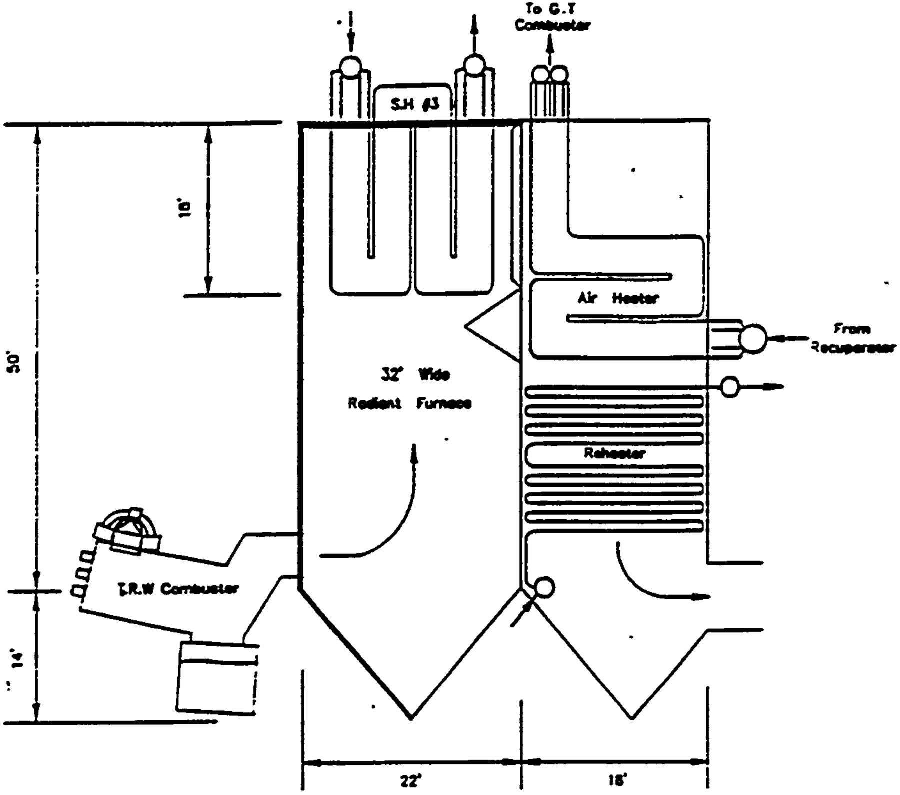


Figure 11 Sectional Side View of the HITAF

Table 6 HITAF Tube Specifications

Item	Dimensions	Material
Furnace Enclosure		
Front and Side Walls	1-1/4 in. O.D. x 0.12 in. wall	SA-213-T2
Rear Wall	3 in. O.D. x 0.314 in. wall	SA-210-C
Pendant Superheater		
Pass 1 and 2	2 in. O.D. x 0.300 wall	SA-213-T22
Pass 3	2 in. O.D. x 0.300 wall	SA-213-TP304H
Air Heater	3 in. O.D. x 0.180 wall	SA-213-TP316H
	3 in. O.D. x 0.180 wall	SA-213-TP304H
Reheater	3 in. O.D. x 0.165 in. wall	SA-213-TP304H
	3 in. O.D. x 0.165 in. wall	SA-213-T22
	3 in. O.D. x 0.165 in. wall	SA-213-T11
	3 in. O.D. x 0.165 in. wall	SA-213-T2
	3 in. O.D. x 0.165 in. wall	SA-178-A
Heat Recovery Area Enclosure	1-1/4 in. O.D. x 120 in. wall	SA-213-T2

Metal temperatures in the air heater are considerably higher than in the boiler tube banks. With 1400°F air outlet, the maximum tube metal temperature will be around 1500°F. At this point, a detailed analysis of temperature upset conditions has not been done, so the maximum tube metal temperature may be a little above or below this level. For temperatures up to 1500°F, austenite stainless steels such as 304H, 347H, and 316H alloys can be used. One of these alloys will be used for the majority of the air heater. Depending on the result of the upset analysis, it may be necessary to use another alloy for the last loop or two of the tube bank. Tubes of 800HT, RA330, Alloy X, 253MA, 556, 230, and 617 have established allowable stresses at temperatures up to 1650°F.

Operating Characteristics

The HITAF is operated in a manner similar to a conventional coal-fired boiler although there are some differences that result from the inclusion of the air heating function. These differences are discussed in more detail in Section 2.5 where the operating procedure for the complete plant is described.

Maturity of Technology

Basic construction techniques and operating procedures used in commercial boilers are used for the HITAF. The all up-flow, multi-pass furnace circuit design is similar to what has been used for domestic once-through boilers. Applying refractory to tubewalls has become very prevalent in refuse-fired boilers and fluidized bed boilers where it is used to protect tubes from erosion and corrosion. Studs are welded to the tubes, and these studs hold the refractory in place.

Refractory coated superheater tubes have not been used as furnace enclosures in the past, but the use of the TRW slagging combustor upstream of the furnace makes it possible to use enclosure walls of this design. The use of these combustors reduces the amount of ash entering the furnace and also results in lower heat fluxes in the furnace. The ash removal reduces the potential of slag accumulations on the furnace walls. The lower heat fluxes also reduce the severity of the design conditions for the furnace wall as compared to a conventional PC furnace. Because of these considerations, it is possible to pick up some superheat duty in the furnace and thereby shift some evaporator duty to lower gas temperature zones.

The tube banks are of conventional design, and gas temperatures through the HITAF are representative of pulverized coal boilers. Final superheater tube banks are not normally located in the upper furnace, but this tube bank has been designed with three intermediate headers to mix the steam so the cooling of the tubes will be uniform. Conventional air or steam soot-blowers are used to clean ash from the tubes, and since 70 to 90 percent of the ash is removed in the char combustors, maintaining surface cleanliness should not be a problem. This area will be investigated in the integrated system test, however, by analyzing ash deposits that form on simulated HITAF tubes located at various points in the flue gas stream.

Choosing the proper tube alloys is an important aspect of the HITAF design. Existing data can be used for the steam cooled tubes and to narrow down the selection of alloys for the air heater tubes and headers. Because there is less available information on the corrosion of alloys at the air heater temperatures, laboratory tests will be run to evaluate the corrosion of several alloys with the ash deposits and atmosphere expected in the air heater. These tests are described in Section 4.4. The average air temperature leaving the HITAF has been established at 1400°F in the commercial plant design. We believe that this is a reasonable upper limit considering several factors. Temperature unbalances and upsets are always present within tube banks, and boilers are designed with tube metal temperatures that consider these conditions. Also, another factor that limits the indirect heating of the air is the availability of reliable safety valves to protect the gas turbine. A discussion of the gas turbine safety valve requirements is included in Section 2.5. At present, we do not know of any gas turbine manufacturer that will accept temperatures of more than 1400°F at a safety valve.

Alternative Designs

For the most part, the HITAF is designed with proven conventional boiler technology. As discussed, the two areas where we have extended this technology are the refractory coated superheater walls and the location of the final superheater in the upper furnace. Similar designs have been used, and because of the operating characteristics of the TRW combustor, we feel that the risk in these areas is low. However, if there should be problems, the HITAF could be redesigned to move the affected superheater into more conventional areas. This could affect the efficiency, but probably only a fraction of a percent. If this should happen, there are other parts of the cycle that could be modified to make up the difference. For instance, the furnace is currently negative pressure. It could be positive pressure, which would reduce auxiliary power. Also the exit flue gas temperature could be lowered further with redesign of the economizer. It is not expected that the changes would have much affect on the capital cost.

2.3.2.2 Char Combustor (Subsection 2.2)

The primary function of the char combustor is to generate a high temperature gas stream to provide heat for both the metallic air heater and steam circuits within the HITAF. Within the char combustor, low-volatile char from the pyrolyzer is burned with gas turbine exhaust air under substoichiometric conditions to minimize NO_x emissions. Additional air is added within the HITAF to complete combustion of gaseous species (primarily CO). The char combustor also removes the majority of ash remaining within the char in the form of vitrified slag, in order to significantly reduce the ash loading within the gas and allow for a more compact furnace design.

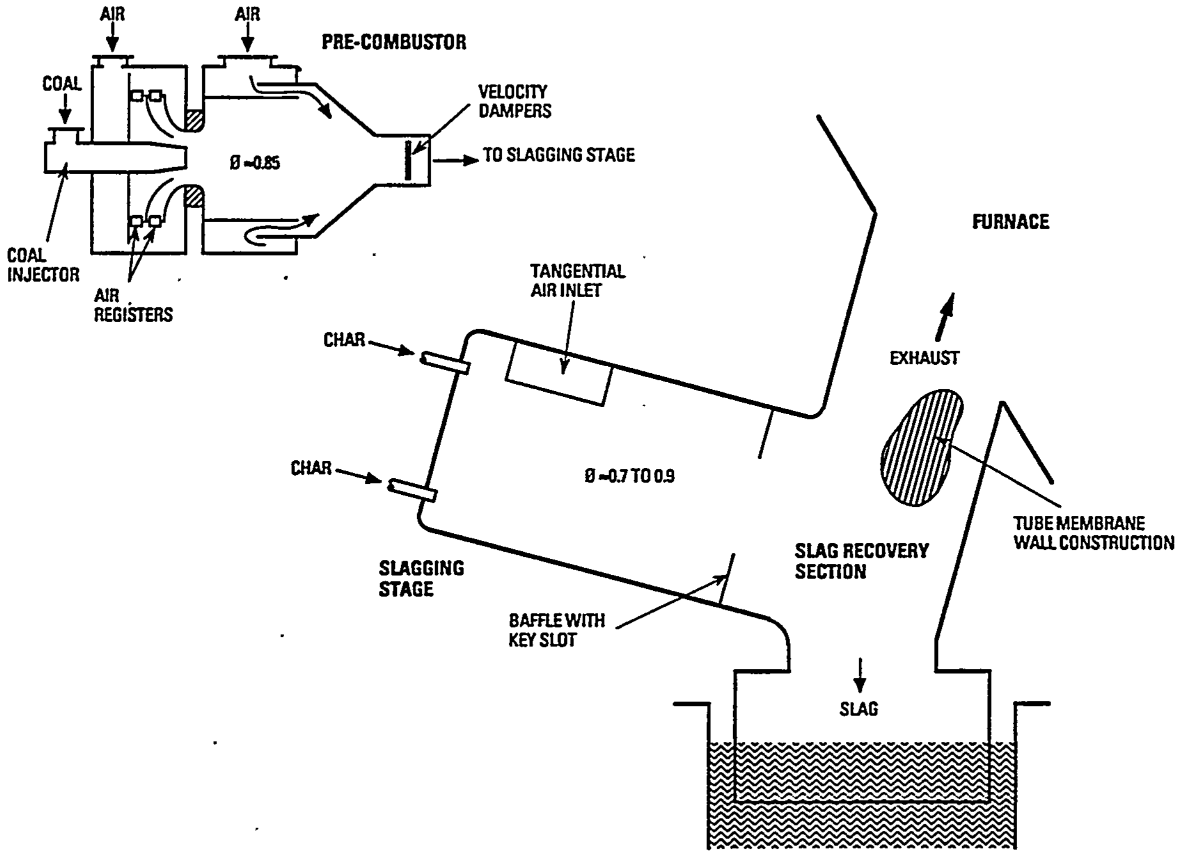


Figure 12 Char Combustor Functional Schematic

General Description

A simplified schematic of the char combustor is shown in Figure 12. The char combustor assembly includes a precombustor, a char-fired slagging stage, and a slag recovery section. The overall char combustor design is similar to that successfully tested as part of the Healy Clean Coal Project [1]. The combustor general arrangement is shown in Figure 13.

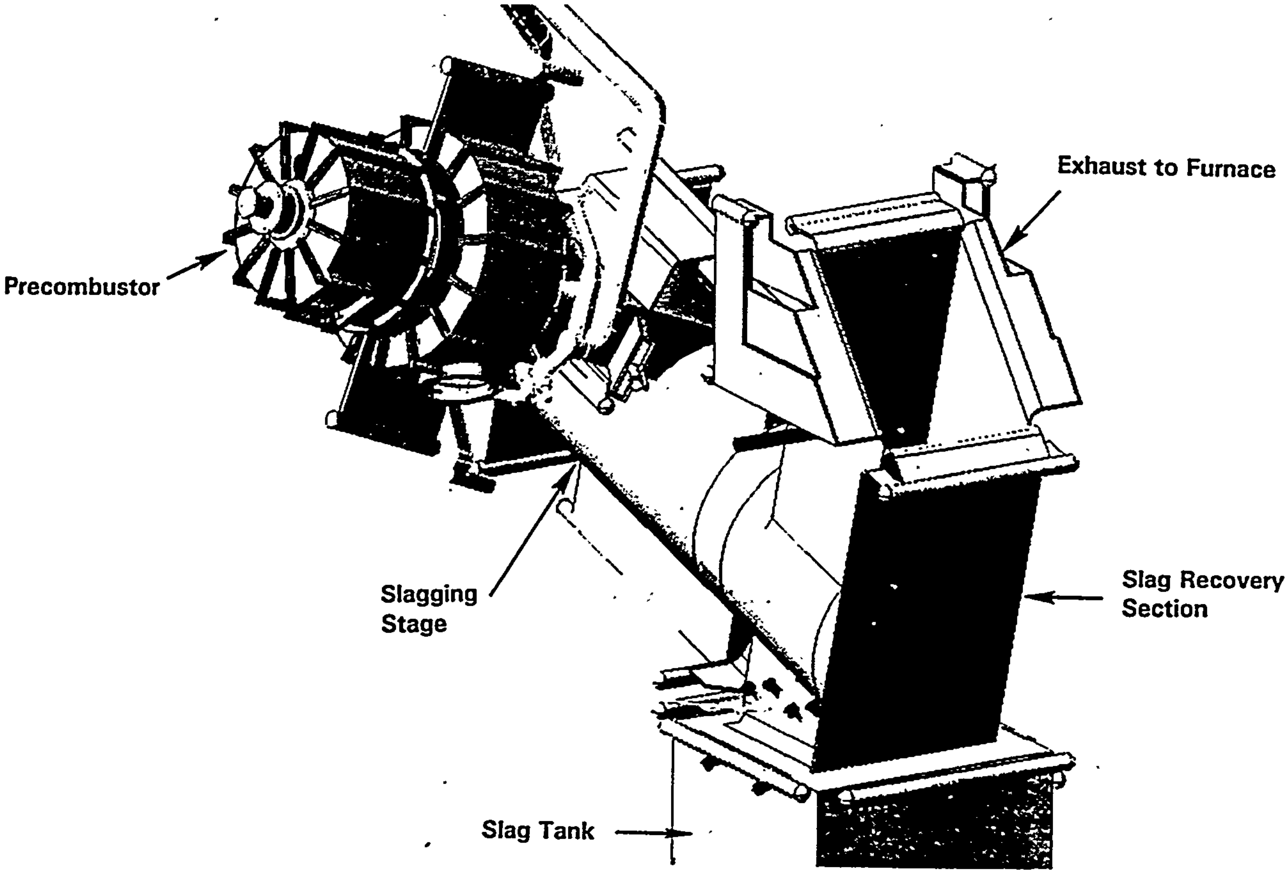


Figure 13 Char Combustor General Arrangement

Precombustor The precombustor, which can be fired with either coal or char, is used to boost the combustion air temperature to 1800-2200°F before entering the slagging stage. When char is used in the precombustor, a small amount of fuel gas from the pyrolyzer may be added for flame stabilization.

The precombustor conists of four major elements:

- Primary coal / char burner and windbox.
- Combustion chamber with integral baffle, which are actively cooled, and secondary air windbox.
- Round to rectangular transition section which is also water-cooled and which connects the precombustor to the slagging stage.
- Swirl damper blades to control slagging stage inlet gas velocity.

An oil or natural gas pilot burner is provided at the center of the precombustor main burner to provide assistance during start-up, shut-down, or load changes, if required. The combustion chamber and transition section cooling circuits are hydraulically connected to the boiler drum. To reduce cooling loads, the combustion chamber inner surface and the transition section are covered with refractory.

Slagging Stage. The high temperature, oxygen-rich gases from the precombustor enter the slagging stage tangentially, as shown in Figure 13, generating a highly turbulent, confined vortex flow. Char from the pyrolyzer is injected through a multiport fuel injector in the headend region of the slagging stage, along with a small amount of fuel gas used as a transport gas. The high air preheat temperature provided by the precombustor promotes the existence of a hot slag surface in the slagging stage, which, combined with strong flow recirculation patterns, provide stable ignition and combustion of low volatile chars. The multiport fuel injector ensures good fuel distribution and hence good fuel/air mixing and combustion. The slagging stage is operated fuel rich at equivalence ratios varying from 0.7 to 0.95. Control of mixing and stoichiometric conditions within the slagging stage provides high combustion efficiencies while minimizing NO_x emissions.

The main stage of the char combustor is operated in a wet, or slagging, mode. Operating temperatures within the combustor are high enough such that the majority of residual ash from the char is fused in-flight. The resultant molten ash droplets are centrifuged to the walls of the combustor, forming a self-replenishing slag layer. This slag coating protects the hardware from both erosion and corrosion and reduces the heat transfer rate and cooling loads. The slag is transported along the walls of the combustor by shear and gravity forces.

The overall dimensions of the slagging stage are indicated in Figure 14. The slagging stage is comprised of a headend section, a tangential inlet section, and a mixing section down to and including a concentric baffle. The slagging stage walls and baffle are made of tube-membrane elements with studs for slag retention. The tube and membrane material is a low alloy steel (½ Cr, ½ Mo). The slag retention pins (approximately ¾" long) are made of stainless steel. The presence of slag reduces peak thermal loads on the combustor wall to approximately 10 W/cm^2. The slagging stage cooling circuit is also connected to the boiler drum circuit for better heat utilization. A circulating pump is provided in the combustor cooling loop to assure the required flow velocity.

Slag Recovery Section. The baffle separates the slagging stage from the slag recovery section. Slag flows to the slag recovery section via a key slot opening along the bottom. The slag recovery section is sized so as to preclude shearing of the slag up to the furnace opening. The majority of slag, 70 to 90%, is tapped (external to the furnace) by gravity out of the system. The slag is quenched in a water tank, forming a granular, vitrified product that is amenable for use as a construction material or for disposal in a landfill. The remaining small flyash particles, nominally 2 to 4 microns, which enter the furnace, are fused and therefore less erosive and less prone to fouling than conventional flyash.

The slag recovery section, is of construction similar to that of the slagging stage. The slagging stage circular geometry is carried through to the back wall of the slag recovery section. The slag tap region and exit duct are designed with a rectangular cross-section. A slag tap dipper skirt is used to interface with the slag quench tank and removal system.

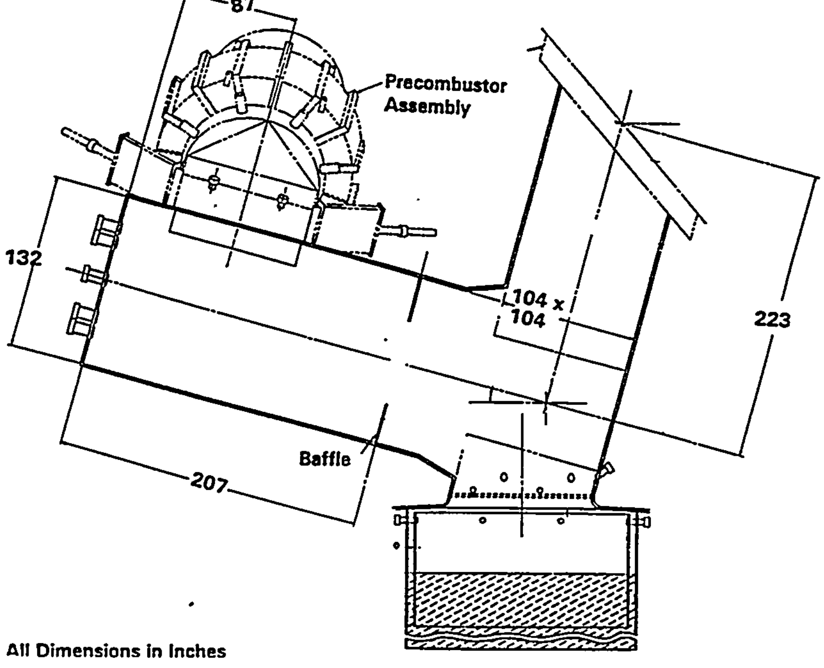


Figure 14 Char Combustor Physical Dimensions

Design Specifications and Features

The char combustor operation and performance characteristics are summarized in Table 7 Two combustors are required to handle the total firing rate of just over 800 MMBtu/hr. The baseline fuel is Pittsburgh # 8 pyrolyzed char, although the combustors are capable of operating with a wide variety of coal-derived fuels. Pittsburgh #8 parent coal is fired in the precombustors, while the pyrolyzed char is fired in the slagging stage of each combustor, along with a small amount of fuel gas used to transport the char to the combustors. High temperature exhaust gas from the gas turbine is used as combustion air. The combustors are operated fuel rich to minimize NO_x emissions. The combustors are cooled with saturated water from the boiler drum.

Table 7 Char Combustor Operation and Performance Characteristics

Parameter	Value
Fuel	Pittsburgh No. 8 Pyrolyzed Char
Median Particle Size	50 microns
Char Firing Rate	597 MMBtu/hr
Coal Firing Rate	205 MMBtu/hr
Total Firing Rate	802 MMBtu/hr
Combustion Air Temperature	1125°F
Combustion Air Oxygen Content	14.8 % O_2 (by weight)
Precombustor Exit Temperature	1860°F
Overall Combustor Stoichiometry	0.85
Cooling Water Pressure	2835 psia
Cooling Water Temperature	669°F
Number of Combustors	2
Slagging Stage Diameter	132 in.
Slagging Stage Length	207 in.
Carbon Burnout	> 99%
Relative Pressure Drop	< 3%
Slag Recovery	>70%
NOx Emissions	< 0.3 lb NO_2 / MMBtu
Relative Cooling Load	< 15% of fuel thermal input

The design of the proposed char combustor is based on TRW's extensive sub-scale slagging coal combustor experimental and operational data, as well as on full-scale precombustor design and development test data obtained during Phase I of the on-going Healy Clean Coal Project [1]. The combustor development status and maturity of the technology is discussed in more detail in Section 3.4.

The basic design approach for the char combustor was to utilize as much of the Healy combustor design as possible, while making modifications to combustor design and operation as needed in order to efficiently burn char with high slag recovery and minimum NO_x emissions. For the commercial plant design, in which a coal-fired precombustor was assumed, the slagging stage combustor diameter is 25 percent larger than the Healy combustor, at 132 inches. For the case of a char-fired precombustor, the coal stream can be eliminated and the overall combustor firing rate would be reduced from 401 to 305 MMBtu/hr (per combustor). This would allow Healy-sized combustors to be utilized in the commercial HIPPS plant, thus reducing combustor design costs.

The most critical operating parameters in determining the combustion system size and its performance are the firing rate, the stoichiometric ratio and the fuel split to the precombustor. For the HIPPS char combustor, which is fan-driven, the pressure drop is one of the key parameters used in determining the size of the combustor. For a given combustor size, the pressure drop increases with firing rate, stoichiometric ratio and swirl number. High swirl numbers are found to increase slag capture efficiency.

When sizing the combustor, an equally important parameter is the effective residence time, as char burn-out is greatly influenced by residence time and temperature / stoichiometry as well as particle size. Increasing stoichiometry improves char combustion efficiency but at the expense of NO_x emissions so that a trade-off between size and operating stoichiometric ratio will usually result. For a given combustor size and stoichiometric ratio, small particle sizes improve combustion performance, but this usually adversely affects slag recovery.

Combustor analytical models developed by TRW were used during Phase 1 to analyze these tradeoffs and to develop a conceptual design. These models had originally been developed for coal-fired combustor operation, and thus required some modification to support char combustor design. Some of the key char data required included char proximate and ultimate analyses, external and internal surface area, particle size distribution, char combustion characteristics, ash properties, and fuel nitrogen evolution during combustion. This data was acquired through fuel characterization tests performed at Brigham Young University (BYU) under contract to TRW and char combustion laboratory testing performed at TRW. The salient results from these experiments are discussed below. More detailed discussions of each experimental activity is provided in Appendices A and B, respectively. A description of the char combustor analytical model results is provided in Appendix C.

The volatile content of the proposed char is approximately 5%, with 25 - 30% ash content. This level of volatiles is comparable to anthracite coal. In fact, thermogravimetric analyses (TGA) performed by Foster Wheeler indicate a low temperature reactivity similar to Wyoming anthracite. The internal surface area of the char, however, is in the 100 - 300 m^2/g range (based on CO_2 surface area), which is comparable to chars previously characterized at BYU and Sandia National Laboratories under DOE contract, and is two orders of magnitude greater than typical anthracite coal. Also, during high temperature ($\geq$1800 K) reactivity tests conducted at BYU, char oxidation rates of the Foster Wheeler pyrolyzed char were comparable to rates obtained for the parent coal, following devolatilization. As a result, char oxidation kinetic rate data obtained for the parent coal [2, 3] was used as input for char combustor burnout calculations.

Results from 700,000 Btu/hr char combustion tests conducted at TRW during Phase 1 validated the use of this char oxidation kinetic rate data for char burnout calculations. Good agreement was found between experimental char combustion profiles and analytical model predictions in the post-devolatilization zone for both coal-fired and char-fired conditions (See Appendix B for more details). Carbon burnout under char-fired conditions was within 5% of that measured during coal-fired conditions. This difference is expected to decrease when scaling to larger combustion chambers which operate with lower relative heat losses.

In Figure 15 we show some preliminary results for variation in char combustion efficiency in the combustor slagging stage as a function of slagging stage stoichiometric ratio and char particle size, as predicted by TRW's CCEP computer program (described in detail in Section 4.3). For the stoichiometric ratio range of 0.8 to 0.9, carbon conversion efficiencies of 99 percent are projected at commercial size using a char particle size distribution provided by Foster Wheeler (approximately 60 percent through 200 mesh). Similar calculations conducted for a sub-scale 34 inch diameter combustor at a 35 MMBtu/hr firing rate, show comparable performance provided that a finer coal grind (70 percent passing through 325 mesh) is utilized.

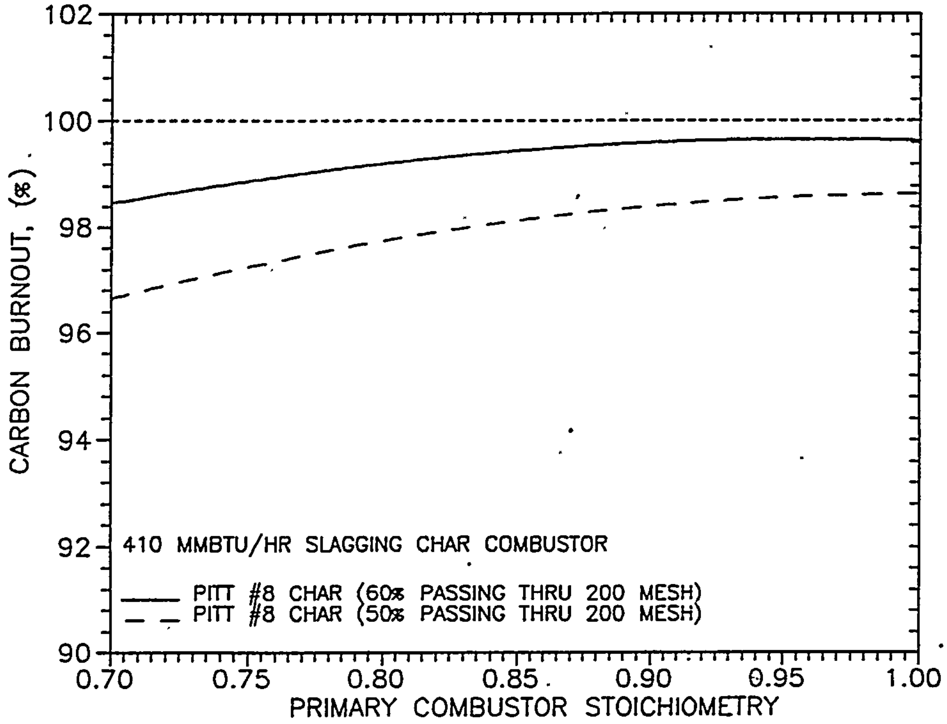


Figure 15 Char Combustor Carbon Burnout Calculations as a Function of Stoichiometry and Particle Size

Another important result from the BYU fuel characterization experiments (Appendix A), as well as the TRW char combustion tests (Appendix B), was that the nitrogen in the char was found to be released at approximately the same rate as the carbon, which was consistent with previous studies of char nitrogen evolution, as well as the assumption used in TRW's NO_x model. Details on this model are provided in Section 4.3. Some preliminary NO_x emission predictions for the char combustor are illustrated in Figure 16. Curves are presented for various levels of ammonia injection within the combustor. For the base case of no ammonia injection, it can be seen that minimum NO_x emissions occur at a stoichiometry of 0.84. However, if it is determined that the combustor must be operated at a higher stoichiometry to minimize carbon losses, ammonia injection can be used to decrease NO_x emissions in the stoichiometric range of 0.85 to 0.93, as shown in Figure 16.

TRW's COMBUST model was also used in support of char combustor conceptual design to determine combustor pressure drop, slag recovery, heat fluxes and cooling loads. A description of the COMBUST model is provided in Section 4.3. The combustor pressure drop, including the precombustor, is approximately 30 inches H_2O, which is comparable to the Healy combustor. For a 60 percent through 200 mesh char particle distribution, a slag recovery of approximately 75 percent is predicted. This value can be improved by moving the fuel injectors closer to the outer walls of the combustor. The predicted combustor cooling load is approximately 12 percent, or 47 MMBtu/hr per combustor.

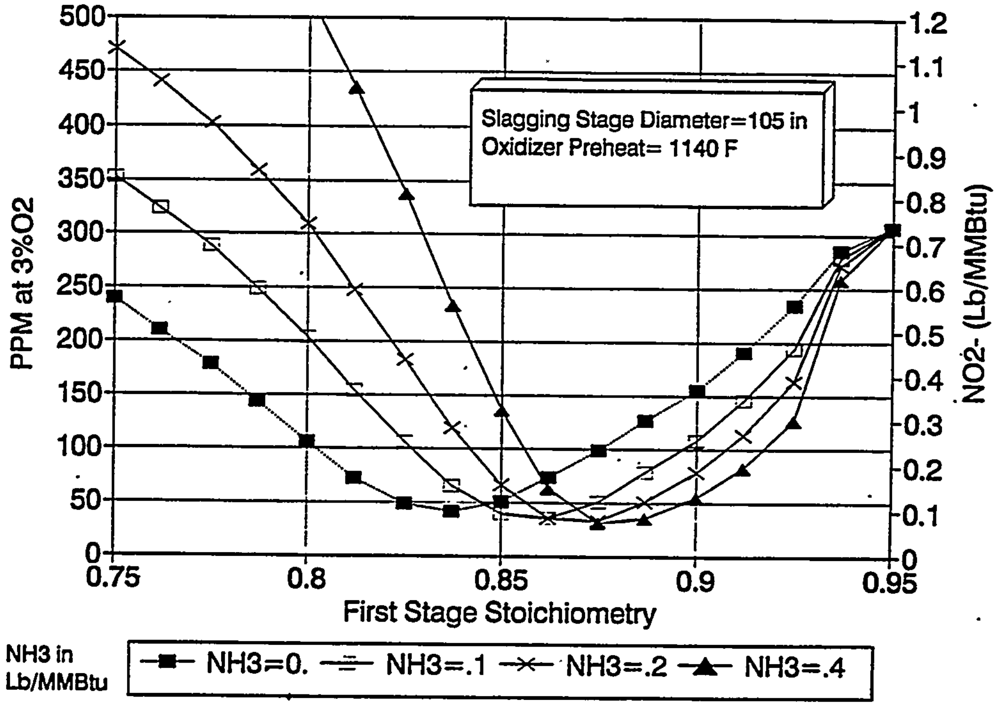


Figure 16 Char Combustor NO_x Emission Calculatons as a Function of Stoichiometry and Ammonia Addition

Discussion of Operation

The operation of the char combustor and its limitations, are best understood by referring to the typical operating envelope shown in Figure 17. The two key operating parameters are the firing rate (proportional to fuel flow rate) and the stoichiometry (proportional to the combustion air flow rate). To a first approximation, other operating parameters, such as precombustor firing rate and swirl number, may be considered to be held constant across the operating range.

At high firing rates, the combustor performance is typically limited by pressure drops either within the combustor (high rates and high stoichiometric ratios that correspond to high volumetric flows) or by the feed system which limits the firing rate. Typical operation is at stoichiometric ratios in the range 0.7 to 0.95 at any load. The air to fuel ratio is chiefly limited on the high side by the NO_x emissions from the combustion system. On the low side, the slagging stage stoichiometry can be limited either by combustion (excessive carbon losses) or in the case of high T_{250} fuels by the occurrence of slag freezing and growth in local areas such as the vicinity of the air inlet to the slagging stage where convective cooling of the slag is required to be small compared to radiation from the headend combustion zone.

Finally, turndown of the combustor is limited by excessive enthalpy losses which may result in exit temperatures too low to support a molten slag layer in the slag recovery section. Combustion limitations do not arise typically as dampers at the inlet of the slagging stage can be used to maintain air velocities at all loads and similarly, fuel injection velocities are maintained by holding the carrier flow rate constant with load.

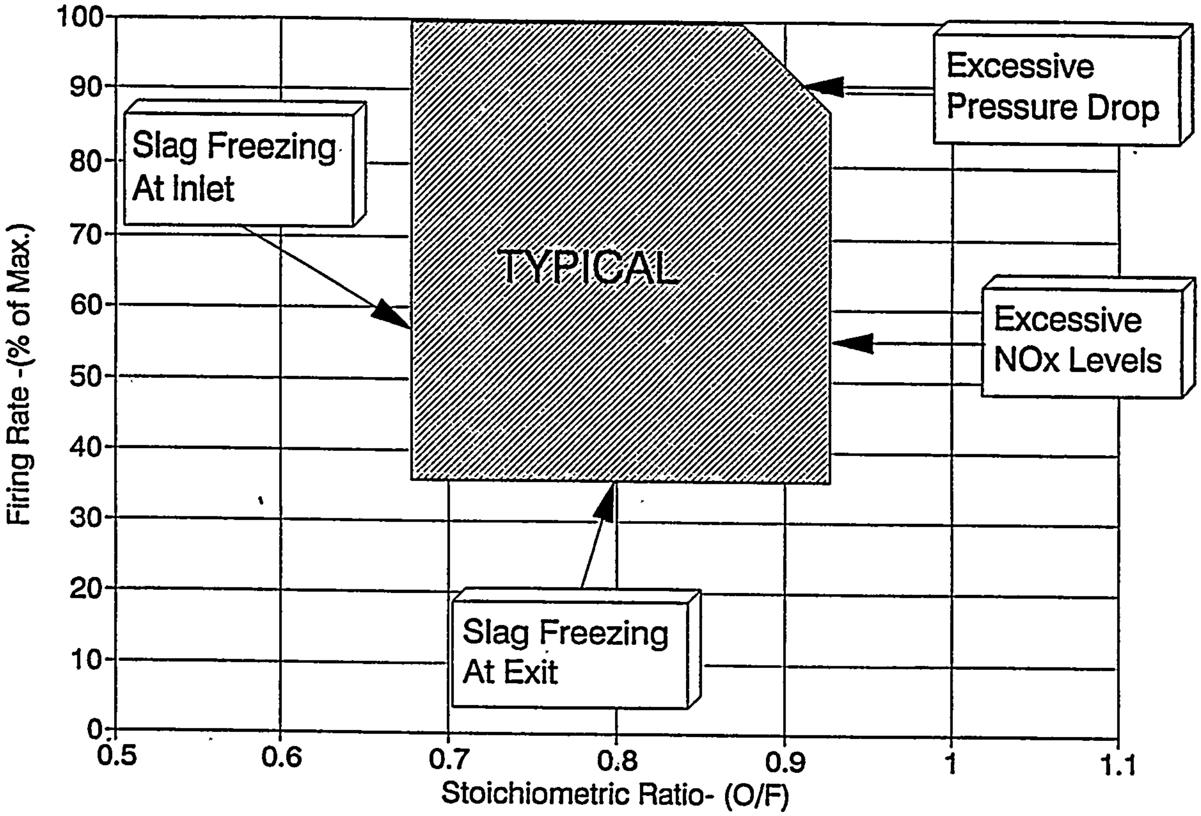


Figure 17 Slagging Char Combustor Operating Envelope

Start-up and control operation depend on the fuel delivery system and other systems operating requirements. Typically, the precombustor ignitor is sized not only so as to ensure stable ignition within the precombustor but also to provide for boiler warm-up. The precombustor also can be used for combustion of pulverizer coal fines during start-up, if required. The precombustor can be started on coal (or char) prior to light-off of the slagging stage provided the fuel delivery system can support this mode of operation. When the main flow to the slagging stage is initiated, the precombustor then acts as an ignitor. If the char flow to the precombustor and slagging stage is started at the same time, then an auxiliary ignitor is also provided at the headend of the slagging stage.

From the control point of view, total fuel flow and total combustion air flow are the principal operating variables. The cooling water flow to the combustor is maintained constant at all loads and other operating variables such as tangential air inlet velocity and fuel flow split to the precombustor are either maintained constant or adjusted with load in a preprogrammed fashion. Fuel flow is adjusted in response to steam demand from the boiler and with combustion air flow splits held constant, combustion air flow is adjusted in response to the excess oxygen level at the boiler exit.

Maturity of the Technology

Slagging coal combustors have been developed and tested by TRW and others in a variety of different applications over the last twenty years. The technology allows for a compact combustion system with extremely low carbon losses, high ash removal, and low NO_x emissions that is suitable for both new and retrofit applications. TRW has been a leading developer of this technology, as evidenced by its Cleveland Pilot Plant Demonstration Project, with over 10,000 hours of operation with a 40 MMBtu/hr combustor (shown in Figure 18), and the Healy Clean Coal Project, which will provide a full-scale (two 350 MMBtu/hr combustors) commercial demonstration of the technology. TRW's slagging combustion technology is ideally suited for low-volatile fuel applications, due to its inherently high combustion intensity and well controlled air-fuel mixing.

An extensive data base has been accumulated by TRW for a variety of coals and coal-derived fuels, including coals with ASTM volatile contents below ten percent. Most of the data was obtained on sub-scale 17 inch and 34 inch diameter units operated in the range of 10 to 50 MMBtu/hr. The data includes measurements and conditions relating to all the major aspects of the operation of the combustion system including the following areas: aerodynamic characteristics and pressure drops; slagging, heat fluxes and cooling loads; carbon conversion and losses; slag containment and tapping; fuel effects and turndown; and scaling data. This extensive data base is applicable to a large extent to the HIPPS char combustor design as are the analytical tools developed in support of the coal combustion development effort.

Alternative Designs

The HIPPS char combustor concept is flexible and various alternatives are available that could be implemented if warranted either by the results of development testing or by the results of system integration studies. Some of the alternative design approaches are discussed below.

Char-Fired Precombustor. A coal-fired precombustor has been selected as the baseline approach due to the lower technical risk involved as well as the increased operational flexibility provided by a coal-fired precombustor during start-up, shut-down, and load changes. A coal-fired precombustor in the range of 100 - 140 MMBtu/hr has already been demonstrated as part of the Healy Clean Coal Project and thus does not require any further development. However, a coal-fired precombustor may require its own coal processing and feed systems. In addition, a coal-fired precombustor adds extra thermal input to the bottoming cycle, which may decrease overall cycle efficiency.

An alternative approach that will be further considered during Phase 2 is a char-fired precombustor, which fires a portion of the total char produced by the pyrolyzers. The potential advantages of this approach include a higher overall system efficiency and lower capital and operating costs. One of the objectives of char combustion tests conducted at TRW during Phase I was to assess the feasibility of a char-fired precombustor. Results of initial testing indicated that additional natural gas assist was required with char-firing (relative to coal-firing) to ensure a well-anchored flame, but that a char-fired precombustor definitely appears feasible. Additional testing is planned early in Phase 2 of the HIPPS program to investigate methods of improving flame anchoring under char-fired conditions.

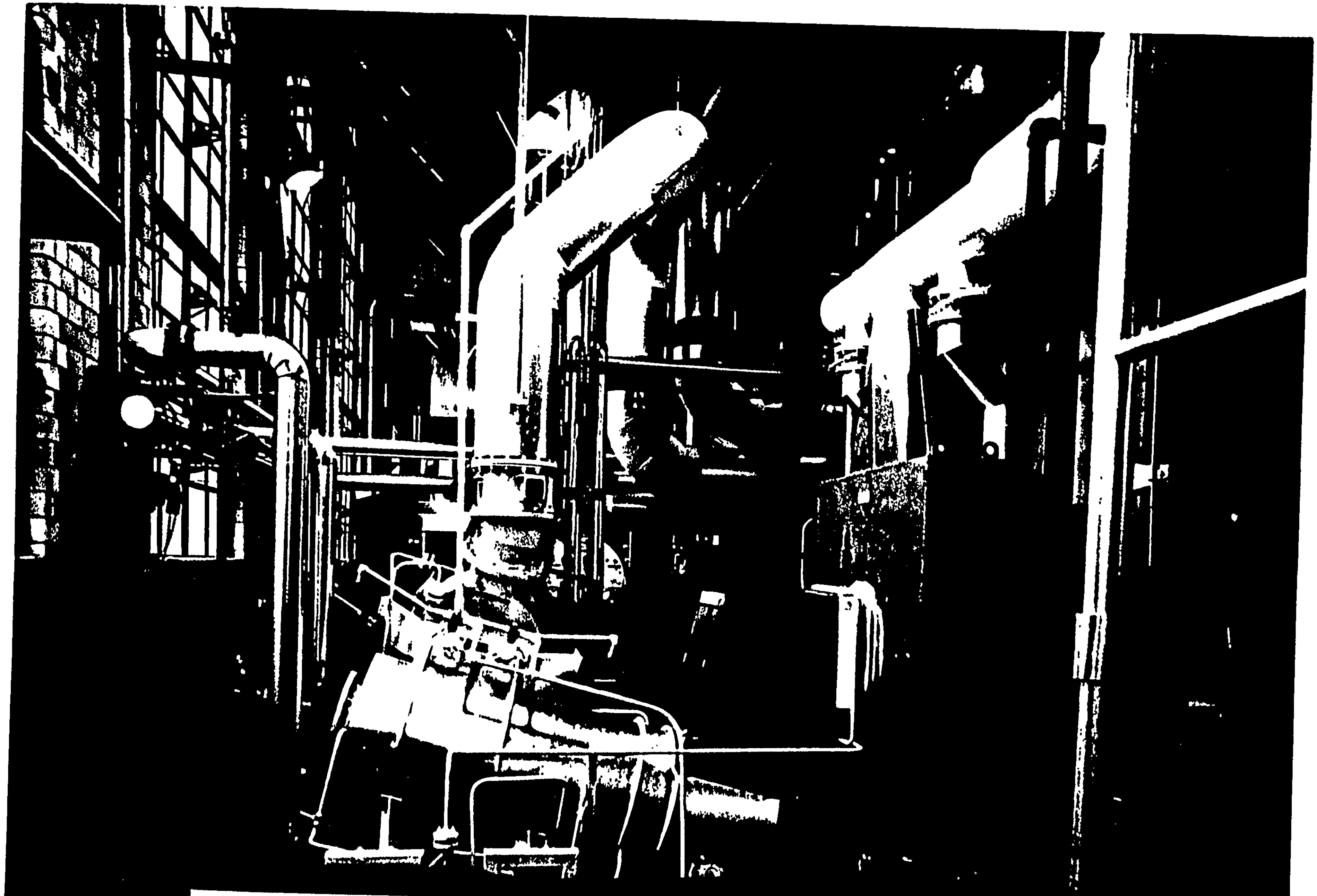


Figure 18 TRW Slagging Combustor Integrated Into Cleveland Demonstration Plant

Alternate NO_x Control.

The slagging stage stoichiometry is the primary operating parameter for controlling both carbon burnout and NO_x emissions. For the HIPPS char combustor, it may prove difficult to optimize both carbon burnout and NO_x emissions at the same stoichiometry. An alternate NO_x control strategy for the slagging combustor may be to operate at higher stoichiometric ratios (and temperatures) than required for minimum NO_x and to destroy the NO_x by injection of ammonia-type compounds. The reaction here is different from the one used for SNCR and under substoichiometric conditions the temperature window is much larger, which should make ammonia slip much less of a problem. Furthermore, this allows operation of the combustor at a higher stoichiometric ratio, consistent with complete char combustion.

Bottom vs. Sidewall Firing.

The baseline combustor configuration calls for bottom (or hopper) firing, which is being demonstrated as part of the Healy Clean Coal Project. An alternate configuration that will be considered for this application is sidewall firing, which was demonstrated as part of the Cleveland Demonstration project (see Figure 18). This configuration may be a more attractive arrangement for a retrofit as part of the Phase 3 Prototype plant, where space limitations could be a significant factor.

Alternative Cooling System.

Whereas the baseline combustor cooling arrangement uses saturated steam drawn water and relies on two-phase flow cooling, an alternate sub-cooled cooling circuit integration arrangement could be used, which would lower cooling tube temperatures, simplify combustor cooling tube arrangements and most likely reduce char combustor capital costs.

Another possible cooling arrangement is to use high pressure air from the gas turbine compressor outlet. While this approach would require the use of higher temperature materials for the char combustor chamber walls, there may be benefits to the overall cycle, and thus this approach deserves additional consideration. An air-cooled combustor approach may make sense for a repowering application where it may be difficult to add a high temperature air heater surface to an existing boiler.

2.3.2.3 Heat Recovery Systems *(Subsection 2.3)*

There are two heat recovery heat exchangers in the HIPPS. They are located in the flue gas stream from the HITAF and in the exhaust gas stream from the gas turbine.

Design Specifications and Features

The flue gas from the HITAF goes through an SCR and then to the economizer. The economizer is a duct type of design with vertical tubes and horizontal flue gas flow. The design is typical of commercial units that have been built for a variety of applications. The economizer operating parameters at full load are shown in Figure 19, and the approximate dimensions are shown in Figure 20. Table 8 is a summary of the design specifications.

The gas turbine exhaust goes through a recuperator before entering the heat recovery steam generator (HRSG). The HRSG design is typical of units sold commercially. The operating parameters at full load are shown in Figure 21, and the approximate dimensions are shown in Figure 22. Table 9 is a summary of the design specifications.

Operation Characteristics

The operation of the economizer and HRSG are discussed in relation to plant operation in Section 2.5.

Maturity of Technology

Economizers and HRSGs are very mature technologies, and the designs specified for the HIPPS plant are typical of commercial offerings. The main area of design where more information would be helpful is the possibility of acid dew point corrosion. In order to keep the system efficiency as high as possible, exit gas temperatures are being kept at relatively low levels. The acid dew point of flue gases depends on the concentration of SO_3 in the gas stream. The concentration of SO_3 depends on the conditions during combustion, and more data will be obtained during Phase 2 testing. At this point, a general procedure by Okkes [4] was used to predict acid dew point and tubes that will operate below this temperature have been specified as Hastelloy C-22. This alloy is quite expensive compared with carbon steel but it is resistive to both the acidic and pitting mechanisms that could be present in the flue gas. If subsequent testing indicates that that the HIPPS conditions resulted in more or less aggresive conditions, the amount of Hastelloy C-22 would be increased or decreased accordingly. This situation would affect the plant capital cost, but not to a significant degree.

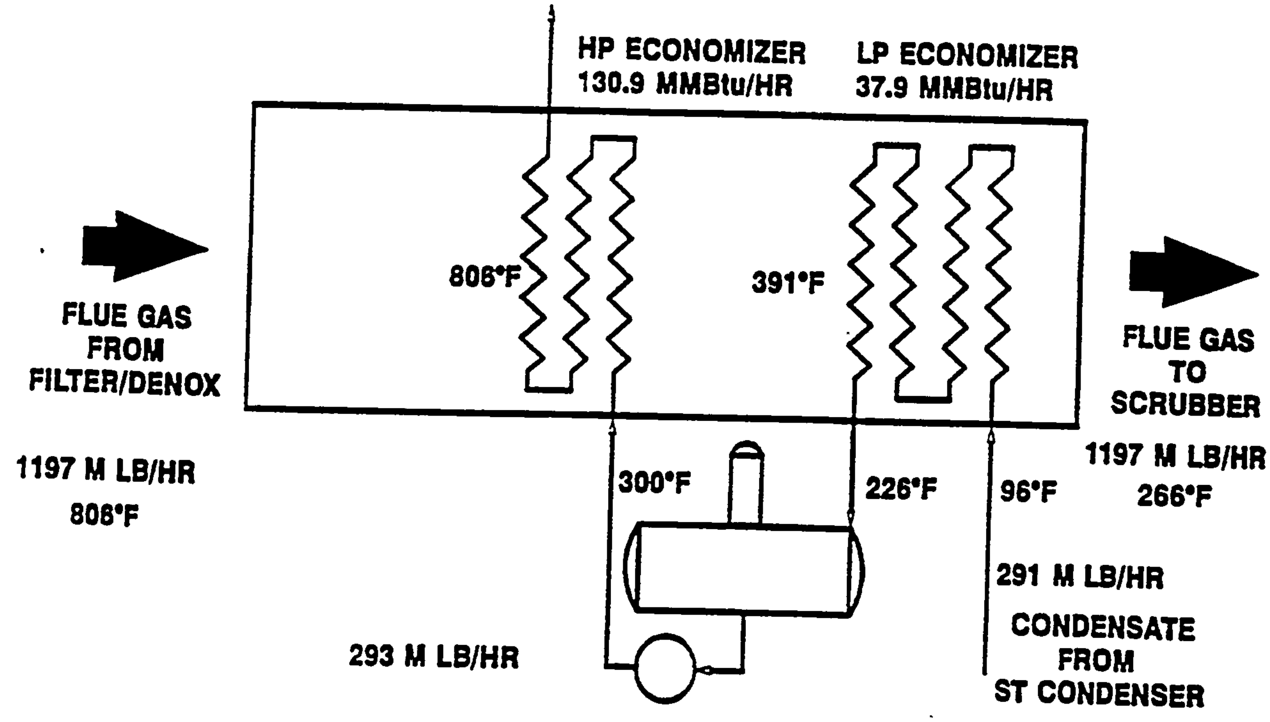


Figure 19 HITAF Economizer

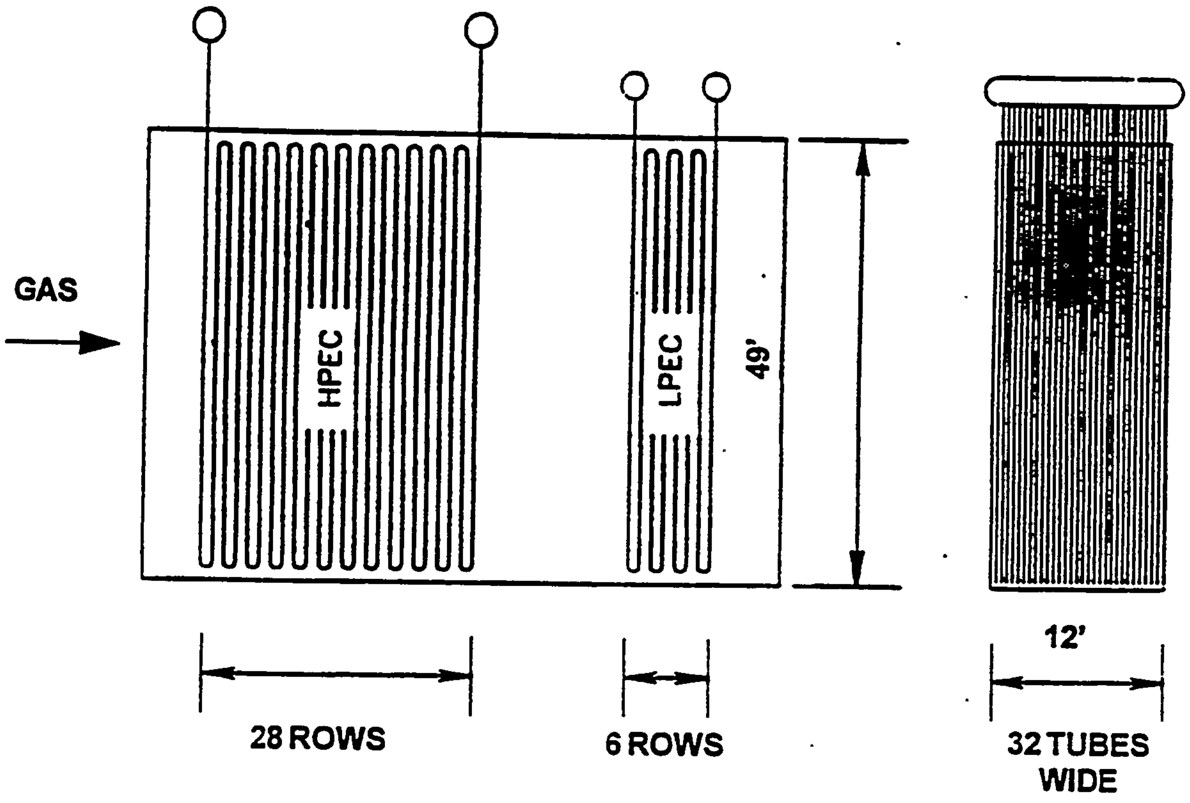


Figure 20 Dimensions of HITAF Economizer

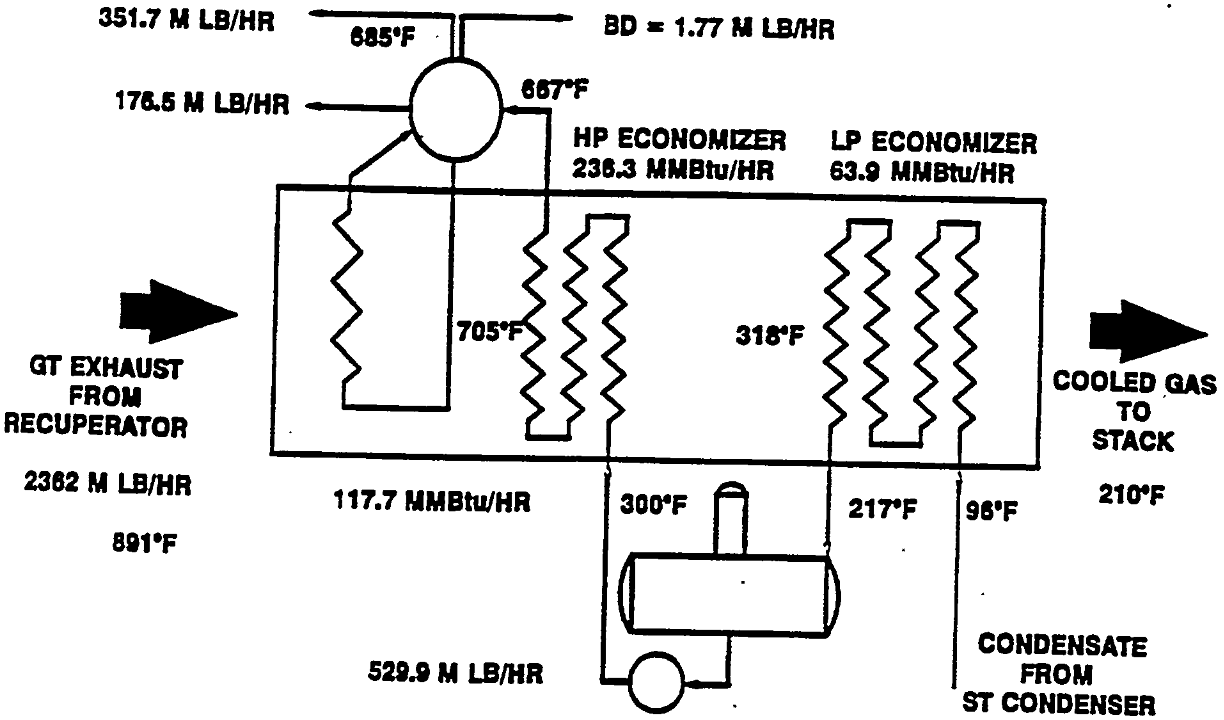


Figure 21 Gas Turbine HRSG

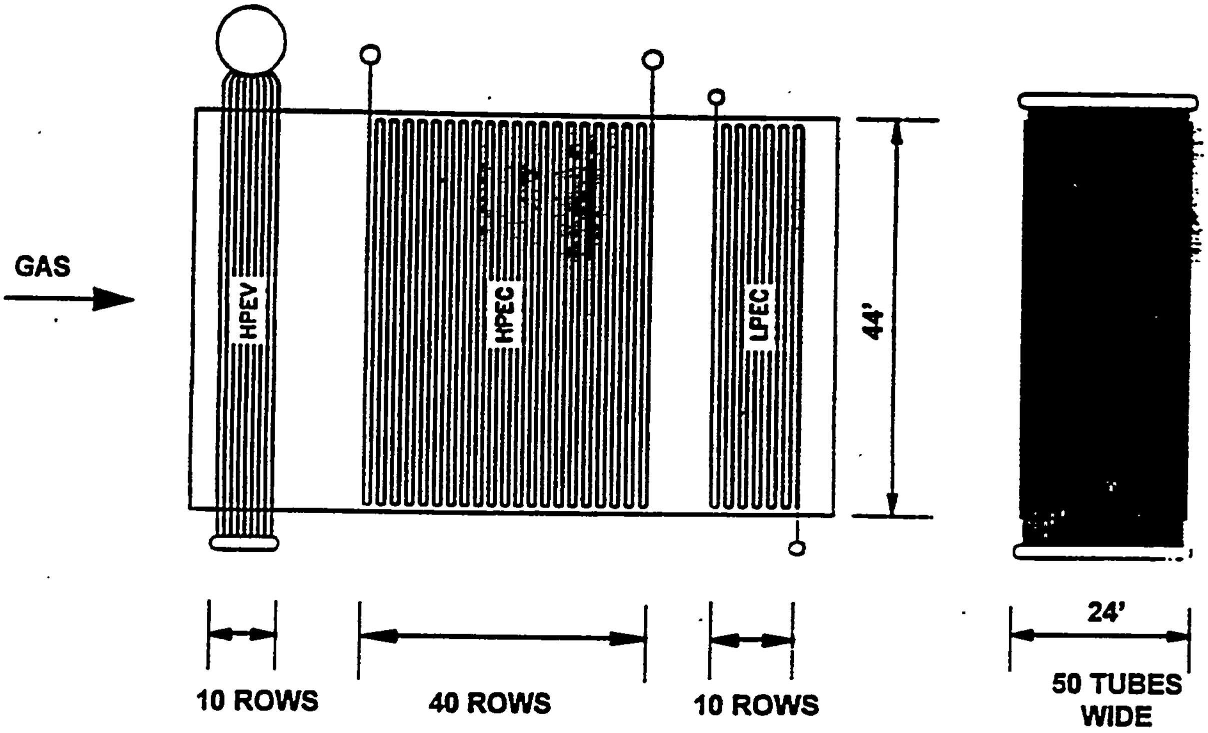


Figure 22 Dimensions of Gas Turbine HRSG

Table 8 HITAF Economizer Specifications

Description	High-Pressure Economizer	Low-Pressure Economizer
Flow Arrangement	Counter	Counter
Tube Dimensions	2 in. O.D. x 0.240 in. wall	2 in. O.D. x 0.120 in. wall
Tube Material	SA 178A	SA 178A/C-22
Number of Tubes Per Row	32	32
Number of Rows	28	4/2
Tube Arrangement	Staggered	Staggered
Tube Type	Finned	Finned

Table 9 Gas Turbine HRSG Specifications

Description	Evaporator	High-Pressure Economizer	Low-Pressure Economizer
Flow Arrangement	Counter	Counter	Counter
Tube Dimensions	2 in. O.D. x 0.240 in. wall	2 in. O.D. x 0.240 in. wall	2 in. O.D. x 0.120 in. wall
Tube Material	SA 178C	SA 178C	SA 178C/C-22
Number of Tubes Per Row	64	64	64
Number of Rows	10	40	7/3
Tube Arrangement	Staggered	Staggered	Staggered
Tube Type	Finned	Finned	Finned

2.3.2.4 Stacks and Low-Temperature Ducting *(Plant Subsection 2.4)*

A single stack is used to handle the desulfurized flue gas exiting the FGD system.

Design Specification and Features

A wet stack design is used consisting of a double wall construction, an outer concrete shell and inner brick liner. Pressurized air is circulated through between the concrete shell and the brick liner to protect the concrete shell from corrosive environment in the event of cracks in the liner. The major design parameters for the stack are given in Table 10.

Table 10 Stack Design Parameters and Specifications

Nominal design flow rate	3,690,000 lb/h
Nominal design temperature	180°F
Concrete Shell diameter	27 ft
Brick liner diameter	19.3 ft (at base)/17.8 ft (at top)
Stack height	250 ft
Sample ports	Six ports; 304 SS
Annulus pressurization system	Complete with seals, dampers, and fans

The flue gas duct penetration is located approximately 20 feet to the centerline from the base of the stack. The breaching entry in the flue gas liner is made up of alloy C-276. A stack sampling platform is located approximately 110 feet above grade.

Maturity of Technology

The stack design is conventional, commercially proven, and has been commonly used in coal fired power plants.

2.3.2.5 Induced-Draft Fan *(Plant Section 2.5)*

An ID fan is used to overcome the pressure loss in the HITAF furnace and the economizers and to provide a pressure boost for the flue gas through the FGD scrubber and the stack. The ID fan will be located downstream of the HITAF low-pressure economizer and ahead of the FGD scrubber. The major design specifications for the fan are as follows:

Nominal inlet flow rate (acfm)	380,000
Differential pressure (psia)	1.60
Efficiency (adiabatic %)	81
Motor horsepower	3280

The ID fan design is conventional and is commonly used in coal fired power plants.

2.3.3 High Temperature Exchanger – Recuperator *(Plant Section 3)*

To meet the pressure drop requirements, the offset fins in the counterflow section of the standard AlliedSignal ASE recuperator core need to be changed to plain fins. This reduces the heat transfer conductance and requires an increase in the number of cores needed to meet the heat transfer requirements.

Design Specifications and Features

The recuperator was sized based on the conditions shown in Figure 23. Thermophysical properties for the gas (vitiated air) side were assumed to be natural gas combustion products at a fuel-to-air ratio of 0.01. The conditions shown in Figure 23 correspond to a recuperator effectiveness of 0.82, a very reasonable operating point. However, the required pressure drops are quite low, especially on the air side where the allowable pressure drop is only 0.3 percent of the total pressure drop.

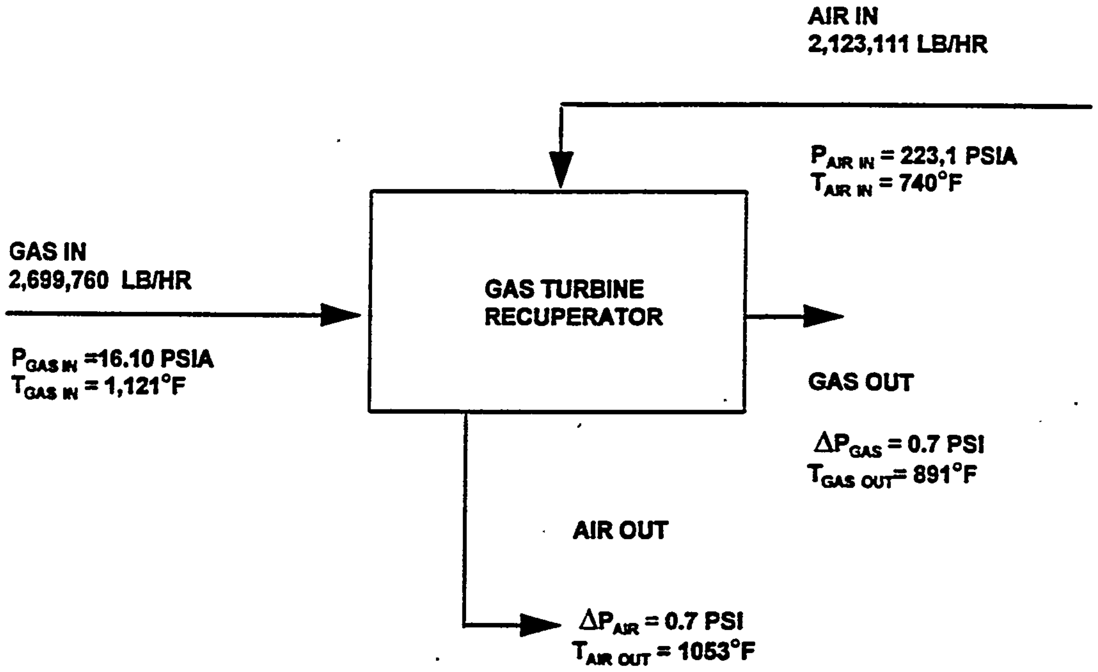


Figure 23 Gas Turbine Recuperator Conditions

The ASE ARG 48P recuperator meets the heat transfer requirement. This recuperator consists of four modules, each module comprising eight cores. The counterflow-section has 7.5 plain fins/in. on the air side and 12 fins/in. on the gas side. The resulting pressure drops are somewhat higher than the requirements: 1.76 psi on the air side (compared to a requirement of 0.7 psi) and 1.55 psi on the gas side (compared to a requirement of 0.7 psi). Thus, to meet the pressure drop requirements currently specified, a few additional cores will be required. When the final specifications are developed, the equipment required will be more fully established, but clearly ASE recuperators can meet the specifications.

Each of the four modules is approximately 22 x 11.3 x 7.7 ft. With each module accepting approximately 25 percent of the flow, the modules can be arranged in any advantageous fashion. A photograph of a unit suitable for forming the modular building blocks required for this project is shown in Figure 24.

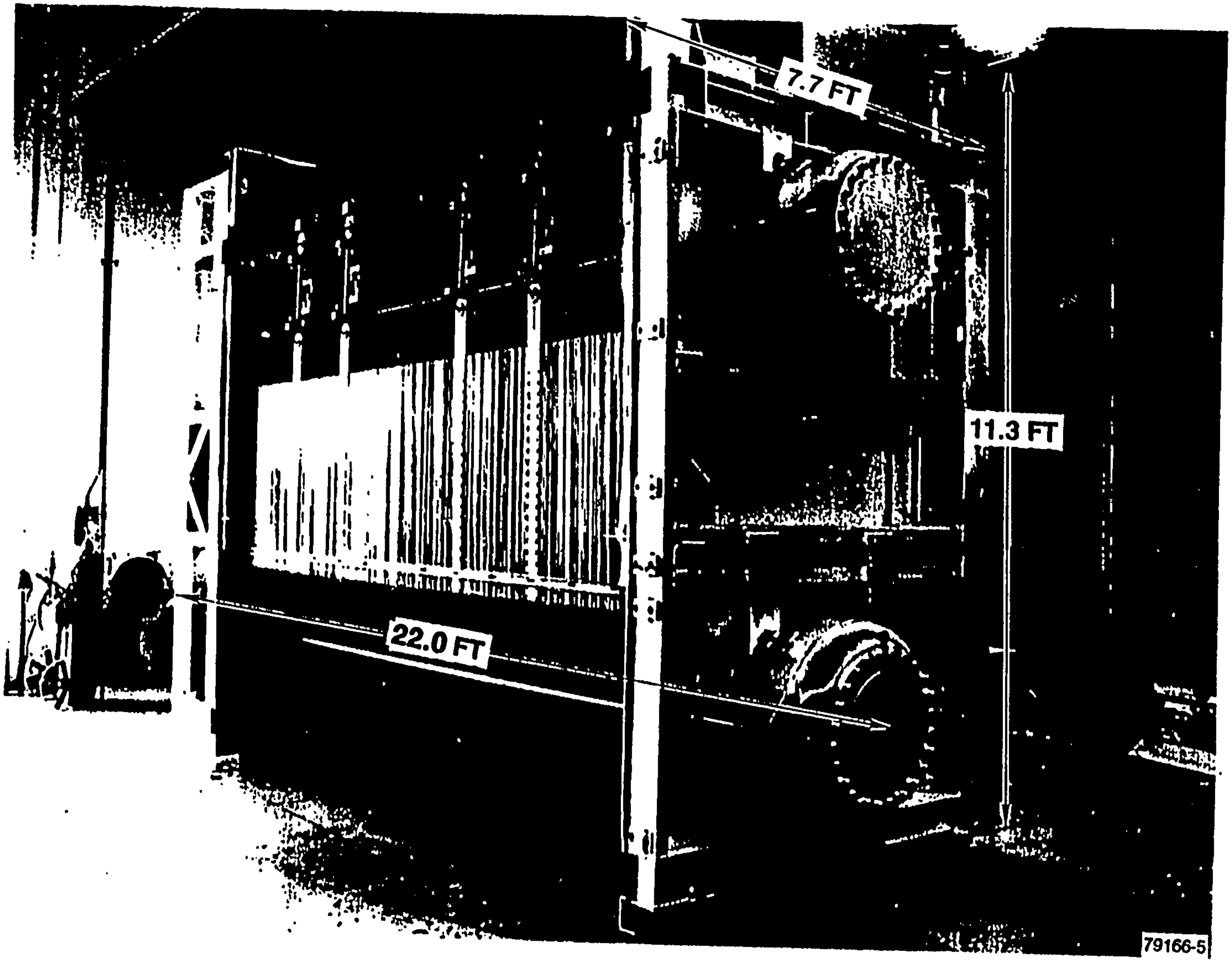


Figure 24 Overall Module Dimensions

Maturity of Technology

AlliedSignal produces a line of industrial recuperators designed for diversified applications with gas turbines in the 1000- to 100,000-hp range. Since these units are modular, they can be extended easily to larger size plants. Applications include systems for electric power generation stations, pumps for oil platforms, oil and gas pipeline pumping stations, chemical processing plants, and marine propulsion. ASE recuperators substantially increase the cycle efficiency of industrial gas turbines and can reduce fuel consumption by as much as 30 percent.

The cores are manufactured from corrosion-resistant stainless steel, and the units are designed for 120,000 operating hr and 5,000 cycles. The units are of modular construction and feature high effectiveness and low pressure drop.

2.3.4 High Temperature Piping and Ducting *(Plant Section 4)*

The HIPPS plant design includes several major pipes and ducts that transport high temperature and high pressure air and gases to various locations in the plant.

Design Specification and Features

Selection of the material of construction and sizes for these pipes and ducts was based on factors that affect their mechanical properties including the internal pressure, design temperature, and thermal expansion stresses. Base on Bechtel in-house data and studies, carbon steel with external and internal refractory lining has been judged suitable for handling the various hot air and gas streams in the plant while maintaining an external surface temperature close to 170°F. Since the maximum air temperature is 1400°F with our HIPPS, it is also possible to use higher alloy piping without internal refractory. A final decision will be made in Phase 2. The design specifications for the major high temperature piping and ducting in the plant are listed below in Table 11. All pipe sizes listed below are based on gas velocities ranging from 110 to 137 ft/s.

Maturity of Technology

All high temperature piping and ducting designs follow conventional and proven practices used in the industry.

2.3.5 Process Systems *(Plant Section 5)*

The process systems of the plant consist of:

- Pyrolyzer (Plant Subsection 5.1)
- Cyclones (Plant Subsection 5.2)
- Fuel Gas Cooler (Plant Subsection 5.3)
- Barrier Filter (Plant Subsection 5.4)
- Solids Transport Equipment (Plant Subsection 5.5)
- Pyrolyzer Compressor (Plant Subsection 5.6)

Table 11 Design Specifications for Piping and Ducting

Pipe/Duct Service	Specifications
Air to recuperator	Design temperature/pressure: 750°F/250 psia Carbon Steel (CS) SA106 grade B Pipe diameter w/o internal refractory: 42 in. External insulation: Thermo-12, 5 in. thick
Air from recuperator to furnace air heater	Design temperature/pressure: 1100°F/250 psia CS SA106 grade C Pipe diameter w/o internal refractory: 60 in. Internal refractory: 6 in. thick External insulation: mineral wool board, 3 in. thick
Air to pyrolyzer booster compressor	Design temperature/pressure: 750°F/250 psia CS SA106 grade B Pipe diameter w/o internal refractory: 12 in. (two required) External insulation: Thermo-12, 5 in. thick
GT exhaust to recuperator	Design temperature/pressure: 1150°F/20 psia CS SA106 grade B Duct size w/o internal refractory: 208 square inches Internal refractory: 8 in. thick External insulation: mineral wool board, 3 in. thick
Secondary air to furnace	Design temperature/pressure: 920°F/20 psia CS SA106 grade B Pipe diameter w/o internal refractory: 96 in. Internal refractory: 6 in. thick External insulation: mineral wool board, 3 in. thick
Primary air to precombustor	Design temperature/pressure: 1150°F/20 psia CS SA106 grade B Pipe diameter w/o internal refractory: 84 in. (two required) Internal refractory: 6 in. thick External insulation: mineral wool board, 3 in. thick
GT exhaust to HRSG	Design temperature/pressure: 920°F/20 psia CS SA106 grade B Duct size w/o internal refractory: 165 square inches Internal refractory: 6 in. thick External insulation: mineral wool board, 3 in. thick
Hot air to GT combustor	Design temperature/pressure: 1450°F/250 psia CS SA106 grade B Pipe diameter w/o internal refractory: 72 in. Internal refractory: 9 in. thick External insulation: ceramic fiber blanket, 1.5 in. thick and mineral wool board, 3 in. thick
Fuel gas from barrier filters to header	Design temperature/pressure: 1200°F/250 psia CS SA106 grade B Pipe diameter w/o internal refractory: 30 in. (four required) Internal refractory: 8 in. thick External insulation: mineral wool board, 3 in. thick
Fuel gas from header to GT combustor	Design temperature/pressure: 1200°F/250 psia CS SA106 grade B Pipe diameter w/o internal refractory: 36 in. (two required) Internal refractory: 8 in. thick External insulation: mineral wool board, 3 in. thick

The pyrolyzer/char transport system (Figure 25) converts the coal into fuel gas to be fired in the gas turbine and char that is fired in the HITAF. It performs the following functions:

- Converts the coal
- Separates the char/fuel gas
- Removes alkalies from fuel gas
- Transports char to char combustors

The pyrolyzer is a pressurized circulating fluidized bed. Coal and sorbent are fed to the pyrolyzer as a paste, and air is injected to maintain the bed temperature at 1700°F under substoichiometric conditions. With this type of operation, a low-Btu fuel gas and char are formed. Fluidized bed pyrolyzers have been built in both jetting bed and circulating bed arrangements. A circulating bed is better suited to the HIPPS plant because of the relatively fine char particle size required for the HITAF char combustor.

The superficial velocity in the bed is maintained at a level where there is significant particle carryover to the primary cyclone. Most of the particles are captured in the cyclone and recirculated through the bed. These recycled solids provide good gas and solids mixing, and they add thermal inertia to the bed. In the HIPPS, the primary cyclone is also used like a classifier in a pulverizer. The cyclone is sized to ensure that the particles leaving with the fuel gas are within the proper size range for the char combustor.

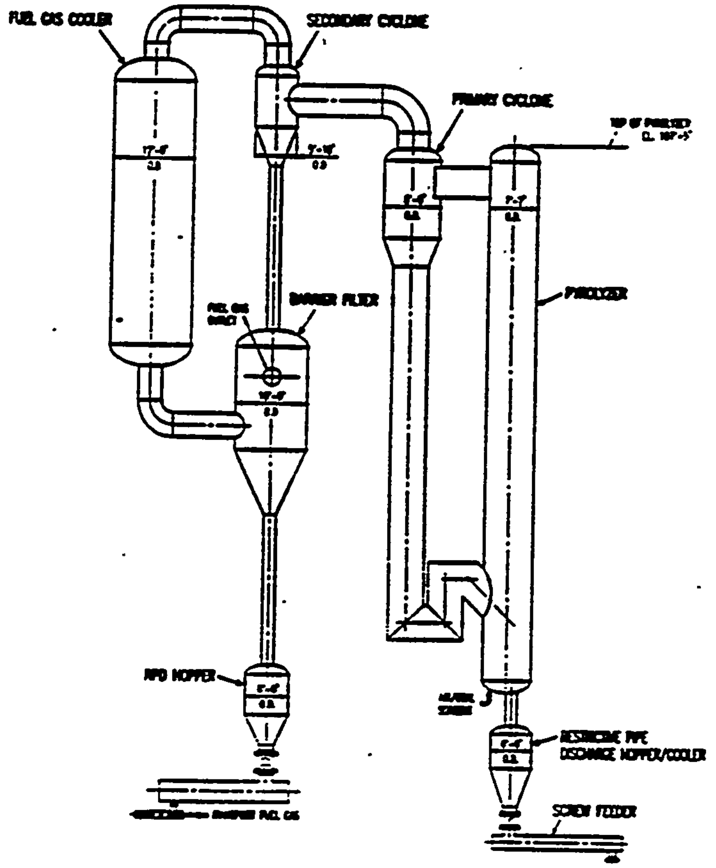


Figure 25 Pyrolyzer/Char Transport System

The secondary cyclone, fuel gas cooler, and barrier filter separate the char and reduce fuel gas alkali. The secondary cyclone separates out about 80 percent of the solids flow; these particles are injected into the bottom of the barrier filter vessel. This arrangement reduces the solids flow through the fuel gas cooler while maintaining the full range of particle sizes at the outlet of the barrier filter vessel. This type of a particle mix flows more readily than a stream consisting solely of very fine particles.

The fuel gas cooler lowers the fuel gas temperature to about 1100°F, where most of the alkalies in the fuel gas will condense out on the solids particles. These particles are then removed from the fuel gas stream in the barrier filter. The char/sorbent particles from the secondary cyclone go through a steam-cooled dip leg into the hopper of the barrier filter vessel. The solids from the secondary cyclone dip leg and those removed by the filter mix in the bottom of the barrier filter vessel. This area also acts as a surge hopper, where an inventory of solids is maintained to feed the restrictive pipe discharge (RPD) system.

The RPD system lowers the pressure of the solids in preparation for their pneumatic transport to the char combustors. The pipe between the barrier filter vessel and the RPD hopper becomes a moving bed of solids. Fuel gas will flow down through this bed of solids from the high pressure in the barrier filter to the low pressure in the RPD hopper. A control valve on the RPD hopper vents sufficient fuel gas to maintain the desired pressure in the RPD hopper. The resulting gas flow will be what is required to obtain the pressure drop through the solids that is equal to the pressure difference between the upper and lower hoppers. The vented fuel gas (in a very small stream) goes to the HITAF, where it is burned.

Each of these pipes feeds a char metering and transport system. Screw coolers control the char flow rate. The char leaves these devices at 600°F. A shutoff valve and purge system upstream of each screw cooler can isolate the screw cooler and downstream equipment for maintenance. The screw cooler moves the solids into a pneumatic transport line feeding the char combustors.

A pressurized fuel gas stream is the solids transport medium. Its flow rate is regulated with a control valve. The solids are transported in dilute phase.

The feed air for the pyrolyzer is obtained from the gas turbine compressor at a pressure of about 220 psia and is then boosted up to 265 psia before entering the pyrolyzer using a pair of centrifugal compressors operating in parallel, with each sized to handle 60 percent of the flow.

Design Specification and Features

Pyrolyzer (Plant Subsection 5.1). The pyrolyzers are adiabatic circulating fluidized beds operated substoichiometrically to convert coal into fuel gas and char. Coal and sorbent are fed to the pyrolyzer in a 25-percent water paste feed. Air is the fluidizing and oxidizing medium. The overall sizing and arrangement of the pyrolyzer are based primarily on analyses of process yields and particle dynamics.

Early in Phase 1, process yields were calculated for different operating conditions to determine the conditions that would result in the best plant performance. The primary mechanism for changing process yields is varying the bed temperature, which is accomplished by changing the air-to-fuel ratio. The best plant performance was achieved at a 1700°F bed temperature. The pyrolyzer heat and material balance for this temperature and Pittsburgh No. 8 coal are shown in Table 12.

Process yields were determined with a proprietary fluidized bed gasifier simulation computer program that incorporates data from the FWDC Second-Generation PFB pilot plant tests. There are three basic elements in the program—kinetics for both the particle and gas reactions, thermodynamics, and residence time distribution of the particles.

The computer model solves char-gasification kinetics and sulfur-capture kinetics simultaneously with mass and energy balances. The single particle reaction history can be integrated with different residence time distribution functions. Some of the program assumptions are:

- *Coal Devolatilization.* Devolatilization kinetics are instantaneous compared with gasification kinetics. The program calculates carbon conversion based on the specified values of mols CH_4 produced/mol carbon fed and of oxygen content of the coal feed. The products of devolatilization go to the gas phase as CO, CO_2, H_2, H_20 and CH_4.

- *Char Combustion.* Combustion kinetics are instantaneous. Combustion products are H_20, CO, and CO_2. Char burns with oxygen to yield CO and CO_2 at a molar ratio of unity.

- *Char Gasification.* Gasification occurs uniformly through the bed. Species present in the gasification zone are CO, CO_2, H_2, H_20, N_2, CH_4, H_2S, NH_3, char, ash, and sorbent. The water-gas shift reaction is at thermal equilibrium at the reactor conditions. Both the gas and solid phases are well mixed, and both the coal and the sorbent have uniform feed particle size distributions. The gas is assumed to behave like an ideal gas.

- *Sulfur Capture.* The amount of sulfur released to the gas phase is proportional to the converted carbon in the coal and is released as H_2S. An algorithm for computing the sulfur-capture rate depending upon whether the CO_2 partial pressure is above or below that required at equilibrium, has been incorporated into the program. According to the dissociation reaction,

  $$CaCO_3 \rightarrow Ca0 + CO_2 \qquad (2.3.5\text{-}1)$$

  If the partial pressure of CO_2 is lower than the equilibrium of the reaction in Eq. (2.3.5-1), we can assume this reaction occurs completely and that there is no $CaCO_3$ existing in the solids withdrawal. The sulfur-capture driving force is calculated according to the reaction of

  $$CaO + H_2S \rightarrow CaS + H_20 \qquad (2.3.5\text{-}2)$$

  If the partial pressure of CO_2 is higher than the equilibrium of Eq. (2.3.5-1), CaO disappears in solids withdrawal. The sulfur-capture equilibrium calculation depends on the reaction

  $$CaCO_3 + H_2S \rightarrow CaS + CO_2 + H_20 \qquad (2.3.5\text{-}3)$$

  In this case, the driving force for the kinetics is calculated according to the equilibrium of Eq. (2.3.5-3).

Table 12 Pyrolyzer Balance at 1700°F and 16 Atmospheres

INPUTS					
Pittsburgh No. 8 (Paste) 100 lb/h (Wet)		Air 201 lb/h		Longview Limestone 8 lb/h (Ca/S = 1.05)	
Description	Weight Percent	Description	Weight Percent	Description	Weight Percent
C	53.85	O_2	23.1	$CaCO_3$	95.5
H	3.51	N_2	76.1	$MgCO_3$	1.5
O	4.74	Moisture	0.8	Moisture	2.0
N	0.94	Temperature = 410°F		Inerts	1.0
S	2.24			Temperature = 70°F	
Ash	7.72				
Moisture	27.00				
HHV = 13247 Btu/lb (MF) LHV = 12801 Btu/lb (MF) Temperature = 70°F					

OUTPUTS						
Char-Sorbent (32 lb/h)				Product Gas (277 lb/h)		
Char (26.1 lb/h)		Spent Sorbent (5.9 lb/h)		(11.46 mol/h)		
Description	Weight (lb/h)	Description	Weight (lb/h)	Description	Weight Percent	mol Percent
C	17.65	$CaCO_3$	1.67	CO	19.62	16.95
H	0.11	CaO	0	CO_2	14.99	8.24
O	0	$MgCO_3$	0	H_2	1.26	15.11
N	0.31	MgO	0.06	H_20	7.39	9.92
S	0.29	CaS	4.09	CH_4	1.06	1.60
Ash	7.72	Inerts	0.07	NH_3	0.14	0.21
HHV = 10150 Btu/lb LHV = 10112 Btu/lb		HHV = 2602 Btu/lb LHV = 2602 Btu/lb		H_2S	0.051	0.036
				O_2	0	0
				N_2	55.49	47.93
				HHV = 124 Btu/sft^3/wet = 1954Btu/lb LHV = 111 Btu/sft^3/wet = 1742 Btu/lb Molecular Weight = 24 Temperature = 1700°F		
HHV = 8760 Btu/lb LHV = 8730 Btu/lb Temperature = 1700°F						

Data from the FWDC Second-Generation PFB pilot plant tests were a general benchmark to validate the computer model and to provide specific input parameters where appropriate. For instance, approach-to-equilibrium factors and yield data from pilot plant operation were used in the program instead of assumed values.

The Second-Generation PFB pilot plant pyrolyzer was successfully operated for 627 hours in a series of 10 test runs that included 45 setpoints. Tests were run with Pittsburgh No. 8, Illinois No. 6, and Eagle Butte coals. Plum Run dolomite and Longview limestone were the sorbents. Most of the tests were run in a jetting bed arrangement, but one series of tests was run with a circulating bed. The operating conditions for all the tests are summarized in Table 13.

Sulfur removal in the pyrolyzer turned out to be better than anticipated, only 2 to 5 percent of the coal sulfur remained in the fuel gas as H_2S; no tars were formed, alleviating the concern that tars would be produced that could condense downstream and cause problems.

Second-Generation PFB pilot plant data are very relevant to the HIPPS pyrolyzer. The feedstocks and bed temperature assumed for the commercial plant were used in the tests, and these are the most important factors when determining process yields. Pilot plant conditions did not exactly match commercial plant conditions. For example, the feed was dry instead of a paste, and heat losses were proportionally greater because of the smaller scale and the proportionately higher nitrogen purge levels. However, the combination of process data obtained from the tests and analytical calculations from the computer model give us a high degree of confidence in the estimated commercial plant heat and material balance.

Table 13 Summary of Second-Generation PFB Pilot Plant Pyrolyzer Test Conditions

Test	Set-point	Coal		Sorbent		Temperature, °F	Pressure, psig	Operating Mode§
		Type*	Flow, lb/h	Type†	Flow, lb/h			
1	4	P	235-400	D	67-98	1510-1695	125-153	JFB
2	5	P	182-508	D	83-160	1605-1800	132-199	JFB
3	3	C,P	230-280	D	70-92	1700-1800	130-180	JFB
4	8	P	207-450	D	86-182	1590-1730	126-193	JFB
5	4	P	198-237	D,L	24-119	1695-1715	130-154	JFB
6	7	W,I	300-427	L	17-67	1505-1638	121-192	JFB
7	¶	—	—	—	—	—	—	—
8	10	P,I,W	300-427	D,L	27-11	1470-1720	127-170	JFB
9	¶	—	—	—	—	—	—	—
10	4	P	232-525	L	25-143	1600-1725	60-116.	CFB

*P = Pittsburgh No. 8, C = Coke, W = Wyoming Eagle Butte, and I = Illinois No. 6.
†D = Plum Run Dolomite and L = Longview Limestone.
§JFB = Jetting Fluidized Bed and CFB = Circulating Fluidized Bed.
¶Test aborted for equipment repair.

Another important aspect of the pyrolyzer design is the particle and gas dynamics. To a great extent, the size of the pyrolyzer components will depend on these dynamics. Considerable research has been done on the dynamics of circulating fluidized bed systems. Foster Wheeler has built seven commercial circulating fluidized bed units ranging in size from 20 to 110 MW, and we have operating data from these units. A program has been developed by FWEC to model the particle-gas dynamics in a circulating fluidized bed. This model is based on analytical approaches proposed by Zenz and Briens and factors obtained from commercial plant operating data.

Circulating fluidized bed systems consist of a riser section, a cyclone, and a solids return system. All of these sections must be analyzed as an integrated system to determine the particle-gas dynamics. A cross-sectional elevation view of the pyrolyzer is shown in Figure 26. The conversion of coal to a fuel gas and char occurs primarily in the riser section. The bed particles are recycled through this section, and the bed temperature is maintained at a level that achieves the desired process yields. For the flow conditions in our design, solids concentrations in the riser section are generally divided into three regimes. In the lowest part of the riser section, there is a dense-phase region. It is characterized by a dilute core, where particle flow is generally upward, and a wall region, where there is a general downward flow of the particles. This type of particle flow distribution is referred to as refluxing. The top area of the bed is the dilute-phase region, where the particles generally move upward in a very dilute solids/gas mixture. There is also a transition regime between these two, where the bed characteristics change.

Cyclones (Plant Subsection 5.2) Another important part of the circulating fluidized bed system is the cyclone. The design of the cyclone determines how the particle mass flow and size distribution will be proportioned between the solids return leg and the fuel gas stream leaving this cyclone. Considerable research on cyclones is available in the general literature. FWDC has also conducted internal R&D with cyclones up to an 80-in. diameter to investigate the effects of cyclone geometry, particle size, and gas velocity. FWEC has data from commercial plants with cyclones up to 20 ft in diameter. The estimated performance of the Commercial Plant cyclones can be seen in Table 14.

Solids are fed back into the riser section with a J-valve. The J-valve is one of a family of nonmechanical valves that uses the fluidization of solids as a pressure seal while transporting solids from a lower- to a higher-pressure region. These valves are used in commercial circulating beds. Research in the general literature includes modeling work by Knowlton; Foster Wheeler has tested both models and commercial applications of these valves.

The bottom of the pyrolyzer vessel includes a section to oxidize particles removed from the bottom of the bed. This section is similar in function to carbon burnout beds that have been used in commercial applications. If enough residence time is provided in an oxidizing fluidized bed, carbon will be consumed, and CaS will be converted to $CaSO_4$. The bottom section of the pyrolyzer vessel will be operated in this manner. Because of the design of this section and the characteristics of the sorbent and char particles, the stream of solids leaving it will primarily be sorbent. This design should permit removal of some sulfur from the system and thereby should reduce the removal requirement for the backend system. However, pending Phase 2 R&D results, no credit has been taken for this sulfur removal in the current Commercial Plant design.

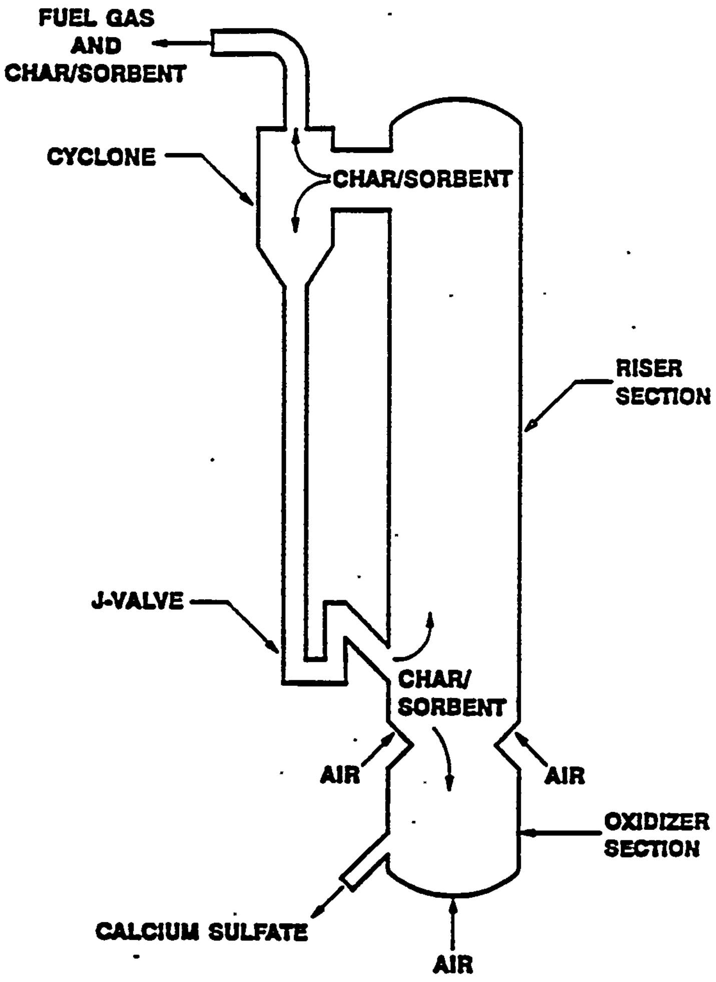


Figure 26 Circulating Fluidized Bed Pyrolyzer

Table 14 shows the results of the particle gas dynamics for the Commercial Plant. The superficial gas velocity in the riser section is 13 ft/s, which results in a solids-to-gas ratio of approximately 11. The coal input size and the primary cyclone design are such that the char carryover flow rate and size distribution (Stream 4) are compatible with the char combustor requirements. The sorbent feed size is slightly larger than the coal feed size. Because of this difference in size and the greater density of the sorbent, the stream of solids removed from the bottom of the bed (Stream 1) is essentially all sorbent. These calculations are based on an input average feed size of 100 microns for the coal and 400 microns for the sorbent with empirical factors applied for attrition. One of the results of the Phase 2 testing will be to more accurately determine the input size requirements.

Table 14 Size Distributions and Flowrates of Solids Streams

	Size, "d" Microns	STREAM NO. (Cumulative Weight Percent Smaller Than "d")					
		1	2	3	4	5	6
CHAR	2.1	0.00	0.06	0.00	5.00	0.00	25.81
	9.8	0.00	0.19	0.01	15.00	1.86	69.70
	21.2	0.00	0.38	0.07	25.00	8.99	91.64
	36.0	0.00	1.35	0.93	35.00	20.25	96.41
	58.4	0.00	4.50	4.00	45.00	32.33	97.76
	82.5	0.00	10.84	10.29	55.00	44.55	98.50
	124.9	0.00	20.19	19.63	65.00	56.81	99.10
	181.6	0.00	32.34	31.80	75.00	69.09	99.59
	272.0	0.00	47.39	46.91	85.00	81.43	99.87
	490.8	0.00	77.80	77.58	95.00	93.81	99.97
Flowrate, lb/h		0.0	2,173,072	2,146,078	26,994.0	21,765.0	5,229.0
SPENT LIMESTONE	19.1	0.00	0.22	0.21	6.49	5.74	24.70
	51.3	0.00	1.49	1.45	19.47	17.31	60.28
	82.1	0.00	3.96	3.90	32.45	28.97	80.04
	117.3	0.04	7.05	6.97	45.41	40.67	92.88
	157.7	0.21	10.81	10.71	58.33	52.40	97.82
	201.7	0.93	16.75	16.63	71.10	64.12	99.29
	256.7	3.47	27.28	27.15	83.33	75.73	99.88
	322.7	12.94	47.18	47.07	93.50	86.90	99.99
	418.0	38.49	75.14	75.09	98.86	95.95	100.00
	623.3	78.27	94.94	94.93	99.98	99.79	100.00
Flowrate, lb/h		1,399	2,334,192	2,329,502	4,690	4,659	31

Stream Identification:

1 — Pyrolyzer Drain
2 — Pyrolyzer to Primary Cyclone
3 — Pyrolyzer Recycle
4 — Primary to Secondary Cyclone
5 — Secondary Cyclone to Barrier Filter
6 — Secondary Cyclone to Fuel Gas Cooler

Fuel Gas Cooling (Plant Subsection 5.3) and Char Separation(Plant Subsection 5.4). The secondary cyclone reduces the solids loading in the fuel gas and prevents erosion and fouling problems in the fuel gas cooler. Cleaning of the cooler tubes is not anticipated, but if it is required, it can be accomplished with either sonic devices or pressurized fuel gas.

The fuel gas temperature is lowered to 1100°F in the fuel gas cooler. At this temperature, sufficient alkalies will have condensed out of the gas stream to prevent corrosion in the gas turbine. This temperature was determined from a combination of laboratory analysis of coal alkalies, thermodynamic equilibrium calculations, and results from the second-generation PFB pyrolyzer tests. The analysis consists of chemical fractionation of the coal to estimate how much of the alkali could be released into the fuel gas during the pyrolyzation process. This technique extracts the organically bound, water-soluble and carbonate forms of the alkalies from the coal sample. The alkalies remaining in the coal are present as clays and are not released during pyrolyzation. The alkalies estimated to be released in this manner constitute a worst-case analysis, because gettering by the ash is not considered. The amount of gaseous-phase alkalies predicted in this manner were input into the thermodynamic equilibrium program SOLGAS MIX, where the concentrations of gaseous-phase sodium and potassium were determined with the gas cooled to different temperatures. This analysis shows the trend of gaseous phase alkalies with a worst case analysis. The curve is shown in Figure 27. As the figure shows, even with the worst-case analysis, a temperature of 1100°F will reduce the alkalies sufficiently.

The fuel gas cooler consists of superheater surface in the form of enclosure walls and a serpentine tube tank. This heat exchanger is contained in a refractory-lined pressure vessel.
The tubes are HR3C with dimensions of 2 in. O.D. x 0.180 in. wall. This alloy is used because of its resistance to sulfidation corrosion. To further minimize the corrosion from sulfidation, the metal temperatures are kept below 1000°F.

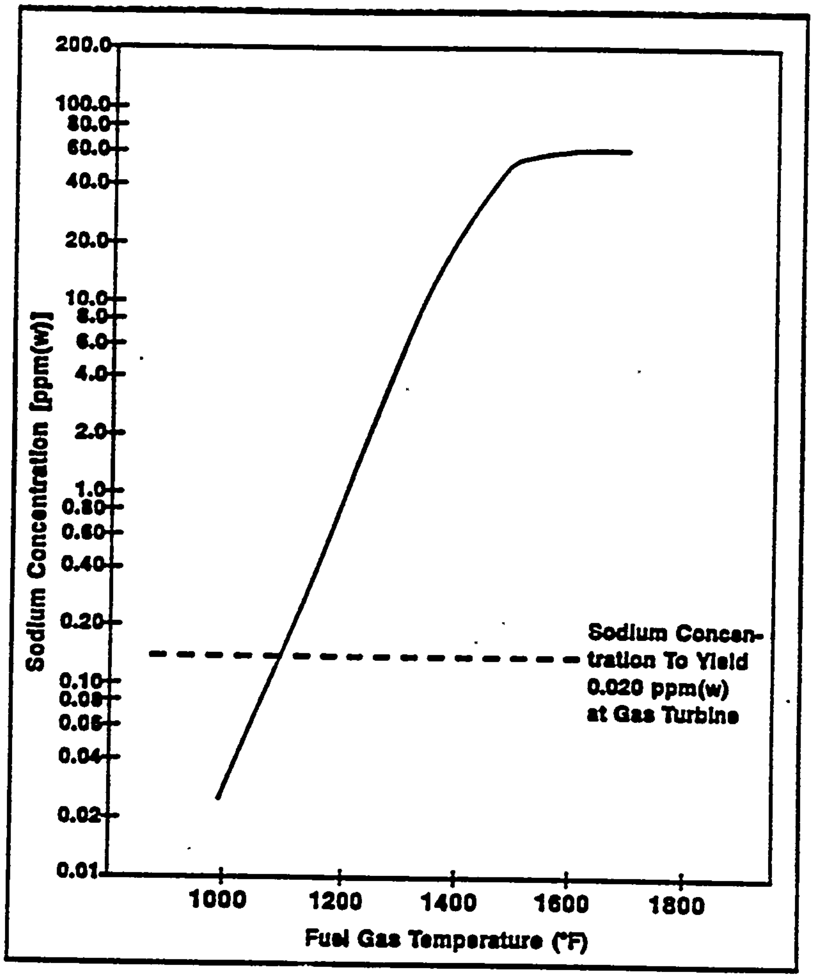


Figure 27 Sodium Concentration in Fuel Gas vs. Temperature

Our fuel gas should be less corrosive than a gasification environment because a significant amount of sulfur is removed from the fuel gas in the pyrolyzer bed. At 1700°F, the fuel gas has a partial pressure of sulfur (PS_2) of 1.69×10^{-9} atm, a partial pressure of oxygen (PO_2) of 1.65×10^{-17} and a carbon activity of 0.19. At this condition, the bulk gas is oxidizing to most of the elements in normal stainless steels. This is a favorable condition to limit sulfidation corrosion. In contrast, many coal gasification atmospheres at 1700°F are sulfidizing to Fe, Mn, CO and Ni and are, therefore, more corrosive than our pyrolyzer gas.

The solids removed by the secondary cyclone are cooled to 1480°F in a steam-jacketed dip leg. These solids enter the bottom of the barrier filter vessel. A J-valve at the bottom of the dip leg forms a gas seal between the pressure in the cyclone and in the barrier filter vessel. The solids exiting the J-valve are thermally shielded from the portion of the vessel that has the filter elements, but the char from the J-valve and the pulsed-cleaned char from the filter elements mix in the bottom of the barrier filter vessel. This mixing of the solids improves the flow characteristics in the vessel hopper. The bottom of the barrier filter vessel also serves as a surge hopper to ensure that the RPD system always has a column of solids.

The base case barrier filter will use candle filter elements made from sintered metal powder medium which has been developed and manufactured by Pall Corporation. This metal filter has a uniform distribution of interconnected pores that represents up to 60 percent of the filter medium's volume. The pore size distribution is optimized to collect particles on the filter's surface as a cake and prevent particle penetration into the depth of the medium. The solids cake is dislodged from the filter elements by initiating a momentary reverse flow using jet pulse blowback. The filter elements are held in place by tube sheets which are housed in pressure vessels. The filter element can withstand high temperatures (up to 1400 °F) and can typically remove more than 99.99 percent of the inlet solids. The barrier filter is discussed in more detail in Section 2.3.8.

The vertical RPD pipe connects the barrier filter and the RPD hopper. The char flows down this pipe and is depressurized. A small amount of fuel gas flows downward through the pipes and is then vented from the RPD hopper to the furnace. A control valve on this vent line maintains the pressure at slightly above the pneumatic transport line pressure. The amount of fuel gas flowing through the solids is a function of the pressure differential between the barrier filter vessel and the RPD hopper. It is also a function of the diameter and length of the vertical pipe and the pressure- drop characteristics of the packed bed. The fuel gas flow rate is calculated by the relative velocity form of the Ergun equation:

(2.3.8-1)

$$\frac{\Delta_P}{L} = \frac{150\mu(1-\varepsilon)^2 \dot{V}_r}{(\phi d_p)^2 \varepsilon^2} + \frac{1.75\rho_g(1-\varepsilon)V_r^2}{(\phi d_p)\varepsilon} \qquad \text{(II.4)}$$

where

Δ_p = Pressure drop, psi
L = Length of pipe, ft
μ = Viscosity, lb/ft×s
ε = Voidage, dimensionless
V_r = Relative gas-particle velocity, ft/s
ρ_g = Density of gas, lb/ft^3
d_p = Average particle size, ft
ϕ = Particle shape factor, dimensionless

For the Commercial Plant conditions, the fuel gas flow rate is approximately 200 lb/h.

Char Transport (Plant Subsection 5.5). The RPD hopper pressure is regulated to be slightly above the pneumatic transport line pressure. In the base-case design, screw coolers meter the flow rate of char into the pneumatic transport lines. These screw feeder devices use a water-cooled screw and jacket. They have been used commercially to cool and control solids flow with inlet solids temperatures above 1700°F. One application is the removal of ash from fluidized bed combustors. Two screw coolers serve each of the pyrolyzer trains. The char temperature leaving the screw coolers is approximately 600°F. These feeders inject the char into separate pneumatic feed lines that go to the char combustors. Isolation valves with purge systems are located upstream of the feeders to isolate individual feeders and transport lines if they become plugged.

Fuel gas is the transport medium in the char transport lines. This gas is taken from the cooled and filtered fuel gas stream and is regulated with control valves at each transport line. A proprietary correlation developed by Particulate Solids Research Institute (PSRI) was used to size the transport lines and establish the gas-to-solids ratio. Each feeder/transport line is designed to move up to 15,000 lb/h char. The elbows of the pneumatic transport lines are lined with nitride-bonded silicon carbide to prevent wear.

Pyrolyzer Booster Compressor *(Plant Subsection 5.6)*

In order not to exceed the operating limits of commercially available centrifugal compressor, the air is precooled to about 360°F before entering the compressor. The major design specifications for the compressor are as follows:

Number of compressors: two/ parallel
Number of stages per compressor: one
Inlet flow rate per compressor (acfm): 4757
Efficiency (adiabatic %): 82
Motor horsepower per compressor: 790

The selection of this compressor will be carefully investigated to make sure that its operating range and characteristics (e.g., surge and choke limits) will not significantly differ from those for the gas turbine compressor. This will ensure the compatible operation of the two compressors during part-load or overload operations.

The booster compressor design is conventional and is commonly used in the industry for air compression services.

Operating Characteristics

During part-load operation, the gas turbine compressor discharge pressure is reduced as a result of closing the compressor inlet guide vanes and lowering the firing rate. The pyrolyzer pressure is also reduced because it obtains its air from the gas turbine compressor and a booster compressor. This situation is beneficial because it allows reduction in the pyrolyzer throughputs while maintaining a relatively constant superficial velocity in the fluidized bed. This condition is reached in the following manner. As the air pressure is reduced at a given superficial velocity, the mass flow of air drops. Because the coal/air ratio is constant for any bed temperature, coal flow is reduced; therefore, fuel gas and char production decrease.

At 50-percent plant load, the superficial velocity in the bed only drops from 13 to about 12 ft/s; thus the hydrodynamics of the fluidized bed do not change significantly. Likewise, velocities in the cyclones and barrier filter remain relatively constant. Velocity is an important parameter in all these components, so general operation at lower loads will be similar to operation at full load.

At reduced load, the RPD system operates with a smaller pressure differential across the system. The change is automatically accommodated by the operation of the RPD hopper vent valve. This valve is controlled to maintain the proper pressure in the RPD hopper. As the pressure in the barrier filter vessel is reduced, the RPD vent valve closes to maintain RPD hopper pressure. This operation will lower the rate of fuel gas flowing down through the RPD pipe and thereby reduce the pressure drop across the solids in the pipe.

Operating characteristics of the pyrolyzer/char transport system are discussed in the context of total plant operation in Section 2.5.

Maturity of Technology

The pyrolyzer/char transport system uses several technologies that vary in their maturity. The status of the system components and total system configuration issues are addressed in detail in Sections 3 and 4. Alternative configurations are also discussed in these sections.

2.3.6 Gas Turbine/Topping Combustor *(Plant Section 6)*

The use of coal fired HIPPS as the primary combustion system for a combustion turbine requires transporting compressor air to the air heater and hot air/fuel gas back to the turbine combustor. The combustion system must be located in the returning air/fuel path, and some of the turbine accessory systems must be changed from the standard design.

Basically, it is the fuel system and turbine center section that require change; these items are addressed in this subsection. The axial flow is a conventional state-of-the-art 19-stage compressor. The effective flow area of the turboexpander is slightly larger than for current machines; it is designed for a 2350°F gas turbine inlet temperature. No major development programs are required for either the compressor or the expander; they have been provided in standard materials of construction, and a blade life commensurate with oil-fired combustion turbines is assumed.

The combustion zone of the 501F turbine currently in production cannot contain the topping combustion system within the main structural pressure shell. Although the pressure casing can be enlarged both radially and longitudinally to accommodate the topping combustor system as well as its air and air nozzles, the integrity and rigidity of the main shell would be significantly affected. Potential problems with these changes include:

- The dynamic response of the rotor would be compromised because a longer casing means a longer rotor system, a lower critical speed, and increased rotor deflection.
- The enlarged unit could not be shipped as a whole. It would have to be disassembled and reassembled in the field—at greater cost.

Therefore at this time an external topping combustion system is proposed. This entails two topping combustor assemblies placed on opposite sides of the gas turbine, each containing eight combustors. This arrangement is proposed primarily because it was more amenable to fuel gas, heated air, and compressor air discharge line manifolding. The following is a discussion of this proposed arrangement.

Design Specifications and Features

The selected arrangement, which utilizes two topping combustor assemblies, one on each side of the unit, is shown in Figure 28. Half of the air from the air heater enters one end of each assembly (Figure 29). This air then enters an internal plenum chamber in which eight Multi-Annual Swirl Burners (MASBs) are mounted. Fuel gas enters the assembly via the fuel nozzles at the head end of the combustor. Combustion occurs, and the products of combustion are ducted into the main shell for distribution to the first-stage turbine vanes. The annular distribution duct is shown in Figures 30 and 31.

Compressor discharge air leaves the main shell, flowing around the annular duct into the adjacent combustion shells. The air flows around the heated air plenums and leaves each combustion assembly via two nozzles (Figures 28 through 31).

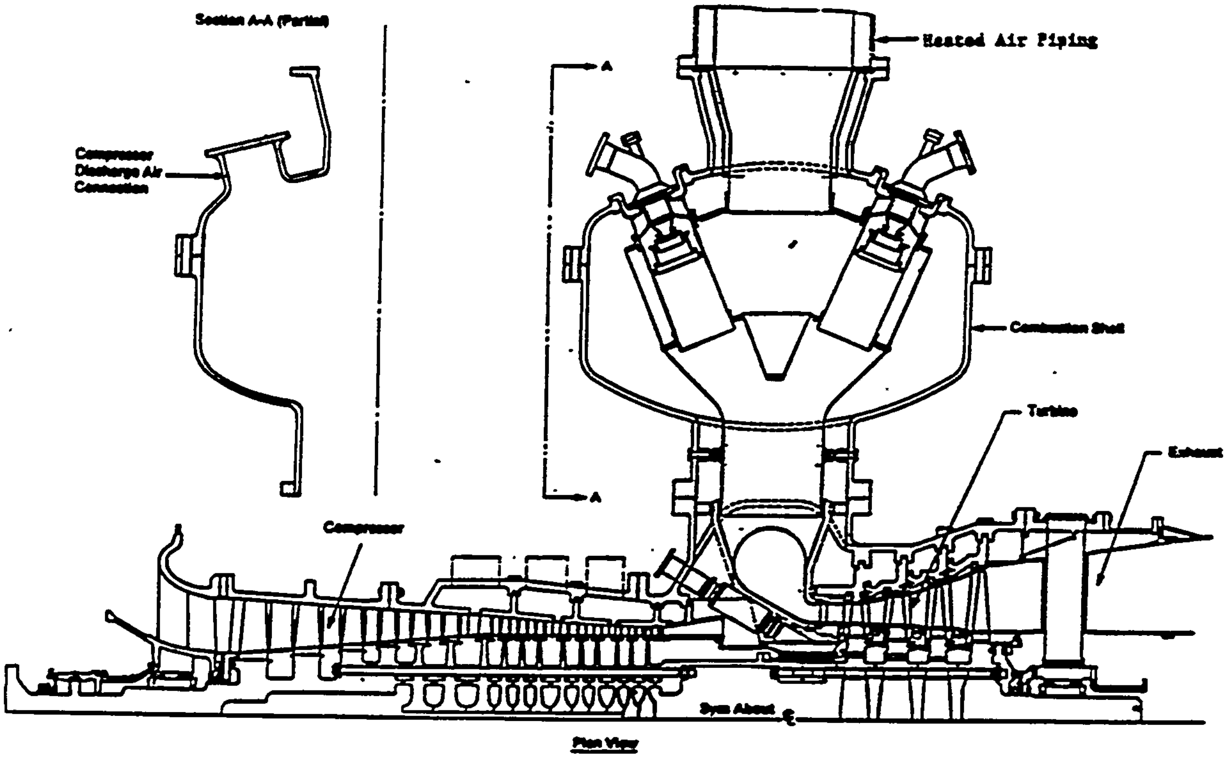


Figure 28 Conceptual Combustion Turbine Arrangement

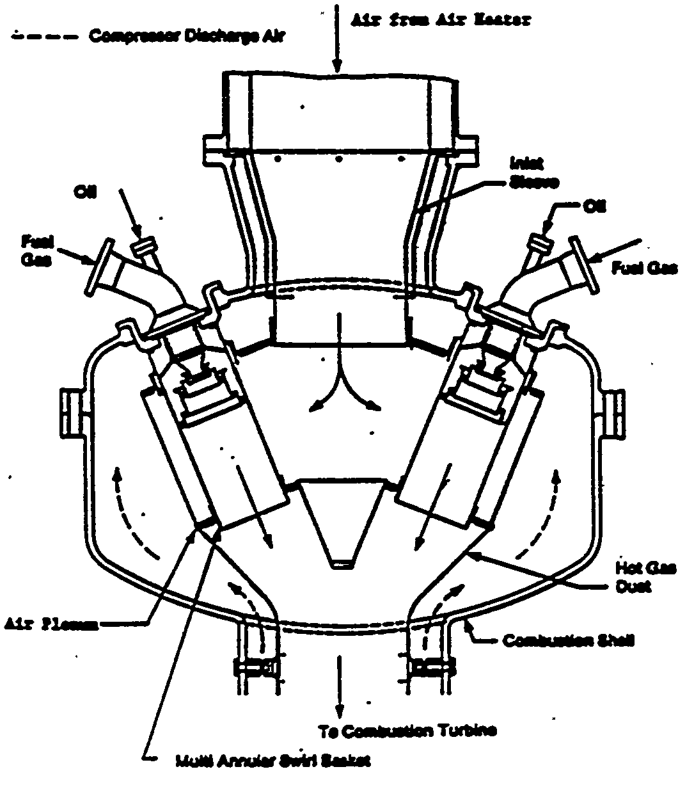


Figure 29 Topping Combustor Assembly

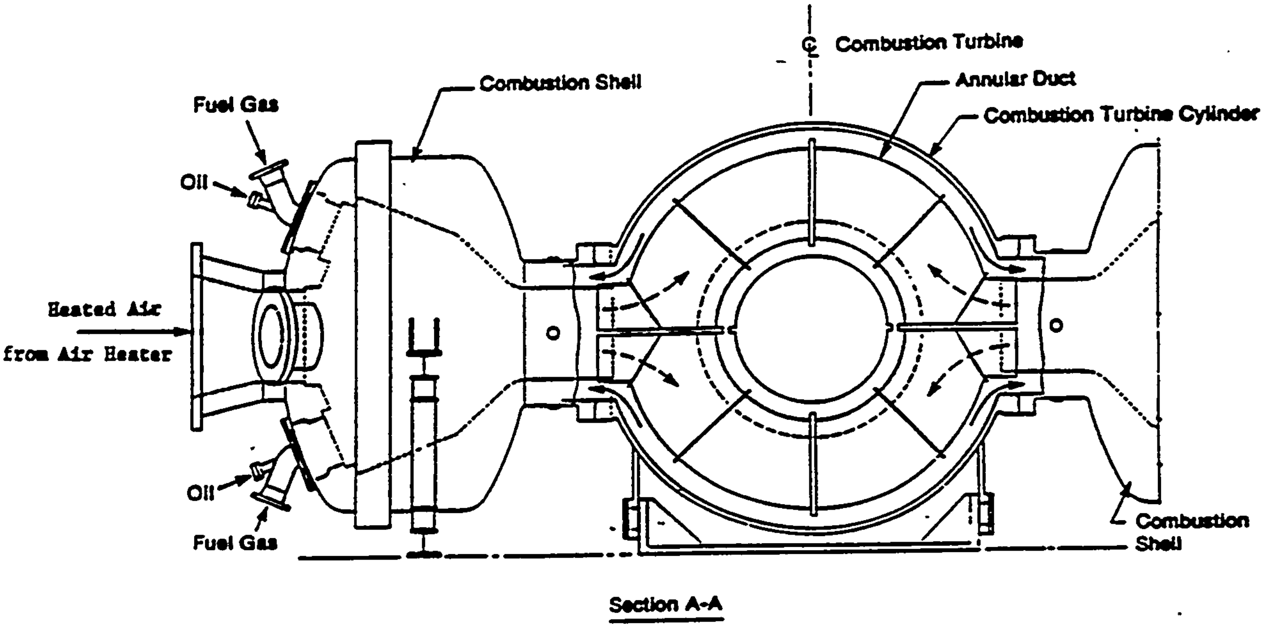


Figure 30 Topping Combustor/Combustion Turbine Arrangement

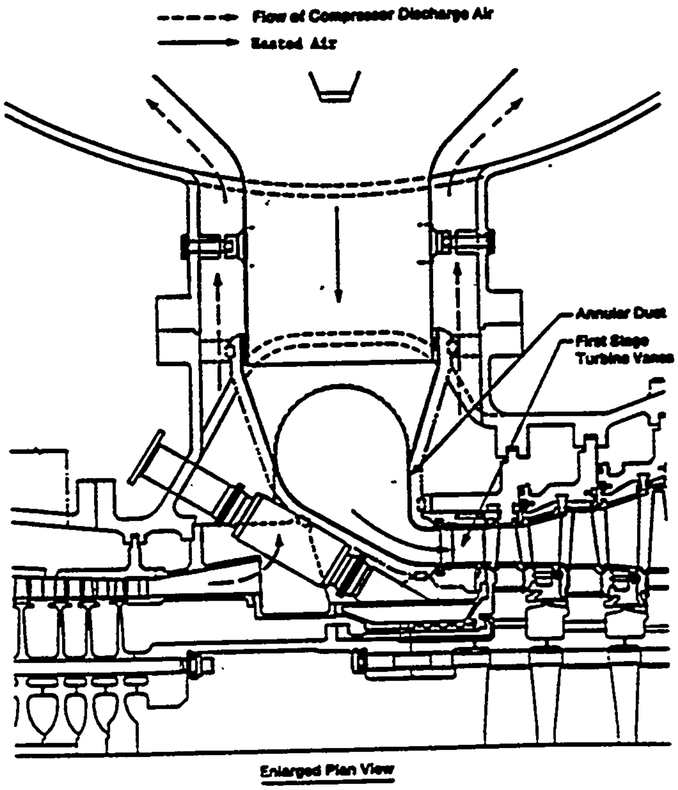


Figure 31 Topping Combustor/Combustion Turbine Interface

The individual burners contained in the two external assemblies are scaled versions of a combustor tested in a DOE-sponsored Second-Generation PFB program. These tests are discussed in section 3.6. The total number of combustors (sixteen) is based on the structural requirement of the turbine casing, the combustion shell and uniform flow distribution to the turbine elements. The diameter of the combustor is based on maintaining the same gas velocity through the combustor as in the test combustor.

The individual components of the fuel nozzle/combustor system are shown in Figure 32. An oil nozzle (for engine start-up), a gas nozzle (for normal operation), the primary swirler, and the combustor (MASB) are the major parts of the system. The path of the air from the plenum to the combustion zone of the combustor via openings in the combustor wall is also shown in Figure 32.

The system is mounted on and supported by a cover plate that bolts to the head end of the combustion shell assembly. The ease of disassembling and maintaining the system is evident in Figure 32. This system is operated on an auxiliary fuel system (oil or natural gas) during turbine start-up, before air heater combustion.

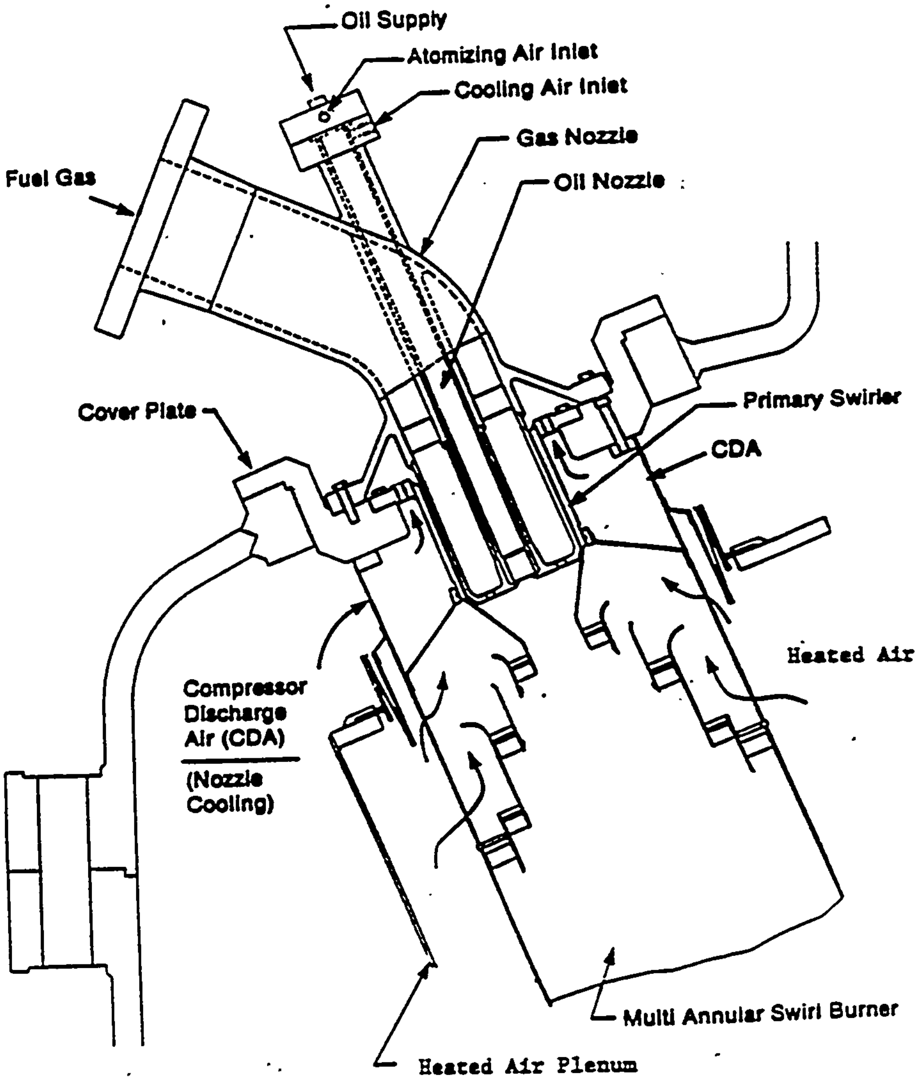


Figure 32 MASB Assembly

During normal operation on oil, when fuel gas is passing through the main nozzle, any oil remaining in the oil nozzle will coke and tend to block the free flow of oil during the next start-up cycle. To prevent coking, an external supply of cooling air is circulated around the oil nozzle to lower its metal temperature below the coking temperature of the oil. As a further aid to prevent coking, the atomizing airflow is kept in operation to blow out any oil residue remaining in the nozzle as well as cool the nozzle when operating with fuel gas.

The combustor/nozzle system is cooled by compressor discharge air flowing through openings in the head end of the combustor, through the primary swirler flange, and out through the annular passage between the fuel nozzle and the primary swirler. Finally, the air impinges against the primary swirler cone.

The combustion turbine fuel system has dual-fuel capability. It can operate with either distillate oil, natural gas or pyrolyzer fuel gas, although the distillate oil is used primarily during start-up. If desired, a dual fuel nozzle can be provided to utilize natural gas for start-up in lieu of distillate and pyrolyzer fuel gas for normal operation.

Operating Characteristics

This basic operation of the gas turbine for the HIPPS application is similar to a standard combustion turbine application.

The Westinghouse Distributed Processing Family (WDPF) will be used with modifications for the HIPPS application. The WDPF can control start-up load following and shut down of the gas turbine.

The MASB design is such that the turndown of the combustor is comparable to a standard commercial combustor. Tests will be conduced to verify turndown capabilities. At this time, by controlling fuel flow and Rich Zone Air Flow the MASB turndown would be in the 40- to 50-percent load range.

Maturity of Technology

The Multi-Annular Swirl Burner (MASB) has undergone continuous improvements for over five years under the sponsorship of the Department of Energy. The size of the MASBs that have been tested were 12-in., 14-in. and 18-in. diameter. The !8-in. combustor is commercial size. These tests have taken place at the University of Tennessee Space Institute (UTSI). In addition to the tests on synthesized fuel gas, the MASB was tested with natural gas, and it performed well on both fuels.

In July of 1994, an 18-in. MASB was tested at UTSI, burning a syngas similar to what will be used at Southern Services Wilsonville demonstration. Wilsonville is presently scheduled for mid 1996 startup. This facility will use a MASB that is connected to a gas turbine. It will be the first test of a complete combustor/turbine/generator system. One Westinghouse MASB will be connected to an Allison 501 gas turbine. This test will be a good demonstration of the system because it contains all the components and the MASB is the same scale as will be required for the commercial plants (except multiple MASB's will be used in the commercial plants).

2.3.7 Steam Turbine/BFW *(Plant Section 7)*

The high-pressure steam received from the boiler island is expanded in a two-casing, single-reheat condensing steam turbine to drive a hydrogen-cooled generator rated for a nominal 170 MWe. The turbine consists of single-flow high- and low-pressure sections in a common casing and a double-flow low-pressure section—all connected on the same shaft. The steam first passes through a main steam stop valve to the turbine high-pressure section, through which it exhausts to the reheater in the HITAF. The reheated steam then passes through a reheater intercept valve to the turbine intermediate-pressure section. The steam further expands through the low-pressure turbine section and exhausts to a surface condenser. The hydrogen-cooled generator comprises the generator, exciter, and auxiliary components for shaft sealing, hydrogen circulation, and CO_2 purging. Additional auxiliary components (including lube oil pumps, filters, blowers, pressure regulators, and instruments and controls) are provided to support steam turbine operation.

The exhaust from the low-pressure steam turbine section is condensed in a shell-and-tube surface condenser by circulating cooling water. The condensate leaves the condenser hot well, entering a condensate surge tank, where it is combined with makeup BFW obtained from the raw water treatment area of the plant (Subsection 11.2). A condensate pump then transfers the total feedwater stream through a condensate heater, where the water is heated to about 174°F by the compressed air fed to the pyrolyzer booster compressor. Approximately 33 percent of the total feedwater is then pumped to the low-pressure economizer section of the HITAF Economizer; the remaining portion flows to the low-pressure economizer section of the Gas Turbine HRSG. Before being pressurized to about 2865 psia and fed to the evaporator sections of the Gas Turbine HRSG and the combustor furnace, the heated feedwater leaving the low-pressure economizers is deaerated using low-pressure steam extracted from the steam turbine.

Design Specification and Features

The major design features and specifications (at full load) for the steam turbine-generator subsystem are summarized in Table 15. The low-pressure section of the turbine has provision for controlled extraction of low-pressure steam for the deaerator and the FGD system. The turbine has high-pressure and intermediate- pressure/low-pressure steam bypass systems that channel steam from the main throttle line to cold reheat and from the hot reheat to the surface condenser during plant start-up, turbine trip, and load rejection.

The surface condenser, a conventional shell-and-tube design, has a divided water box, dished heads, and a hot well with approximately 3 minutes of condensate storage at the rated turbine load. The major design parameters and specifications for the condensate BFW subsystem are listed in Table 16.

The two feedwater pumps are not spared, but each has one spare inner assembly (rotor) that can be slid out for repair or replacement in less than 8 hours.

Table 15 Design Specification and Features: Steam Turbine-Generator Subsystem

Throttle Steam Conditions:	
Inlet Temperature/Pressure	1075°F /2615 psia
Inlet Flow Rate	819,960 lb/h
Reheat Temperature/Pressure	1076°F/420 psia
Exhaust Pressure	0.90 psia
Low-Pressure Steam Extraction	688°F /90 psia
Turbine Nominal Power Output	170 MWe (3600 rpm)
Turbine Gross Power Output (at 60°F amb.)	169.3 MWe
Generator Rating	182,000 kVA; 3600 rpm; 3-phase, 60 Hz, 13.8 kV, 0.8 power factor

Table 16 Design Specification and Features: Condensate BFW Subsystem

Cooling Water Inlet/Outlet Temperature	63/80°F
Condenser	
Duty	787 MMBtu/h
Surface Area	51,050 ft^2
Tube Velocity	8 ft/s
Shell Material	Carbon Steel SA-516
Tube Material	Admiralty SB-111
Tube Length/Quantity	34 ft/5770
Deaerator	Two : 67 psia (min.)/295°F
Feedwater Pump	Two : 2865 psia discharge, 1230 hp (GT econo mizer), 2100 hp (HITAF economizer)
Condensate Pump	One: 1640 gpm, 90 hp
Condensate Surge Tank	One: 50,000 gal, aluminum alloy

Operating Characteristics

During part-load operation, the extraction steam pressure will drop and may eventually be unacceptably low for deaerator use. The design has a provision to use part of the main throttle steam if needed for this use. The steam pressure is controlled by the steam turbine. The pressure slides over most of the operating range, varying with the steam flow through the turbine at full and part loads. Low-pressure steam extraction is uncontrolled to maintain higher turbine efficiency. For 50-percent part-load operation, the inlet throttle steam conditions are approximately 1457 psia/1007°F/801°F, and the turbine exhaust temperature drops to about 87°F, corresponding to a reduced gross power output of about 81 MWe. Condenser duty can be met by the circulating cooling water at full and part loads. Steam turbine operation at 50-percent load results in a condenser load of about 470 x MMBtu/h. The flow of circulating cooling water can be varied to meet this load requirement while maintaining the water inlet at a constant 63°F.

Steam-cycle start-up begins with all the steam drums operating at reduced pressure and steam dumping to the surface condenser through the steam turbine bypass systems. When steam flows and drum levels stabilize, high-pressure steam is fed to the turbine. Pressure is ramped up as load is increased until the design throttle steam pressure (2615 psia) is reached.

Maturity of Technology

All components used in the steam-turbine generator and condensate and BFW subsystems selected for this preliminary design are commercially available and proven. The use of a surface condenser followed by a separate deaerator is common practice in the power generation industry. The more cost effective but less proven design integrating the condenser with a vacuum deaerator will be investigated during the final design stage.

2.3.8 Emissions Control Systems *(Plant Section 8)*

The emission control system consist of SO_2 control, NO_x control, and particulate control. The target emission limits are set at 0.06 lb/MMBtu for SO_2 and NO_2 emissions and 0.003 lb/MMBtu for particulate emissions. This means that that postcombustion SO_2 removal must be better than 98 percent, postcombustion NO_x removal must be better than 90 percent, and particulate removal greater than 99.8 percent.

Figure 33 is a simplified flow schematic of the overall emission control system components and flow streams. As shown, two separate streams, following the pyrolyzer, require slightly different emission control methods. The fuel gas from coal pyrolysis (Stream 2) requires pre- as well as post-combustion pollution treatment, while the flue gas from char combustion (Stream 11) requires only post-combustion treatment. This emission control strategy is necessary to maximize efficiency and minimize cost.

Table 17 gives a summary of the emission control parameters and stream conditions corresponding to Figure 33. It was decided to remove particulates at high temperature from the fuel gas upstream of the gas turbine combustor. The particulate filter (barrier filter) is comprised of multiple sintered-metal candle elements that can withstand high temperature while providing a large surface area in a relatively small volume. These filter elements have demonstrated particle collection efficiency exceeding 99.9 percent. On the char side, approximately 80 percent of the ash and sorbent solids are removed in the combustor as slag material. The remaining particulates and nitrogen oxides are removed using a combined filter and NO_x reduction unit comprised of a high-surface-area ceramic filter whose filter elements are coated with a NO_x reduction catalyst. Sulfur dioxide control is accomplished for both the vitiated air and flue gas streams using a wet lime scrubbing process that produces a stabilized calcium sulfite solid waste.

According to Title III of the Clean Air Act Amendments of 1990, any stationary source emitting 10 tons per year of one air toxic or 25 tons per year of a combination of air toxics shall be considered and designated as a major source. Many coal fired utility plants may fall into this category. While not specifically identified as a targeted emission for Combustion 2000, the maximum reduction of air toxics contained in the flue gases of the HIPPS system is a team goal.

Although the actual data of heavy metal emissions of coal burning plants is still being collected by the EPA, the potential exists that the emissions of fine particulates from coal burning will contain the majority of the heavy metals emitted. Most of the particulate emissions of heavy metals such as zinc, beryllium, chromium, nickel and copper are emitted in a solid form of the metal itself or its various oxides. The final emission of these metals is therefore directly proportional to the actual total particulate emission provided that their distribution is uniform among the particulates. These particulate emissions also include oxides of metals such as lead and arsenic which volatilize during combustion and subsequently condense in the downstream and arsenic which volatilize during combustion and subsequently condense in the downstream equipment on cooling and before the final particulate collection equipment. These are predominately concentrated in the 0-2 micron range. The total particulate emission limit of 0.003 lb/MMBtu and the use of particle removal by filtration will help insure that heavy metal emissions are limited to the smallest possible value.

The emission control system of the HIPPS plant consists of the following plant units:
Fuel gas particulate control (high temperature filtration) (5.4)
Gas turbine exhaust NO_x control by SCR (8.3)
Flue gas particulate control and NO_x control (8.1/8.3)
Flue gas SO2 control (8.2)

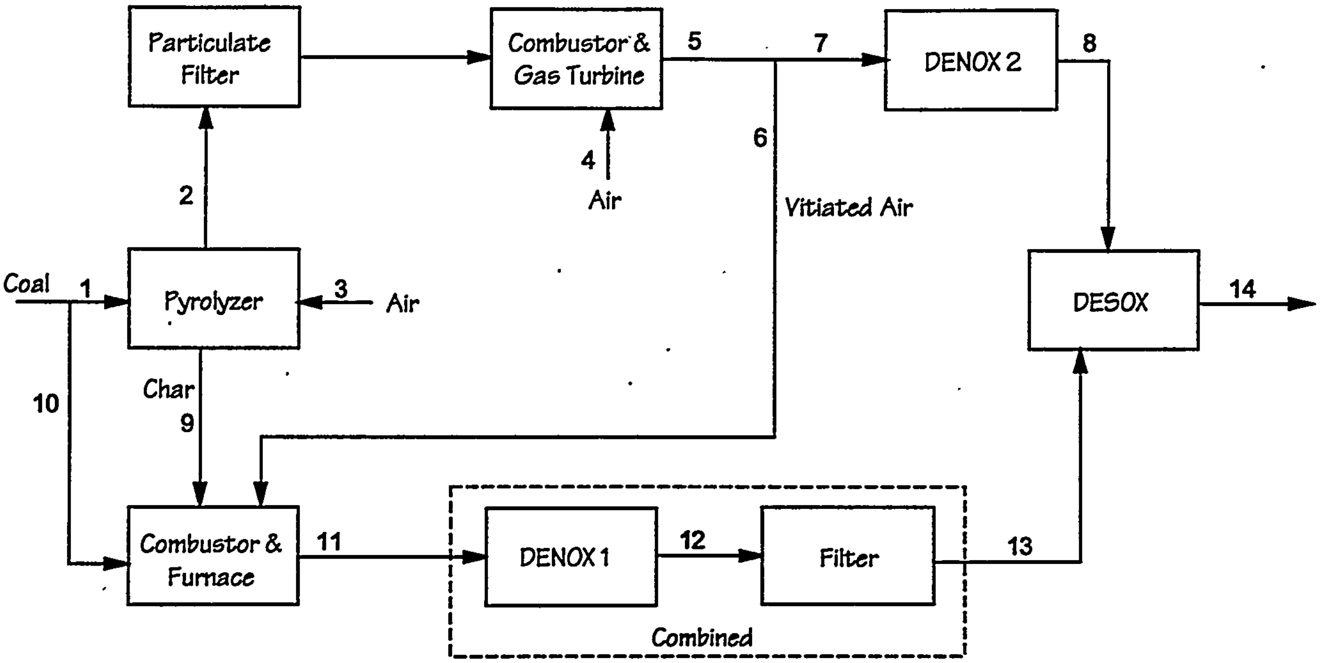


Figure 33 All Coal HIPPS Emission Control Flow System

Table 17 Emission Summary

Emission Control Parameters		Emission Rates	
			lb/10º Btu
Wet coal percent ash	7.72	SO_2	0.059
Wet coal percent sulfur	2.24	NO_2	0.052
CaS to pyrolyzer	1.7	Particulates	0.0026
Percent S to H_2S	6		
Combustor percent ash capture	80		
Fuel gas particulate removal, %	99.9		
Flue gas particulate removal, %	99.9		
SO_2 removal, %	98.7		
NO_x removal, %	90		

Emission Flow Streams

Stream	Flow klb/h	Pressure psia	Temperature F	S lb/h	NO_2 lb/h	Particulate lb/h
1 Coal+Sorbent	227.9	258	70	4743	0.0	32610
2 Fuel Gas	587.6	230	1100	315.6	0.0	4.5
3 Air	427.3	265	410	0.0	0.0	0.0
4 Air	2880.0	14.6	60	0.0	0.0	0.0
5 Vitiated Air	3463.6	16.1	1121	277.5	1181	4.5
6 Vitiated Air	1100.8	15.8	1050	88.0	375	1.3
7 Vitiated Air	2362.6	15.4	891	189.5	805.0	3.2
8 Vitiated Air	2361.9	15.1	210	189.1	77.0	3.2
9 Char	71.7	25	600	4464	295.9	28799
10 Coal	16.5	25	70	474.0	90.5	1636
11 Flue Gas	1202.5	13.6	806	5023	391.0	5391
12 Flue Gas	1202.2	13.5	806	5023	39.0	5391
13 Flue Gas	1196.8	13.4	266	5023	39.0	2.7
14 Stack Gas	3702.4	14.7	126	66.5	116.0	5.9

2.3.8.1 Fuel Gas Particulate Control

We have seen that 99.9 percent must be removed from the fuel gas in order to achieve the overall emission limit of .003 lb/MMBtu. This level of particle capture mandates the use of hot gas filtration. Fuel gas particulate filtration at 1100 °F allows for more materials choices and simpler engineering design than is allowed at higher temperatures. Ceramic and certain sintered metal media are now available for filtration at temperatures higher than 1200 °F; however, at these temperatures alkali attack may pose a problem, especially for ceramic filter media. The design proposed for the barrier filter is based on Pall Corporation's Gas Solid Separation (GSS) system which uses candle filter elements, manufactured from sintered powder metal, with sufficiently small pores to effectively retain solids at or near the filter surface.

Design Specifications and Features

The construction of the GSS filter system consists of a vertical pressure vessel that houses a tubesheet assembly that holds the candle filter elements as schematically shown in Figure 34.

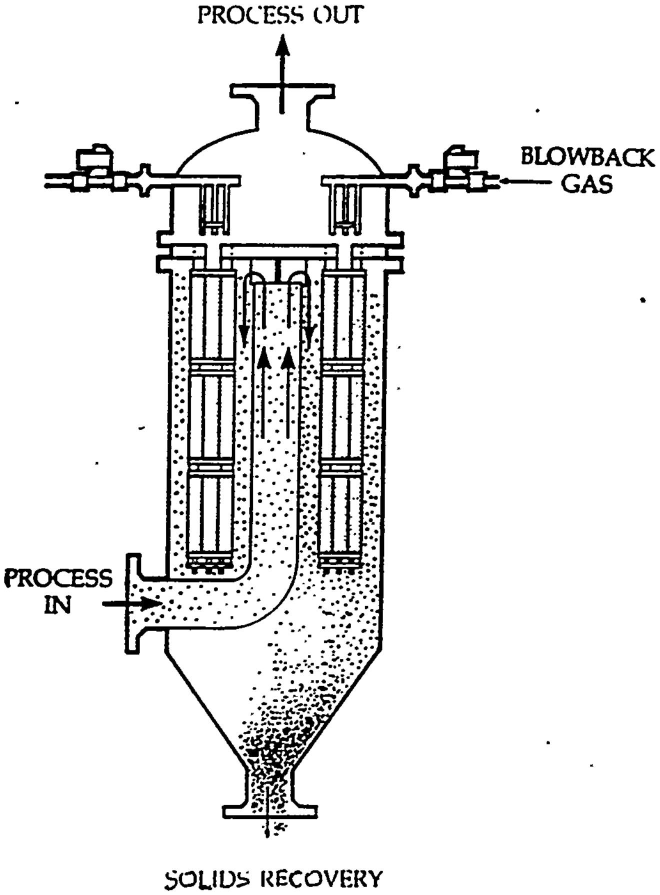


Figure 34 Barrier Filter Assembly

The filter medium chosen for the design is manufactured by a patented method from Iron Aluminide sintered powder; this porous metal filter medium has the following characteristics:

- Optimum pore size distribution to collect particles on the filter's surface and prevent particle penetration into the depth of the medium.
- A uniform distribution of the interconnected pores representing up to 60 percent of the filter medium's volume.
- A very high efficiency of particulate capture. Typically, more that 99.99 percent of the solids are removed on the surface of the filter medium. The pore dimensions are carefully controlled and do not change in service.
- Physical strength and durability to withstand the cyclical loads applied during cleaning cycles.
- Chemical and thermal compatibility with the fuel gas process conditions to ensure long life.

In operation, the particulate-laden fuel gas flows upwards through a central pipe and then flows downwards around the filter elements; this downdraft design assists the settling and discharge of the accumulated solids. The flow rate of the gas per unit of filter area is set to allow for the formation of a permeable cake of solids which is dislodged at a predetermined pressure drop by initiating a reverse flow. The dislodged solids are discharged through the a conical hopper at the bottom.

To dislodge the solids, groups of filter elements are blown back sequentially by directing a high-pressure pulse of gas into the throat of each element for a period of one second and at 2-3 times the process pressure. The shock wave set up by the reverse pulse (enhanced by a venturi in each element throat), effectively removes the accumulated cake from the filter element and then the filter elements are returned to full forward flow and to a pressure drop which remains essentially constant through repeated blowback cycles. To maintain continuous fuel gas flow in the vessel, the total number of filter elements are divided into equal sections. At a predetermined pressure drop (or timer default) the sections are blown back sequentially. As each section is blown back, fuel gas flow to the elements in that section is automatically redistributed to the balance of the vessel.

The commercial plant fuel gas flow of 587,500 lb/h at 240 psia will require approximately 3500 sq. ft. of filter surface area; two pressure vessels each providing half of this filter surface area will be required. Complete specifications of the GSS filter system is given below.

Barrier Filter Specifications

Item	Value
Inlet flow rate	29,015 acfm
Particulate loading	5270 lb/h
Filtration efficiency	99.9%
Filter element size	2.37" dia. x 57"
Filter element area	3 sq. ft.
Gas face velocity	7 fpm
Pressure drop	1.5 psi
Jet pulse blowback duration	1 second
Number of elements per vessel	680
Number of vessels	2
Element material of construction	Iron Aluminide
Vessel material of construction	Carbon steel (lined)
Tubesheet material of construction	347 Stainless steel
Blowback gas	Dry nitrogen or equivalent

Maturity of Technology

Pall GSS filter systems have been commercially operating in the chemical, petroleum, and mineral industries for many years. The Iron Aluminide filter medium is a relatively recent development; this medium has been extensively tested in Pall's pilot facility at process conditions similar to the one used here.

Alternative Technologies

Ceramic filters elements of varying constructions potentially offer the possibility of more compact and less costly filtration systems. However, proven operation of these filters at temperatures above 1200 °F still remains. Various constructions are now available such as the Vitropore candle filters manufactured by Pall for their GSS filter systems; the CeraMem honeycomb ceramic monoliths, and the Westinghouse cross flow ceramic filters.

2.3.8.2 Gas Turbine NO_x Control by SCR

Nitrogen oxides must be reduced by at least 90 percent in both the gas turbine exhaust and downstream of the char combustor. Only selective catalytic reduction (SCR) of the NO_x can achieve this level of reduction, and as a result this technology is utilized for both deNO_x applications

Design Specifications and Features

The selective catalytic reduction process uses ammonia (NH_3), in gaseous form, which is diluted with air to about 5 percent by volume and injected into the flue gas stream. The NH_3 reacts with the NO_x, in the presence of catalyst, at reaction temperatures ranging between 600°F and 750°F, as shown in the equations below. The catalyst used in this process is generally a vanadium compound impregnated on a honeycomb substrate.

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$

$$4NH_3 + 2NO_2 + O_2 \rightarrow 3N_2 + 6H_2O$$

Excess ammonia in the flue gas combines with the SO_3 in the flue gas to form ammonium bisulfate and ammonium sulfate as shown in the equations below:

$$NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4$$

$$NH_4HSO_4 + NH_3 \rightarrow (NH_4)_2SO_4$$

Ammonium bisulfate liquefies at about 410°F. This can lead to increased pressure drop and eventual plugging of downstream heat exchangers.

The SCR catalyst also catalyzes SO_2 to SO_3 in the presence of oxygen. This conversion rate can range from 1 percent to 3 percent. SO_3 formation is a function of the initial SO_2 concentration, space velocity and process temperature. High temperatures and low space velocities promote SO_3 formation.

A space velocity of 3000 hr^{-1} will be needed to provide 90 percent NO_x reduction and to keep ammonia slip under 5 ppm. This represents about 24,000 ft^3 of catalyst, which can be contained in a housing of dimensions approximately 50 ft x 50 ft x 50 ft.

Maturity of Technology

The SCR technology is a very mature technology with hundreds of worldwide applications on boilers and turbines. The technology is commercially offered by scores of vendors and catalysts are available from several large suppliers.

2.3.8.3 Flue Gas Particulate and NO_x Control

Particulate and nitrogen oxides removal efficiencies of 99.95 percent and 90 percent in the flue gas stream are required in order to achieve the program goals of 0.003 and 0.06 lb/MMBtu respectively for particulate and NO_2. The SCR must again be specified in order to obtain the needed NO_x removal efficiency. A filter or an electrostatic precipitator would be capable of 99.95 percent control, but a new technology, combining particulate and NO_x control, is now available and is selected for this application.

Design Specifications and Features

A control technology capable of combined removal of particulate and nitrogen oxides is proposed to be located upstream of the economizer. This technology consists of ammionia injection into the flue gas, followed by a CeraMem ceramic filter. The construction of this filter is based on use of porous honeycomb ceramic monoliths. These high surface area, low cost materials are widely used as catalyst supports for automotive catalytic converters. The monoliths have a multiplicity of cells, or passageways, that extend from an inlet face to an opposing outlet end face. This structure is adapted to function as a filter by plugging every other cell at the upstream face of the structure with high-temperature cement. Cells which are open at the upstream face are plugged at the downstream face. Gas is thereby constrained to flow through the porous cell walls as shown in Figure 35.

To filter particles from the flue gas, the device described above is modified by applying a ceramic microporous membrane to the inlet cell wall surfaces. This creates a composit filter which can be operated as a backpulsable surface filter. The thin membrane coating has a pore size approximately 100-fold finer than that of the monolith support. Thus the retention efficiency of the filter for fine particles is determined by the membrane pore size. By keeping the membrane thin (ca. 50 microns), the resistance to gas flow is kept low. Because it is coated by the membrane, the pores of the structure do not become plugged by particulate matter.

In operation, ash-laden flue gas flows into the inlet cells. Particulates are collected on the membrane surface and the filtered flue gas exits the module via the downstream cells. As particulate material accumulates on the membrane surface, pressure drop increases to a preselected level at which time the filter is isolated for cleaning by backpulsing from the downstream end of the filter.

When used for NO_x control, an SCR coating is also applied to the filter surface. This catalytic filter combines the advantages of a conventional SCR reactor and a fine particulate filter in a single compact device. This device is similar to the fuel gas particulate filter described above but is further coated with a suitable NO_x SCR catalyst. The SCR catalyst coating is located "downstream" of the membrane coating itself. This location allows the catalyst to function in a dust free environment, ie., in the absence of fly ash.

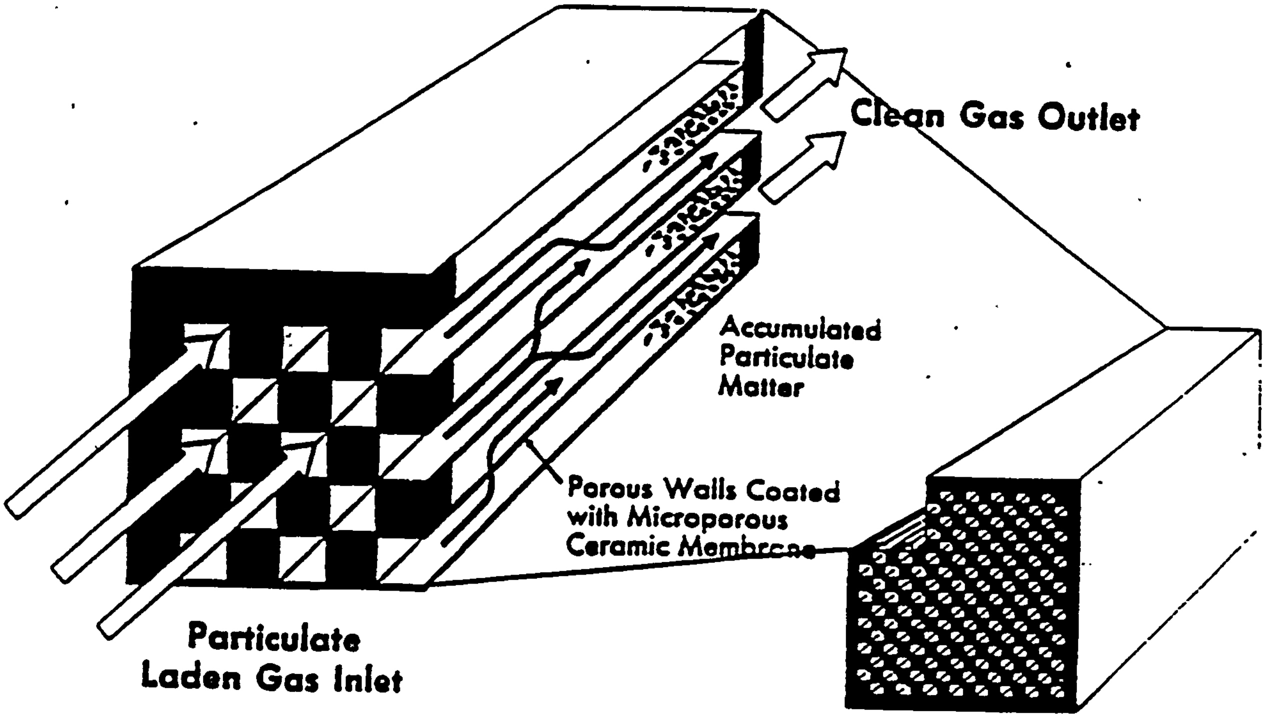


Figure 35 Gas Flow Through Porous Cell Walls

The catalytic filter is used in a two-step process. The first step is filtration to remove particulates. This is followed by the second step, the catalytic reduction of NO_x in the particulate-free gas as it passes through catalyst coating. This flow path for the flue gases differs from that of typical channel flow SCR devices. The flue gas flow is "dead-ended" in the catalytic filter, i.e, the flue gas passes through the membrane coating, then the SCR catalyst coating. This flow path for the flue gas substantially eliminates bulk-diffusion and pore-diffusion limitations that exist in channel flow SCR catalyst configurations. Tests have demonstrated that greater than 90 percent NO_x can be removed at space velocities three times higher than those used by conventional SCR systems at particulate collection efficiencies greater than 99.99 percent.

A face velocity of 5 ft/min is required. For a filter surface area to frontal area ratio of 72, a total filter frontal area of 1700 sq ft is needed. The best arrangement of the filters would be mounted on diagonal tube sheets. Four modules would be required, each containing a 22 ft x 22 ft tube sheet on a 45° diagonal.

Maturity of Technology

This CeraMem technology has only been tested in bench scale experiments. Results have been encouraging.

Alternative Designs

The alternative design is NO_x control by means of conventional SCR and subsequent particulate control by means of conventional fabric filter. These technologies are capable of meeting the emissions limits, but together would be larger and more expensive than the proposed CeraMem system.

2.3.8.4 SO_2 Control

A wet FGD system is proposed for SO_2 control; the FGD system uses a magnesium-enhanced lime process. This process, licensed by Babcock & Wilcox, can achieve SO_2 removal of 99 percent and has shown high operating reliability and relatively low power consumption in currently operating power generation installations totaling more than 5700 MW of generating capacity.

Figure 36 is a schematic of the process flow diagram for the FGD system. The HITAF flue gas leaving the LP economizer is pressure-boosted through an ID fan and is combined with the gas turbine flue gas leaving the HRSG economizer, and the combined stream enters an absorber tower (scrubber) which uses magnesium-enhanced lime slurry to absorb 98.7 percent of the SO_2 in the gas. The absorber tower features counterflow-liquid/gas contact and a patented perforated tray design that provides even gas distribution across the tower, ensuring complete gas/slurry contact, plus providing a surface of intimate contact between the gas and slurry. The even gas distribution provided by the tray also relieves the mist eliminator of localized high gas velocity upsets. The tray also provides a natural platform for inspection of the tower internals.

The lime slurry preparation unit includes two 100 percent redundant ball mills to supply the FGD system with the slaked lime reagent. One mill slakes approximately 5 tons per hour. The milling system also grinds the pebble lime and inerts to the design particle size. Using a ball mill rather than paste slakers eliminates the need for a separate grit handling and disposal system.

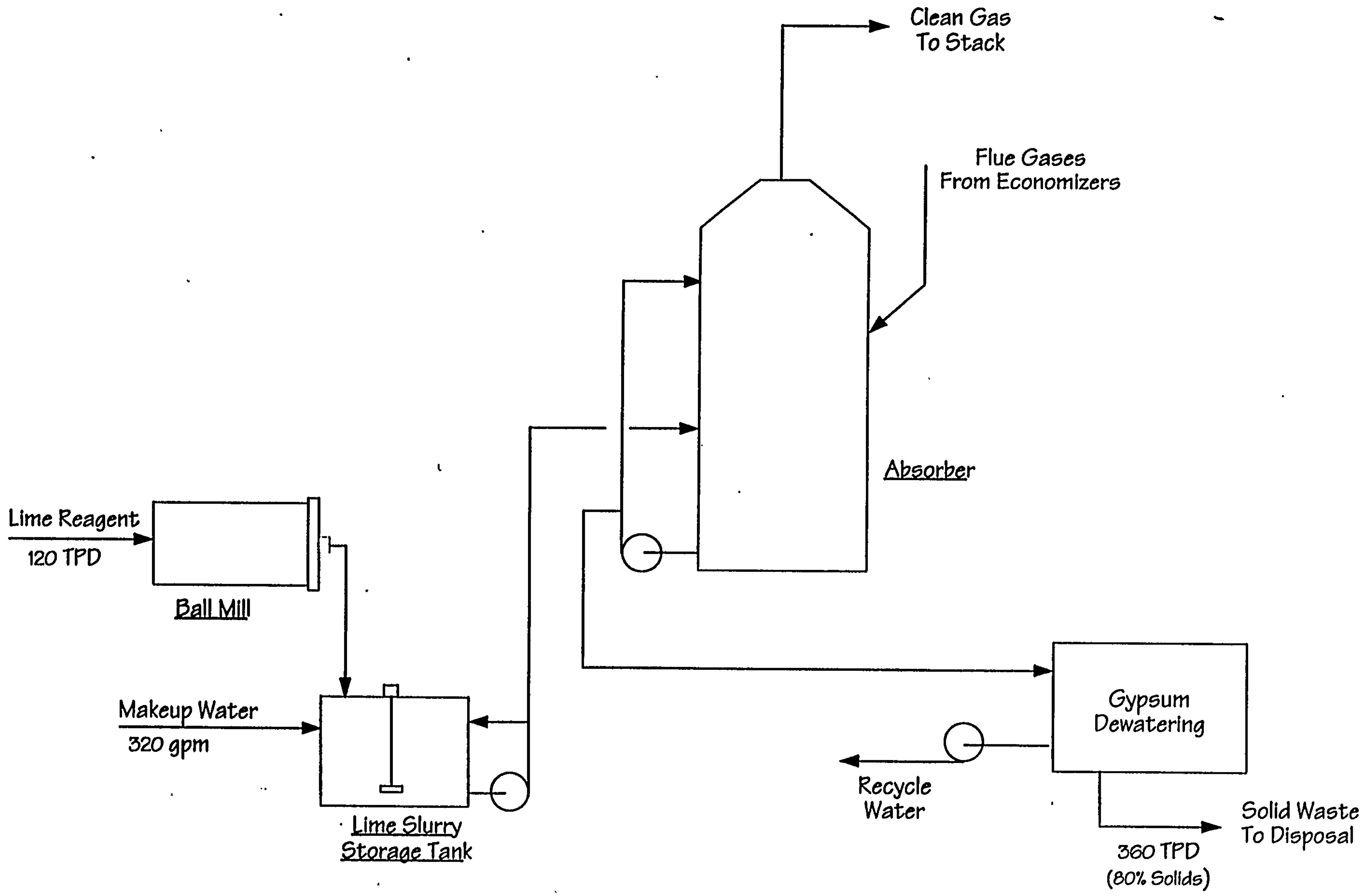


Figure 36 Magnesium-Enhanced Lime FGD System

A dewatering unit, consisting of hydroclones and vertical basket centrifuges is designed to concentrate the spent slurry from the absorber vessel to approximately 80 percent (by weight) solids. Production of this solid waste material is estimated to be about 15 tons per hour. The dewatered solid waste material is stacked on a pad and then hauled for offsite disposal.

Process Chemistry and Design Features

The magnesium-enhanced process depends on the relatively high solubility of the alkaline species (SO_3, HCO_3, CO_3) of magnesium compared to their calcium counterparts. The magnesium enhanced lime liquor contains 10 to 15 times more dissolved alkalinity in solution than calcium-based process liquors. The high solubility of magnesium salts allows high concentrations of soluble sulfite ions, which reduces the concentration of calcium ions in solution. The chemistry is more complex than limestone or lime systems due to magnesium alkalinity and regeneration of sulfite within the absorber and reaction tank.

Briefly, SO_2 reacts with the soluble magnesium sulfite ions to form magnesium bisulfite. A portion of the bisulfite precipitates as calcium sulfite. The remaining portion reacts with calcium hydroxide to regenerate magnesium sulfite for further reactions. The SO_2 is therefore removed from the reaction medium primarily as solid calcium sulfite. The magnesium sulfite stays in solution to scrub the gas and maintain the solution alkalinity.

In the magnesium enhanced process the soluble alkaline magnesium species promote SO_2 mass transfer through the gas-liquid contact. The rate limiting step of the reaction in this system is the rate of diffusion of the gas into the liquid phase. In contrast, the rate limiting step in a lime or limestone-based system is the rate of dissolution of the calcium salts to form soluble ions available for scrubbing. This rate of dissolution is much slower than the gas-liquid diffusion rate.

With sufficient liquid-phase alkalinity, the equilibrium SO_2 concentration at the gas-liquid interface is essentially zero. This means that the design of the system is based upon obtaining sufficient interfacial surface area for the desired mass transfer with the least energy. The design of the scrubber trays provide intimate contact between the gas and the liquor. As a result, the process achieves high removal efficiencies on high sulfur coal with low tray pressure drop, low L/G, and low nozzle pressure compared to calcium-only-based systems. Consequently, the power consumption for the magnesium-enhanced lime system is typically less than half that for limestone forced oxidation systems. The total power consumption for the proposed FGD system is about 2300 kW.

The FGD system can be designed to enhance the settling of calcium sulfite so it can be dewatered in a cost effective manner. Controlled oxidation or even full oxidation to gypsum can be accomodated to achieve this goal. Refer to Section 3.7 for more detailed discussion.

2.3.9 Balance of Plant

The balance of plant consists of:

- Solid material handling systems
- Water supply and treatment systems
- Support systems
- Civil/Structural

These systems are described in the following sections:

2.3.10 Solids Material Handling *(Plant Section 10)*

This subsystem includes the equipment needed, outside the power island, for in-plant transportation and storage of the coal/limestone feeds and handling and disposal of ash/slag.

Coal Receiving and Handling *(Plant Subsection 10.1)*. This subsystem is designed to receive coal delivered in railcars. It includes coal storage and reclaim facilities. It also includes conveyors to transport the coal reclaimed from storage to the pulverizers used in the coal preparation and feeding subsystem (*Plant Section 1*). Figure 37 is a flow diagram of the subsystem. Coal is assumed to be delivered precrushed at a top size of 2 in. in 30 bottom-dumping railcars, each with a 100-ton capacity. Coal is unloaded through dump hoppers and vibrating feeders to a conveyor that delivers it to an above-ground sampling and transfer station, from which it can be directed either to the active storage silos or to emergency pile and inactive storage. Coal is reclaimed from the active storage silos using two sets of vibrating bin activators and reclaim feeders and is transported to mill feed bins from which it is fed to the coal preparation area in the power island. To control fugitive dust during the coal unloading operation, a chemical dust suppression unit using surfactant and water dosing and spraying is provided. Facilities are provided to collect storm water run-off from the emergency and inactive coal storage piles and deliver it to the effluent water treatment area of the plant.

Sorbent Receiving and Handling *(Plant Subsection 10.2).* In this subsystem, limestone is delivered by dump truck, crushed to a 1/2-in. top size, and stored in silos before being supplied to the sorbent pulverizers in the power island. Figure 38 is the flow diagram for this subsystem. Trucks unload the limestone (2-in. top size) through a hopper to a hammermill crusher, from which the crushed product is delivered by a bucket elevator and a conveyor to storage silos. To meet plant demand during prolonged interruptions in limestone supply, additional as-received limestone is held in an open and inactive pile beside the dump hopper. All limestone transfer points are equipped with baghouse dust collectors and exhausters to minimize fugitive emissions.

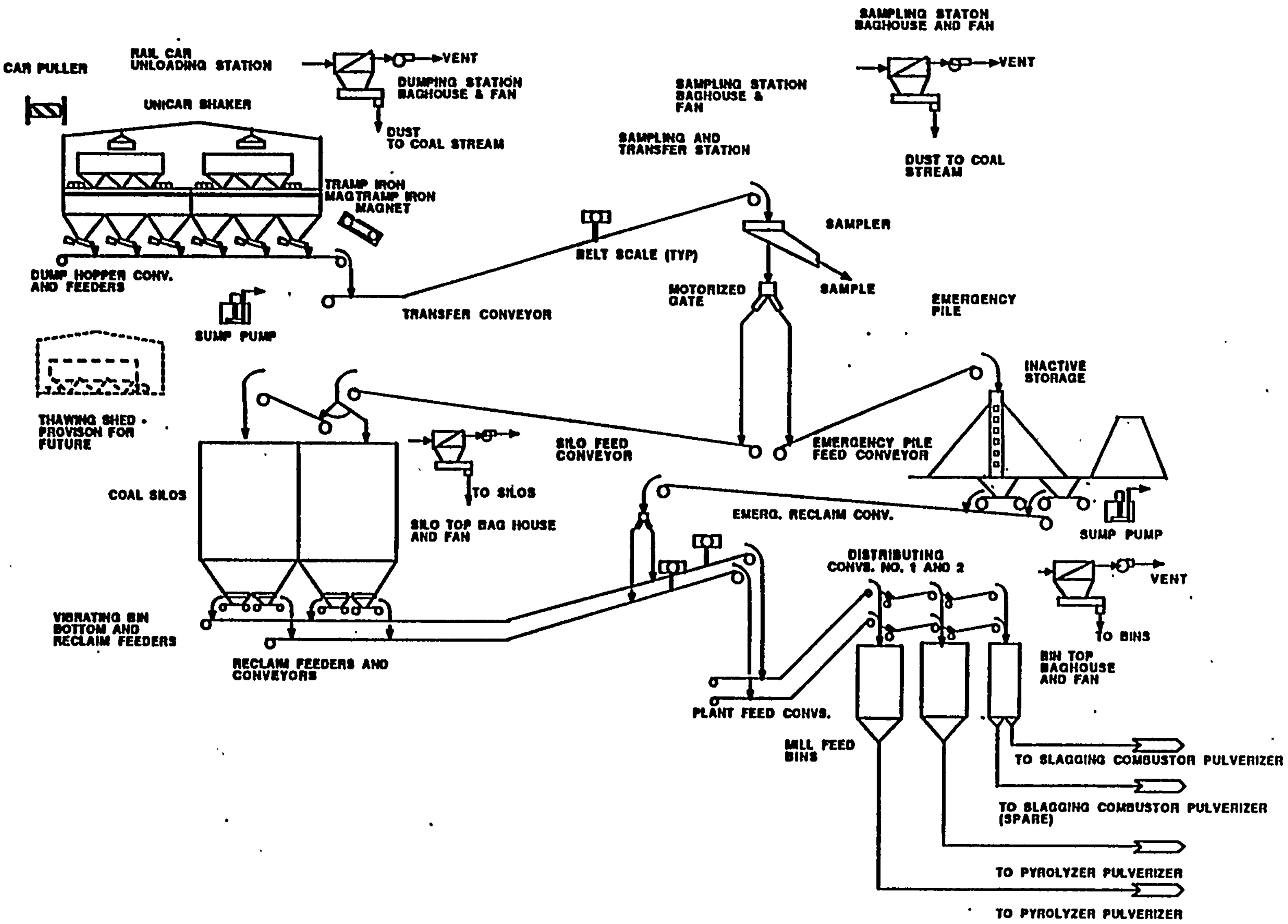


Figure 37 Flow Diagram: Coal Receiving and Handling

Ash and Slag Handling and Disposal *(Plant Subsection 10.3).* This subsystem includes the equipment (outside of the power island) for in-plant transportation, temporary storage, and unloading of the fly ash and slag by-products. Plant Subsection 10.3 contains the equipment required for this subsystem; Figure 39 is the process flow diagram. As shown, cooled, crushed, and dewatered slag from the slag-collecting conveyor in the boiler island is conveyed to a slag loading bin under which two vibrating feeders load the slag into trucks for offsite disposal. Fly ash collected in the power island baghouse is first cooled to about 300°F and then pneumatically transported by air to a loading bin, where the air is separated from the ash and is vented through a dust collector at the top of the fully enclosed bin. Rotary feeders load the collected fly ash into trucks for offsite disposal. A small amount of water reduces dusting during loading.

Design Specification and Features

Coal Receiving and Handling. The coal unloading unit is designed for a maximum unloading rate of 1000 t/h, which is adequate for unloading two trains during a single shift. The compacted inactive storage pile is designed to hold a 90-day supply of coal. The entire reclaim facility consists of two identical trains—each rated at 120 t/h. The major design parameters and specifications for this subsystem are listed in Table 18.

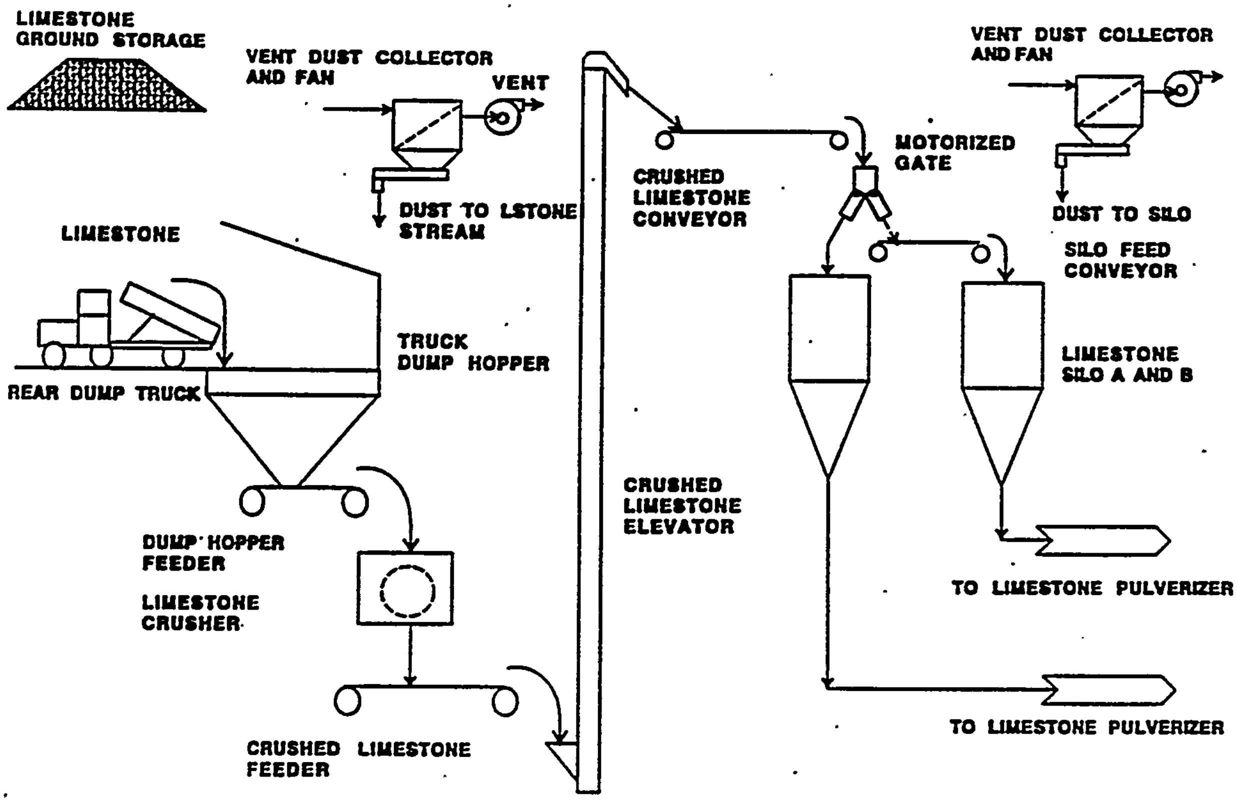


Figure 38 Flow Diagram: Sorbent Receiving and Handling

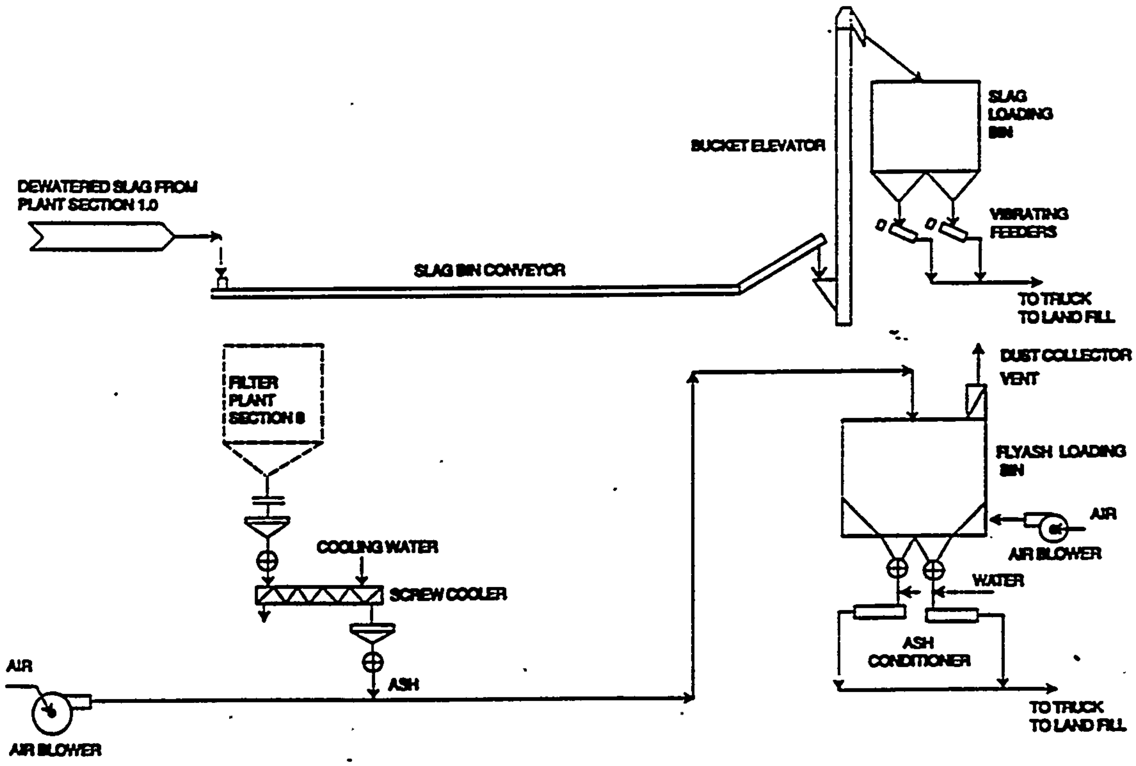


Figure 39 Ash and Slag Handling and Disposal

Table 18 Design Specifications and Features: Coal Receiving and Handling

Received Coal Size	2 in x 0 (unwashed)
Coal Consumption	2170 t/d
Dump Hopper	Two: 80 tons (each), concrete and steel plate
Active Storage Silos	Two: 7200 tons (each), concrete with steel cone
Pyrolyzer Feed Bin	Two: 360 tons capacity (each), steel
Combustor Feed Bin	One: 60 tons capacity
Dust Collectors	Four: 6000 ft^2 filter area and 3 hp (each)
Motorized Gate	Seven: 2 hp (each)
Dump Hopper Feeder	Six: Vibrating type, adjustable capacity to 350 t/h, 10 hp (each)
Silo Bottom Feeder	Four: Vibrating type, 10 hp (each)
Reclaim Feeder	Four: Belt type, 60 t/h, 5 hp (each)
Emergency Reclaim Feeder	Two: Belt type, 120 t/h, 10 hp (each)
Sump Pump	Two: 150 gpm, 5 hp (each)
Pile Run-Off Pump	Two: 300 gpm, 10 hp (each)

Sorbent Receiving and Handling. The major design parameters and specifications for this subsystem are listed in Table 19.

Table 19 Design Specifications and Features: Sorbent Receiving and Handling

Received Limestone Size		2 in. x 0
Limestone Consumption		195 t/d
Hourly Unloading Rate		45 t/h
Dump Hopper	Active	One: 25-ton capacity, concrete and steel plate
Storage Silos	Limestone	Two: 225 ton (each), steel construction
Crusher		One: Hammermill, 30 t/h, 20 hp
Dump Hopper Feeder		One: Belt type, 30 t/h, 3 hp
Inactive Storage		Open pile, 30 days of storage

Ash and Slag Handling. Ash and slag loading operations are scheduled for one shift a day, 5 days a week. The loading bins are adequately sized to hold the slag or ash generated during the weekend, when truck loading is suspended. The slag and ash bin-bottom feeders are adequately sized for fast loading of 20-ton trucks to reduce the turnaround time for the trucks. The major design parameters and specifications for the ash and slag handling subsystem are listed in Table 20.

Table 20 Design Specifications and Features: Ash and Slag Handling and Disposal

Slag and Fly Ash Total Production Rate	26,900 lb/h
Slag-to-Fly Ash Assumed Ratio	4
Slag	
Design Flow Rate (maximum)	20 t/h (wet basis)
Maximum Particle Size	1 in.
Loading Bin Capacity	420 tons
Vibrating Feeders (number/capacity)	Two: 50 t/h (each)
Fly ash	
Design Flow Rate (maximum)	5 t/h
Maximum Temperature	300°F
Particle Size (assumed)	95% <200 microns
Bulk Density	40 lb/ft^3
Loading Bin Capacity	105 tons
Fluidizing Blower	One: 5 HP motor
Screw Cooler	One: Water-jacketed 950,000 Btu/h

Operating Characteristics

The coal and sorbent handling subsystem is designed to operate at full or part load, using the variable capacity feeders provided at the head of each respective transport point in the subsystem. Emergency stop switches are provided along conveyor runs to stop the conveyor at any instant. When a conveyor is stopped with the emergency switch, sequence controls provided in the electrical control circuit will stop all other conveyors and feeders that feed into it in an orderly manner. This procedure will prevent accumulation of coal at the transfer points. All conveyors can be restarted in a fully loaded condition.

The ash/slag transport system included in this subsection is designed with adequate safety margins to allow for variations over the calculated rate at which the ash/slag materials are produced when the generating plant operates at the maximum burn rate. The system will operate satisfactorily at any rate below this maximum. Start-up and normal shutdown of the pneumatic fly ash transport system is set to automatic controls based on ash levels in the feeding hoppers and the loading bin. The mechanical conveying equipment for slag handling is electrically interlocked; it is started up in sequence, with the last unit in the equipment chain (the bucket elevator) started first. Equipment is shut down in the reverse order.

Maturity of Technology

Conventional and commercially proven solids material handling technology is used in the coal and sorbent receiving and handling design. The provision for storage capacities in the form of active (silos), emergency, and inactive storage piles and the inclusion of duplicate equipment trains for reclaiming coal from storage are intended to ensure a highly reliable, adequate flow of coal to the downstream pulverizers and process units. The ash/slag handling and disposal subsystem uses conventional and commercially proven equipment common in coal-based power plants for similar duties.

2.3.11 Water Supply and Treatment *(Plant Section 11)*

This plant section includes facilities for treating the raw intake water and supplying cooling water, makeup BFW, makeup process water for the FGD system, potable water, and water for other plant uses. Figure 40 is a block flow diagram of this subsystem; Table 21 gives the corresponding water balance for the full-load, 60°F plant operation. Raw water is first filtered in dual-media pressure filters to produce process makeup water for the plant. Part of the filtered water is treated in a packaged potable water unit before being distributed to potable water users. Untreated water is used for the cooling tower makeup, but appropriate doses of the various inhibitors are injected into the cooling water circulation loop to prevent scale formation, corrosion, and organic growth. A portion of the raw water is further demineralized to produce the required makeup for the BFW in the plant.

Cooling Water Circuit (Plant Subsection 11.1). A mechanical-draft cooling tower handles the cooling loads in the plant. The cooling tower consists of nine cells and associated auxiliaries including fans, water distribution system, and piping and instrumentation.

The makeup water is fed to the cooling tower basin. Provisions are included for bypassing tower fill during freezing weather. Two 50-percent capacity, vertical, wet-pit pumps provide cooling water for the main cooling water circuit, which feeds the surface condenser, condenser vacuum pump coolers, steam and gas turbine lube oil coolers, and FGD area.

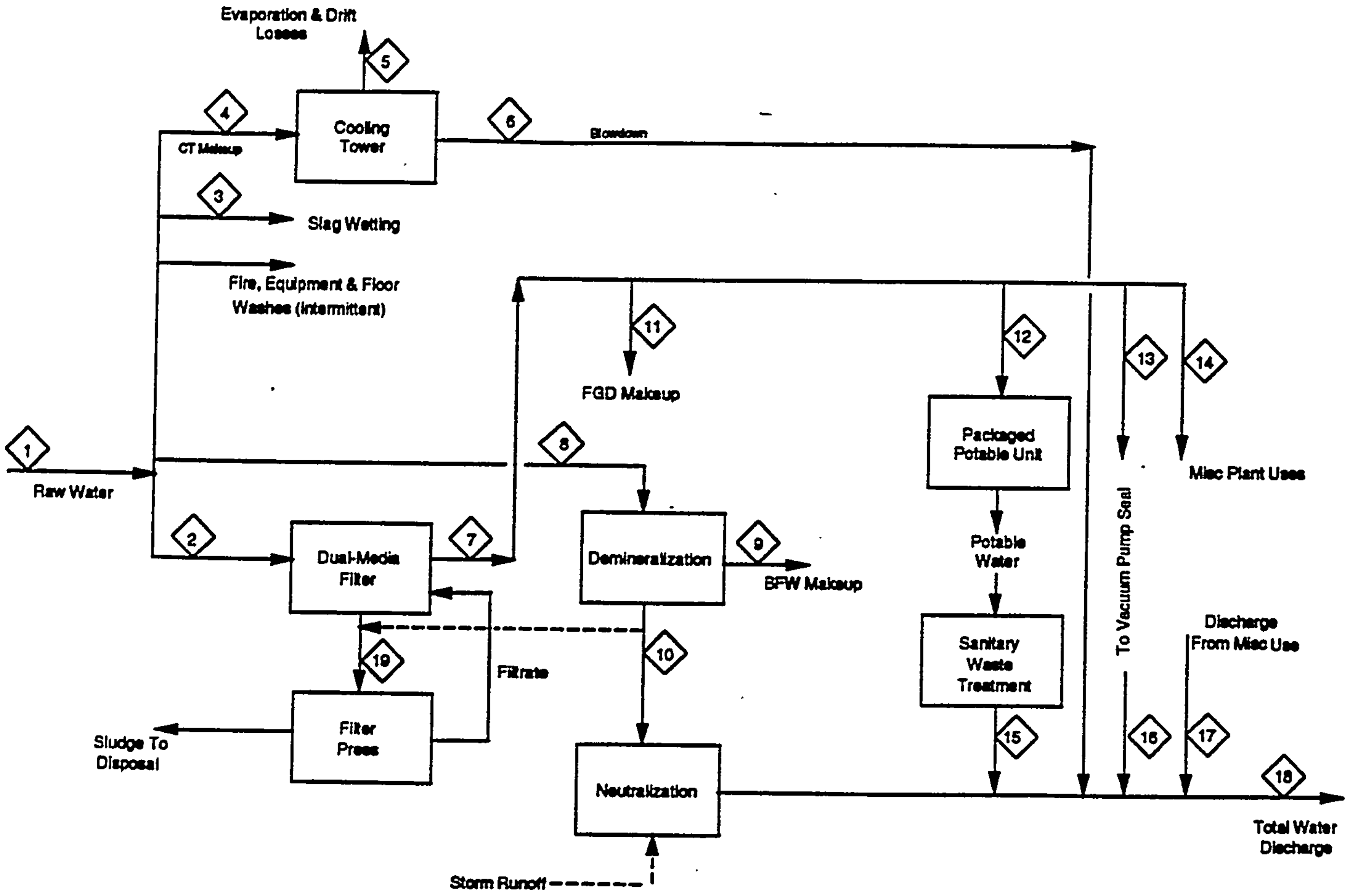


Figure 40 Block Flow Diagram: Raw Water Supply and Treatment

Table 21 Overall Water Balance Flow Rates of Major Streams (gal/min)

Stream	Stream Name	Operating Point 100% Load/60°F
1	Total Raw Water Intake	2,216
2	Gravity Filter Feedwater	709
3	Water to Slag Wetting	9
4	Cooling Tower Water Makeup	1,498
5	Cooling Tower Evaporation and Drift Losses	1,295
6	Cooling Tower Blowdown	203
7	Filtered Water	695
8	Demineralizer makeup water	11
9	BFW Makeup Water	9
10	Demineralizer Regenerants	2
11	Process & FGD Makeup Water	416
12	Potable Water	5
13	Water to Vacuum Pumps Seals	100
14	Water for Miscellaneous Plant Uses	174
15	Treated Sanitary Wastewater	2
16	Water Discharge From Vacuum Pumps Seals	117
17	Water Discharge From Miscellaneous Use	100
18	Total Water Discharge	422
19	Gravity Filter Spent Backwash	3

A closed-loop demineralized water circuit handles the cooling loads for miscellaneous auxiliaries such as BFW pump coolers, steam sample coolers, and generator hydrogen coolers. The heat picked up by the circulating demineralized water is rejected to cooling water in a separate heat exchanger.

Boiler Feedwater Treatment ***(Plant Subsection 11.2)***. The primary function of this subsystem is to supply condensate-quality feedwater to the HRSG loop. Raw water to be used as BFW is treated in a packaged ion exchange unit, utilizing strong acid cation and strong base anion columns and a mixed-bed demineralizer. Two 100-percent capacity skid-mounted parallel trains are used for demineralization. The demineralized water is stored in a BFW tank which provides about 5 hours of storage capacity. The exhausted ion exchange resins are regenerated with hydrochloric acid and caustic soda.

Design Specification and Features

The major process parameters in designing and selecting the various components of the water treatment and supply subsystem are summarized in Table 22.

Table 22 Major Process Parameters: Water Treatment and Supply Subsystem

Inlet/Outlet Cooling Water Temperature	63/80°F
Maximum/Average Dry Bulb Temperature	95/60°F
Maximum/Average Wet Bulb Temperature	75/52°F
Cooling Water Flow Velocity	9 ft/s
Cooling Tower Cycles of Concentration	5
BFW Blowdown Rate	1% of total flow
BFW Quality:	
TDS	50 ppb (max.)
Dissolved Oxygen	7 ppb (max.)
Total Silica	20 ppb (max.)
Total Copper	2 ppb (max.)
pH Value	9 to 9.5 at 77°F
Potable Water Consumption Rate	50 gal/person/day

The design specifications for the major equipment and components of this subsystem are summarized in Table 23.

Table 23 Design Specifications and Features: Water Treatment and Supply Subsystem

Demineralized Water Head Tank	Two: 2000 gal; 5'ID x 13-7" H
Cooling Tower	9 cells; 48'W x 487'L x49' H; Motor: 200 hp (each)
Demineralized Water/Cooling Water	Two: Shell & Tube; 31.5 x 1 0^6 Btu/h; 9500 ft^2
Heat exchanger	
Cooling Tower Circulating Water	Two: Vertical axial flow; 50,000 gpm; 1000 hp (each)
Pump	Two: 25 gpm each (packaged unit)
Demineralizer	Two: 250 gpm (each)
Dual-Media Filters	Three: 150 gpm (each); 7.5 hp (each)
Intake Raw Water Pump	One: 5000 gal; 8'ID x 13.5' H
Demineralized Water Storage Tank	Two: 2000 gpm (each); 50 hp (each)
Cooling Water Makeup Pump	Two: 200 gpm (each); 10 hp (each)
FGD Makeup Water Pump	Two: 700 gpm (each); 40 hp (each)
Discharge Water Pump	

Operating Characteristics

Two 100 percent capacity parallel trains supply makeup boiler feedwater. Under normal full-load operating conditions, both trains are operated in parallel at 50 percent capacity. However, at 50 percent plant operating load, one can be operated at 50 percent capacity while the second can be maintained in a standby mode. Most critical pumps are sized, spared adequately, and have recirculating lines so they can handle the plant operating range.

Maturity of Technology

The design and equipment used in the water supply and treatment subsystem are all commonly used in commercial power plants.

2.3.12 Support Systems *(Plant Section 12)*

The HIPPS plant incorporates several ancillary systems that support the operation of the power island. A brief description of these systems is given in the following paragraphs.

Service and Instrument Air System *(Plant Subsection 12.1)*

This system delivers dry and oil-free compressed air for plant and instrument use and gaseous nitrogen to the coal preparation and combustor areas. The instrument and plant air system is designed to provide approximately 2500 scfm of plant air and 2500 scfm of instrument air at 100 psig. The nitrogen system uses liquid nitrogen storage and vaporizer to deliver up to 800 scfm of gaseous nitrogen.

Electrical Distribution *(Plant Subsection 12.3)*

The electrical distribution system controls and delivers the generated power to a 230 kV distribution grid and provides auxiliary power for in-plant loads. The electrical single line diagram for the plant is given in Section 2.2 of the proposal.

The battery limits for the high-voltage portion of the electrical system include the 230 kV main switchyard, using a circuit breaker-and-half scheme. All interfacing high-voltage equipment required in the switchyard is part of this design.

The plant electrical system includes both the gas and steam turbine generators, close coupled to an associated step-up transformer and 230 kV distribution system. It also includes a distribution transformer and a startup transformer for 7.2 kV auxiliary load service.

The gas and steam turbine generators are each rated at 13.8 kV. A 15 kV non-segregated phase bus connects each generator output to a 13.8-230 kV power transformer for delivery to the main switchyard. The 15 kV buses for the gas and steam turbine generators are tapped to feed two 13.8 kV to 7.2 kV and 4.16 kV units auxiliary transformers which serve as the primary power source for the plant auxiliaries. Each unit auxiliary transformer is sized to supply the total load required by the plant.

Static inverters provide un-interruptible ac power for programmable logic, relay protection, and operating circuits. One diesel generator provides emergency power for the BFW pumps, fire water pumps, and house loads.

A detailed motor list for the entire plant was developed and used in generating all electrical equipment sizes and single line diagram.

Instrumentation and Controls System (*Plant Subsection 12.4*)

This system automatically controls and sequence plant-wide operations, with manual backup; it also provides condition monitoring and diagnostic capabilities. A centralized distributed control system (DCS) with high redundant microprocessor-based controls is used to provide a high level of control flexibility and reliability.

Interconnecting Piping *(Plant Subsection 12.5)*

This system provides all the piping and pipeways required for transmitting the process, utility, and waste fluids among the various process, power, and utility areas of the plant; it includes piping for cooling water (makeup, circulation, and blowdown), raw and BFW makeups, instrument and plant service air, treated wastewater, steam line between the boiler and steam turbine, and slag disposal line.

Fire Protection (Plant Subsection 12.6)

This system provides plant-wide fire protection and includes the necessary water yard mains; hydrants, automatic sprinklers; carbon dioxide units, fire and smoke monitors; detectors and alarms; portable extinguishers; and fire water piping and pumps.

General Services and Mobile Equipment *(Plant Subsection 12.7)* This system provides plant-wide fire protection and includes the necessary water yard mains; hydrants, automatic sprinklers; carbon dioxide units, fire and smoke monitors; detectors and alarms; portable extinguishers; and fire water piping and pumps.

These include furniture and fixtures for the warehouse, maintenance shop, control room, and administration building as well as front-end loaders, forklifts, mobile cranes for filters lift-up and other heavy equipment operation and routine daily maintenance, pickup trucks, and large bridge cranes for the turbine building.

2.3.13 Civil Works and Structures *(Plant Section 13)*

These include site preparation works/facilities and miscellaneous buildings.

Site Preparation and Facilities *(Plant Subsection 13.1)*

These include all the civil works necessary to accommodate the plant on a greenfield site which is assumed to be clear and level land with no adverse features. Seismic zone 1 is assumed, and foundations are to be on 100-foot piles. Site preparation will include site grading, paving 0.50-acre parking areas and one-mile access road, and erection of two-mile railroad spur, rainwater runoff pond, and plant enclosure fencing.

Miscellaneous Buildings *(Plant Subsection 13.2)*

These are buildings and structures not specifically related to any process or power generation equipment or systems and they include the control room building, administration building, warehouse, water treatment building, and maintenance shop. Appropriate building codes and standards will be followed in establishing structural engineering criteria and steel and concrete requirements. The building structures and equipment supports will be steel framed.

2.4 PLANT PERFORMANCE AND EMISSIONS

Table 24 shows the required plant resources and wastes discharged, gross and net power outputs, and overall heat rate and efficiencies at the 60°F ambient for both full and 50 percent load operations. The heat rates are calculated based on the higher heating value (HHV) of the coal fed to the plant.

Table 24 Overall Projected Plant Performance (60°F Ambient)

Description	Full Load	50% Load
Coal Flow to Pyrolyzer, 10^3 lb/h	164.36	92.97
Coal to Boiler, 10^3 lb/h	16.45	7.92
Total Coal Flow, 10^3 lb/h	180.81	100.89
Coal LHV (wet), 10^3 Btu/No.	12.00	12.00
Coal HHV, 10^3 Btu/lb	12.45	12.45
Pyrogas Flow, 10^3 lb/h	583.50	344.46
Char Flow, 10^3 lb/h	71.73	39.70
Sorbent to Pyrolyzer	16.27	9.58
Air to Compressor, 10^6 lb/h	3.31	2.72
Gas Turbine		
Inlet Temperature, °F	2,200	1,852
Inlet Press, psia	208.7	117.0
Outlet Temperature, °F	1,121	893
Gross Power, MW	153.16	81.39
Steam Turbine		
Inlet Press, psia	2,615	1,457
SH/RH Temperature, °F	1075/1075	1007/801
Steam Flow, 10^6 lb/h	0.82	0.46
Exit Pressure, psia	0.90	0.60
Outlet Temperature, °F	98.6	87.0
Condenser Duty, 10^6 Btu/h	787.5	414.0
Gross Power, MW	169.25	80.68
Total Gross Power, MW	322.41	162.07
Total Coal LHV, 10^6 Btu/h	2,169.7	1,256.08
Total Coal HHV, 10^6 Btu/h	2251.1	1,303.10
Booster Compressor, MW	1.60	0.85
ID Fan, MW	1.15	1.17
FGD, MW	2.30	1.97
Other Aux Power, MW	6.97	3.83
Total Net Power, MW	310.39	154.25
Efficiency – HHV Percent	47.06	40.55
Efficiency – LHV Percent	48.95	42.07
FG Temperature fm HITAF Econ, °F	266	347
FG Temperature fm GT Econ, °F	210	317

Emissions Control

The emissions control system consists of SO_2 control, NO_x control, and particulate control. The program emissions limits of 0.06 lb/MMBtu for SO_2 and NO_2 emissions and .003 lb/MMBtu for particulate emissions mean that postcombustion SO_2 removal must be better than 98 percent; postcombustion NO_x removal must be better than 90 percent; particulate removal must be greater than 99.9 percent.

As described in Section 2.3.8, various emission control system components are integrated into the HIPPS plant. The emission mass balance of the plant is shown reviously in Table 17. To achieve the program goals as indicated by this table, the flue gas SO_2 scrubber must be capable of 98.0 percent efficiency. The deNO_x systems must both be capable of 90 percent NO_x reduction, and the particle removal systems must be capable of a combined removal efficiency of 99.8 percent. All emission control systems are designed to meet or exceed these efficiency requirements.

2.5 PLANT OPERATING PROCEDURE AND MAINTENANCE

Enough analysis of the HIPPS operation has been completed to establish that the system can be operated with reasonable procedures. Detailed operating procedures will be developed in Phase 2 for the prototype plant and the commercial plant. The following discussion summarizes the general operating procedures.

Startup. Figure 41 is a diagram of the system showing the basic components that are important for the startup and control of the HIPPS plant. The details of the steam turbine system are omitted for clarity, but the location of the steam heat transfer surfaces are indicated. The steam turbine control system will be of conventional design.

The gas turbine first is driven at low speed by an electric motor and then fired with oil or natural gas. For the case of natural gas firing, it is accelerated to full speed with natural gas firing in the conventional manner. Gas turbine operation is then established at a minimum firing rate suitable for the extraction of air for the pyrolyzer. The compressed air that goes to the pyrolyzer is heated in a natural gas-fired heater to warm up the refractory in the pyrolyzer subsystem vessels. This air is vented upstream of the gas turbine through a flare. The heating of the air is regulated to increase the refractory temperature at 200°F to 300°F per hour.

While the pyrolyzer is warming up, oil or gas ignitors are fired in the char combustor precombustors. This then is followed with coal firing in the precombustors. Between the coal firing in the HITAF and the duty from the HRSG, enough steam is generated to cool the superheaters in the HITAF and in the fuel gas cooler. This steam initially bypasses the steam turbine in the normal manner. When steam conditions reach the proper level, the steam turbine is rolled, synchronized and loaded.

When the lower bed temperature in the pyrolyzer reaches approximately 1100°F a shallow bed of sorbent will be established. After the temperature of the bed is stabilized at approximately 1100°F, coal or coke is added to the bed and ignition occurs. Fuel, air and the vent valve are controlled to raise the bed temperature and pressure and start solids circulation. When fuel gas is produced in sufficient quantity, the fuel valve to the gas turbine is ramped open and fuel gas gradually displaces the natural gas as the natural gas is correspondingly ramped down.

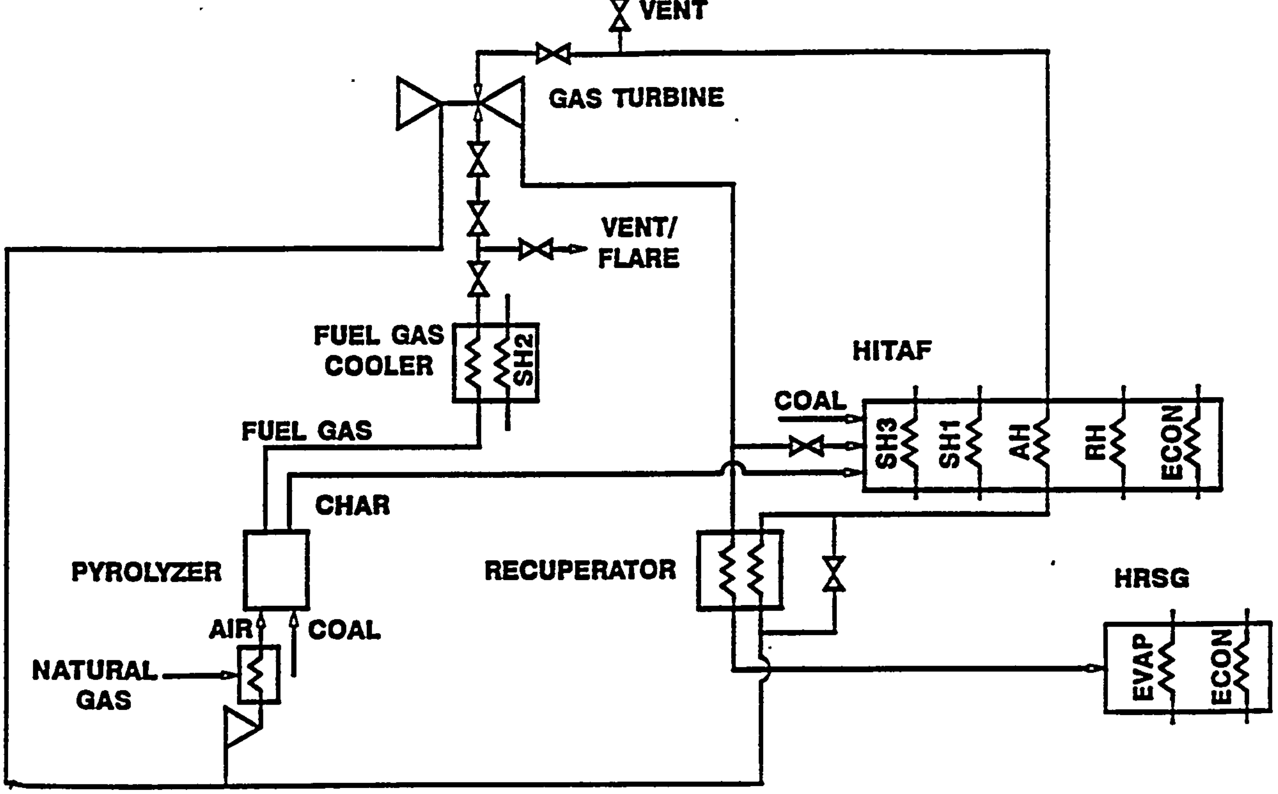


Figure 41 HIPPS System Control

As char is produced, it is fired in the HITAF, and steam generation increases. Load is then increased by increasing the coal flow to the pyrolyzer.

Load Control. The main means of controlling load is controlling the flow of coal and air to the pyrolyzer. The quantities of air and coal fed to the pyrolyzer determine the quantities of char and fuel gas that are produced. To a limited extent, the air/coal ratio can also be varied to change the proportions of char and fuel gas that are produced. A more detailed discussion of pyrolyzer operation at various loads is included in Section 2.3.5.

Although the general load is controlled by the fuel feed to the pyrolyzer, other mechanisms are also used to trim load and adjust for changes in heat transfer at different loads. Sprays are used for steam temperature control just as they are in conventional boilers. A valve is also provided to bypass gas turbine air around the recuperator. This valve is the equivalent of a spray system for the air heater sections of the HITAF. It will be controlled to maintain the air temperature leaving the HITAF at 1400°F or less.

Coal that is fired directly in the HITAF can also be used to trim the load and effect changes in the split of heat input to the gas turbine and steam turbine systems. This coal is fired in the precombustor in general operation and is supplied with a separate, direct fire pulverizer system. This coal flow can be rapidly adjusted to change the heat input to the char combustors. The char flow to the combustors is regulated with screw feeders so the response of the char feed is also good.

Part Load Operation. Plant operating parameters at 50 percent load are summarized in Table 24. Operation at partial load is accomplished by reducing the coal flow to the pyrolyzer. The gas turbine compressor discharge pressure is also reduced by closing the compressor inlet guide vanes and lowering the firing rate. This type of operation results in a reduction of fuel gas and char production while maintaining proper fluidization conditions in the pyrolyzer. Operation of the pyrolyzer at reduced load is discussed in Section 2.3.5.

The individual char combustors are also capable of turn-down to at least 50 percent load, so the preferred method of turn-down will be to decrease the throughput of both pyrolyzer/char combustor trains. When turn-down limits of either the pyrolyzer or char combustor are reached, one train would have to be taken out of service.

Shutdown. During a normal shutdown, the coal input to the pyrolyzer is reduced, thereby reducing the fuel gas flow to the gas turbine and the char flow to the HITAF. Loads on both the steam turbine and gas turbine are reduced until the point where the gas turbine can be switched to natural gas firing. The fuel gas from the pyrolyzer is then sent to the flare. Coal and air flow to the pyrolyzer will then be reduced further, and the bed level is reduced to a minimal level. Coal flow then is stopped and the remaining char is burned off. Air flow rate is used to control temperatures as the char is consumed.

While maintaining a low load on the gas turbine with natural gas firing, char flow and coal flow to the HITAF stops. The combustion air continues to flow through the HITAF to purge it, and steam flow is bypassed around the steam turbine in the usual manner. Natural gas flow to the gas turbine then stops, thus completing the shutdown.

Emergency shutdown situations will exist. All of these situations have not been analyzed in detail, but general plans have been developed to deal with aspects of the HIPPS plant that differ from conventional plants. One difference between the HIPPS plant and a conventional gas turbine is that the external heating provides a reservoir of hot air that could continue to power the gas turbine even if the fuel is shut off. In order to prevent gas turbine runaway on loss of load, block and vent valves are provided in the air line as well as the fuel line.

Another difference between HIPPS and conventional plants is the need to safely shut down the pyrolyzer if the plant is quickly brought down for any reason. In a trip situation, fuel and air flow to the pyrolyzer is stopped. The gas turbine fuel stop valve is closed and the vent valve is opened. Nitrogen is injected into the pyrolyzer, and it flows through to the vent. After purging in this manner for a certain number of minutes, the vent valve also closes, and the pyrolyzer is sealed off with a blanket of nitrogen.

Loss of the gas turbine will necessitate tripping the HITAF to protect the air heater surface. If this occurs, fuel flow will be stopped immediately and the fans will continue to operate to purge the unit.

Maintenance

Customary power plant operating practice calls for a five-week annual shutdown to perform programmed maintenance and inspections. The programmed maintenance involves change-out or repair of all subcomponents known to break down approximately once a year. The inspections are performed for special signs of deterioration indicating a need for overhaul when detected, such as wear, appearance of cracks, and indicators of fatigue. Failure frequencies and outage times are well defined for the conventional power island and BOP system. The projected maintenance activities and schedules for all non-conventional equipment are addressed as follows.

High Temperature Advanced Furnace *(2.1)*. For the refractory coated superheat tube walls, inspection during annual plant shutdown will be conducted. The refractory is held in place by studs welded to the tubes. This type of construction is expected to operate for five years without major repair. High temperature sections of the air heater will be subject to yearly visual inspection for apparent corrosion and distortion. Non-destructive examinations, which include ultrasonic tests for tube wall thickness and penetrant tests for possible tube cracking, will be performed if required.

Char Combustor ***(2.2)*****.** During the regularly scheduled maintenance outages, anticipated as ten days on an annual basis, inspection of the char combustion subsystem shall be performed. In general, the char combustion subsystem inspection is similar to standard boiler inspection procedures and includes inspection of all components for excessive deposits, corrosion, scale, pitting, and overheating. Inspection of the combustor internal surface will be performed by entering the combustor assembly through the boiler. Inspection of the external surface will be performed by removing inspection plates provided in the external insulation surface. If excessive erosion, corrosion, or pitting is noted, or any regions of overheating or cracking are identified during the inspection procedure, a more detailed inspection of the region will be performed and, if required, the region will be repaired prior to placing the unit back into service. The detailed inspection will include such processes as ultrasonic inspection to determine material thicknesses as well as determining the root cause of the problem. The repair procedure will be specific to the actual area or problem identified but will include general procedures such as cutting and replacing the affected tube or protecting the surface with a weld overlay or similar process.

Pyrolyzer ***(5.1)*** **and Cyclones** ***(5.2)*****.** These are refractory lined high-temperature pressure vessels. Visual check of interior refractory surfaces for cracking will be performed during the scheduled plant shutdowns. Generally, under normal operation, no major repair is expected for these vessels in five years. However, the maintenance schedule can greatly be affected by increasing numbers of shutdowns or cyclic operation.

Fuel Gas Cooler ***(5.3)*****.** The tube bundle elements at the inlet and outlet regions will be visually inspected during annual scheduled shutdown. Non-destructive examinations as described previously will be performed if needed.

Barrier Filter ***(5.4)*** Periodic observation and record keeping should be carried out in order to be sure that the performance of the unit does not degrade. The principal parameters to be observed are particulate collection efficiency and pressure drop. Of these two parameters, the pressure drop is by far the most easily monitored, although the collection efficiency should be measured via sample extraction at least semiannually.

A decrease in collection efficiency or in pressure drop generally indicates that the structural integrity of one or more of the filter elements has been compromised, i.e., an element has broken and allows gas to bypass it. This development would require the vessel to be isolated from the fuel gas system, brought to atmospheric pressure and temperature, opened, and the broken elements(s) replaced.

2.6 COST AND ECONOMICS

2.6.1 Cost Estimate Basis

A capital cost estimate developed for the commercial HIPPS plant is based on the level of conceptual engineering performed. The estimating approach and the engineering information provided to support the estimate are consistent with an EPRI Class II, Preliminary Estimate, as defined in EPRI's Technical Assessment Guide (June 1993 TAG). The cost estimate reflects 4th-Quarter, 1993 prices. The expected accuracy for the estimate is in the range of ± 25 percent. The estimating approach used for the boiler island included maximum use of information available from the major equipment manufacturers, and the approach used for the Balance-of-Plant (BOP) included maximum use of informal vendor quotes supplemented by historical data from constructed facilities that use similar equipment or systems. The data sources for the capital cost estimate are listed below:

Pyrolyzer	Foster Wheeler
HITAF furnace	Foster Wheeler
HRSG	Foster Wheeler
Slagging combustor	TRW
Recuperator	Allied Signal
Gas and steam turbines	Westinghouse
FGD and particulate removal	Research Cottrell
Balance of plant:	
Cooling water system	Vendor budget quotes (VBQ)
Coal/limestone preparation	VBQ & Bechtel in-house data
Stack	VBQ
Raw water supply and treatment	VBQ
Plant and instrument air	VBQ
Plant instrumentation & controls	VBQ & Bechtel in-house data
Other BOP	Bechtel in-house data

The total value of the above manufacturer and vendor quotations represent approximately 70 percent of the total equipment, materials, and subcontracts for the plant, while cost/capacity factoring and adjustments from historical data represent only about 30 percent of the estimate.

2.6.2 Capital Cost

Table 25 shows a summary of the direct field cost of the various sections of the commercial HIPPS plant. The cost is broken down according to a standard code of accounts that has been developed to be used for all HIPPS programs in DOE. The direct field cost for each account includes the delivered price of major equipment, the cost of necessary bulk commodities (piping, electrical, concrete, and civil structures), the cost of installation labor, and in some cases an all-in-one subcontract cost. The installation labor cost is based on a composite wage rate of $28 per manhour, representing a craft mix typical of this project in the Northeast region.

Table 25 HIPPS Total Direct Field Cost (millions of December 1993 dollars)

Item	Total
Power Island	
1 Solids feed removal	
1.1 Coal prep/ feeding	8.59
1.2 Sorbent prep/feeding	2.35
1.3 Ash/slag removal	3.61
	14.55
2 Steam generator island	
2.1 High-temp furnace	25.64
2.2 Coal/char combustor	11.42
2.3 HRSG's	10.06
2.4 Stacks/ducting	2.28
2.5 ID fan	0.41
	49.80
3 High temperature exchanger	
3.1 Recuperator	3.73
3.2 Ceranmic air heater	0.00
	3.73
4 High temperature piping/ducting	1.53
5 Process systems	
5.1 Pyrolyzer	2.50
5.2 Fuel gas furnace	0.00
5.3 Cyclones	0.94
5.4 Fuel gas coolers	2.88
5.5 Barrier filter	3.31
5.6 Solids transport equipment	3.09
5.7 Pyrolyzer comperssor	0.96
	13.68
6 Gas turbine	41.77
7 Steam turbine/BFW	29.78
8 Emissions control systems	
8.1	4.38
8.2 SO2 removal	25.75
8.3 NO_x	5.83
	35.96
Balance of plant	
10 Solids material handling	
10.1 Coal receiving/handling	16.05
10.2 Sorbent receiving/handling	2.23
10.3 Ash/slag handling & receiving	3.24
	21.52
11 Water systems	
11.1 Cooling water systems	4.19
11.2 Raw water/treatment system	2.29
	6.49
12 Support systems	
12.1 Service/instrument air	0.60
12.2 Natural gas supply	0.01
12.3 Electrical distribution	9.31
12.4 Instrument & controls	1.46
12.5 Interconnecting piping	2.91
12.6 Fire protection	0.80
12.7 General services & mobile equipment	0.71
	15.80
13 Civil/structural	
13.1 Site preparation/facilities	3.76
13.2 Miscellaneous buildings	2.08
	5.83
Total direct field cost	240.44

Table 26 shows a summary of the total capital requirements for the HIPPS project. The total plant cost (TPC) is estimated by adding indirect field costs, home office engineering fee, and appropriate contingencies. The indirects cover costs for labor for miscellaneous construction services (e.g., maintenance of tools and equipment, performance and operations testing, and material testing), and costs for temporary construction materials. The indirects were factored from the direct field labor costs based on Bechtel's experience with projects of similar size and features. The home office engineering manhours and other office services were estimated at about 11 percent of total field cost. A project contingency of about 15 percent was applied to the complete estimate to denote the level of confidence in the values ascribed to the various elements of the estimate. The amount of this contingency is suitable, in Bechtel's judgment, to achieve about 50 percent probability of project underrun. An additional process contingency is assigned to the estimate to account for process design/engineering uncertainties in certain equipment/systems resulting from lack of commercial maturity. The amount of this contingency is derived by assigning contingencies to different process systems and subsystems ranging from 0 to 25 percent of their respective direct field costs. An allowance for funds used during construction (AFUDC) and owner's costs complete the capital requirements for the project.

Table 26 Total Capital Requirements (millions of December 1993 dollars)

Items	Cost
Plant Costs	
Power island	190.79
Balance of plant	49.61
Total direct costs	240.40
Field indirect costs	31.39
Total field cost	271.79
Home office engineering	29.28
Contingency (project)	44.45
Contingency (process)	13.57
Total plant cost (TPC)	359.09
Capital requirements	
AFUDC	37.92
Owner's costs	20.16
Total capital requirement	417.17
Net power to grid, MWe	310.39
Dollar per kilowatt	1,344.0

Table 27 shows the elements of the owner's cost which follow the recommended estimation method used in EPRI's TAG.

Table 27 HIPPS Owner's Cost Summary (thousands of December 1993 dollars)

Item	Total Project Cost
Organization and startup costs*	
One month's fixed O&M	692
One month's variable cost (excluding fuel)	800
One weeks fuel	663
Two percent of TPC	7,182
Subtotal	9,336
Working capital*	
Two month's fuel	5,742
Two month's other consumables	1,600
Spare parts inventory (0.5% of TPC)	1,795
Subtotal	9,138
Initial catalyst and chemicals	450
Land costs	1,235
Total owner's costs	20,159

* Based on 100 percent of capacity factor

2.6.3 Operating and Maintenance Costs

Table 28 shows a summary of the operating and maintenance costs for the HIPPS commercial plant. The operating labor estimate is based on projected staffing requirements and an aggregate manhour wage of $29 per manhour. Maintenance cost is estimated as a percentage of the TPC per EPRI's TAG guidelines. The costs and credits for consumables, byproducts, and fuel are based on $37.44 per ton for limestone, $45 per ton for lime, $18.22 per ton for solids disposal and $1.75 per million Btu for coal. No acquisition charge is assumed for raw water intake.

Table 28 HIPPS First Year Annual Operating and Maintenance Costs (thousands of December 1993 dollars per year)*

Item	Cost
Fixed costs	
Operating labor	2,890
Technical services	361
Management	542
Maintenance	8,977
Total	12,770
Fixed costs, mills/kWh	4.11
Variable costs — consumables	
Catalysts and chemicals*	572
Limestone*	2,565
Lime*	1,987
Solids disposal*	4,478
Total	9,602
At capacity factor	6,241
Consumables, mills/kWh	2.01
Variable costs — fuel	
Fuel cost*	34,454
At capacity factor	22,395
Mills/kWh	7.22
Total O&M (including fuel) at capacity factor	41,406
Mills/kWe	13.34

* Based on 100 percent capacity factor

2.6.4 Economic Analysis

Table 29 was a summary of the input and results from the economic analysis done for the HIPPS commercial plant. The derived economic model uses financial criteria and revenue requirement analysis that follow EPRI's TAG guidelines. At a capacity factor of 65 percent, the HIPPS commercial plant is projected to generate electricity at a constant dollar levelized cost of about 49 mills per kWh.

Table 29. HIPPS Economic Inputs and Results
(Unless indicated, cost are thousands of December 1993 dollars)

Item	Cost
Total plant cost	359,090
Cost of land	1,235
Organizational and start-up expenses	9,336
Working capital	9,138
AFUDC	37,920
Coal Cost, $/MMBtu	1.75
Allocation of TPC over design/const. years	
Year	
1	0.15
2	0.45
3	.040
Annual fixed O&M costs	12,770
Annual variable O&M costs @ 100% CF	6,241
Power output (kWe) @ design capacity	310,390
Heat rate, Btu/kWh	7,252
Constant dollar levelized cost of electricity (COE), mills/kWh*	49.13

* At 65% CF

2.6.5 Cost Sensitivity Analysis

Table 30 summarizes the results of analyzing the sensitivity of the levelized cost of electricity (COE) for the HIPPS commercial plant to changes in various cost and operation parameters. As shown, the most significant impact on electricity cost results from changing either the fuel cost or plant capacity.

Table 30 HIPPS Sensitivity Analysis

Item	Base	Adjusted	COE	%Change
Base case — all coal HIPPS	—	—	49.13	0.0%
Increase of $10MM in total direct field costs $MM	240.40	250.40	50.00	1.8%
Increase of $0.50/MM Btu for coal, $/MM Btu	1.75	2.25	52.88	7.6%
Double cost of slag disposal, $/ton	18.00	36.00	50.27	2.3%
Increase capacity factor, %	65.00	80.00	43.26	-11.9%

Note: Results are for each shown and not compounded.

2.6.6 Comparison of HIPPS and Pulverized Coal Plant

Capital costs for the pulverized coal fired power plant with flue gas desulfurization, as presented in Table 31, were derived from previous studies performed by Bechtel for EPRI, escalated to December, 1993 dollars. Costs were also adjusted for the appropriate plants to reflect the differences in coal characteristics.

Table 31 Capital Costs Comparison Between PCF Power Plant and HIPPS

Item	All Coal HITAF	PCF w/PGD
Power Island		
1 Solids feed removal		
1.1 Coal prep/ feeding	8.59	1.78
1.2 Sorbent prep/feeding	2.35	0.42
1.3 Ash/slag removal	3.61	1.44
	14.55	3.64
2 Steam generator island		
2.1 High-temp furnace	25.64	76.15
2.2 Coal/char combustor	11.42	0.00
2.3 HRSG's	10.06	0.00
2.4 Stacks/ducting	2.28	4.79
2.5 ID fan	0.41	0.74
	49.80	81.68
3 High temperature exchanger		
3.1 Recuperator	3.73	0.00
3.2 Ceramic air heater	0.00	0.00
	3.73	0.00
4 High temperature piping/ducting	1.53	0.00
5 Process systems		
5.1 Pyrolyzer	2.50	0.00
5.2 Fuel gas furnace	0.00	0.00
5.3 Cyclones	0.94	0.00
5.4 Fuel gas coolers	2.88	0.00
5.5 Barrier filter	3.31	0.00
5.6 Solids transport equipment	3.09	0.00
5.7 Pyrolyzer comperssor	0.96	0.00
	13.68	0.00
6 Gas turbine	41.77	0.00
7 Steam turbine/BFW	29.78	53.26
8 Emissions control systems		
8.1 Particulate removal	4.38	4.04
8.2 SO2 removal	25.75	25.36
8.3 NO_x removal	5.83	0.00
	35.96	39.41
Balance of plant		
10 Solids material handling		
10.1 Coal receiving/handling	16.05	18.52
10.2 Sorbent receiving/handling	2.23	4.10
10.3 Ash/slag handling & receiving	3.24	2.82
	21.52	25.44
11 Water systems		
11.1 Cooling water systems	4.19	5.66
11.2 Raw water treatment	2.29	3.50
	6.49	9.17
12 Support systems		
12.1 Service/instrument air	0.60	3.97
12.2 Natural gas supply	0.01	0.00
12.3 Electrical distribution	9.31	37.66
12.4 Instrument & controls	1.46	5.14
12.5 Interconnecting piping	2.91	10.57
12.6 Fire protection	0.80	1.17
12.7 General services & mobile equipment	0.71	0.00
	15.80	58.52
13 Civil/structural		
13.1 Site preparation/facilities	3.76	13.79
13.2 Miscellaneous buildings	2.08	16.52
	5.83	30.31
Total direct field cost	240.44	301.42

In the previous PCF studies a different cost code of accounts was used. A best effort was made to assign all costs to the appropriate subsystem but some items, notably Civil/Structural, remain undivided and, as a result, appear high relative to HITAF costs. The results show that the TPC for the HIPPS plant is lower by about $39 million.

A comparison of the major economic components and COE is presented in Table 32. It appears from the results presented in this Table that the COE for HIPPS is approximately 14 percent less than that for a comparably sized PCF facility.

Table 32 Comparison of PCF and HIPPS Economics Inputs and Results (Unless indicated, costs are thousands of December 1993 dollars)

Item	PCFw/FGD	HIPPS
Total plant cost	425,720	359,090
Cost of land	1,122	1,235
Organizational and start-up expenses	10,639	9,336
Working capital	10,493	9,138
AFUDC	33,632	37,920
Coal Cost, $/MMBtu	1.75	1.75
Allocation of TPC over design/const. years		
Year		
1	0.15	0.15
2	0.45	0.45
3	0.40	0.40
Annual fixed O&M costs	14,436	12,770
Annual variable O&M costs @ 100% CF	3,831	6,241
Power output (kWe) @ design capacity	310,000	310,390
Heat Rate, Btu/kWh	9,336	7,252
Constant dollar levelized cost of electricity (COE), mills/kWh	57.80	49.13

2.7 REPOWERING APPLICATION

An outgrowth of our studies of the FWDC HIPPS concept was the development of a concept for the repowering of existing boilers. The initial analysis of this concept indicates that it will be both technically and economically viable. A unique feature of our greenfields HIPPS concept is that it integrates the operation of a pressurized pyrolyzer and a pulverized fuel-fired boiler/air heater. Once this type of operation is achieved, there are a few different applications of this core technology. Two greenfields plant options are the base case plant and a plant where ceramic air heaters are used to extend the limit of air heating in the HITAF. The greenfields designs can be used for repowering in the conventional sense which involves replacing almost everything in the plant except the steam turbine and accessories. Another option is to keep the existing boiler and add a pyrolyzer and gas turbine to the plant.

A simplified schematic diagram of this repowering concept is shown in Figure 42. The design and operation of the pyrolyzer will be the same as in the base case, greenfields plant. The fuel gas produced will be used as fuel in a gas turbine. In the repowering concept, the compressor discharge air will not be taken off the machine so a standard gas turbine can be used. The char from the pyrolyzer is transported to the existing boiler where it is used as fuel along with coal. The gas turbine can be sized such that all the exhaust air is used for combustion or a larger gas turbine can be used and some of the gas turbine exhaust can go to heat recovery devices. The base case repowering concept has been designed around using all of the gas turbine exhaust as combustion air for the boiler. This approach results in a simpler system with only one flue gas exhaust stream.

The repowering application of HIPPS is similar to hot windbox repowering where gas turbine exhaust is used as combustion air in a boiler. This approach to repowering has found favor in Europe and Japan. One of the major differences between HIPPS and hot windbox repowering is that HIPPS is a coal based system for use on coal-fired boilers. Coal is the predominant fuel for the generation of electricity in the U.S. and HIPPS has the potential for rapidly increasing the efficiency of these plants.

In order to assess the the technological and economic aspects of HIPPS repowering, a study was done on a specific boiler. Doing this study allowed us to work through the real world problems of site restrictions and equipment compatability. The repowering concept evolved as a result of trade-off studies made during this design effort. We now believe that we have a practical system that can be commercialized in the short term.

The study was done on an Eastern utility plant. The owner is currently considering replacing two units with atmospheric fluidized bed boilers, but is interested in a comparison with HIPPS technology. After repowering, the emissions levels need to be 0.25 lb SO_x/MMBtu and 0.15 lb NO_x/MMBtu. This section of the report will include performance data and a general description of the physical changes to the plant. Details of the design and an economic analysis are presented in Appendix G.

Table 33 shows a performance comparison between the HIPPS repowering arrangement and the original power plant. The net power output of the unit increases from 94 MW to 116 MW, and the efficiency increases from 33.6 percent to 39.2 percent. Figure 43 is a process flow diagram for the repowered plant. The corresponding heat and material balance is listed in Table 34.

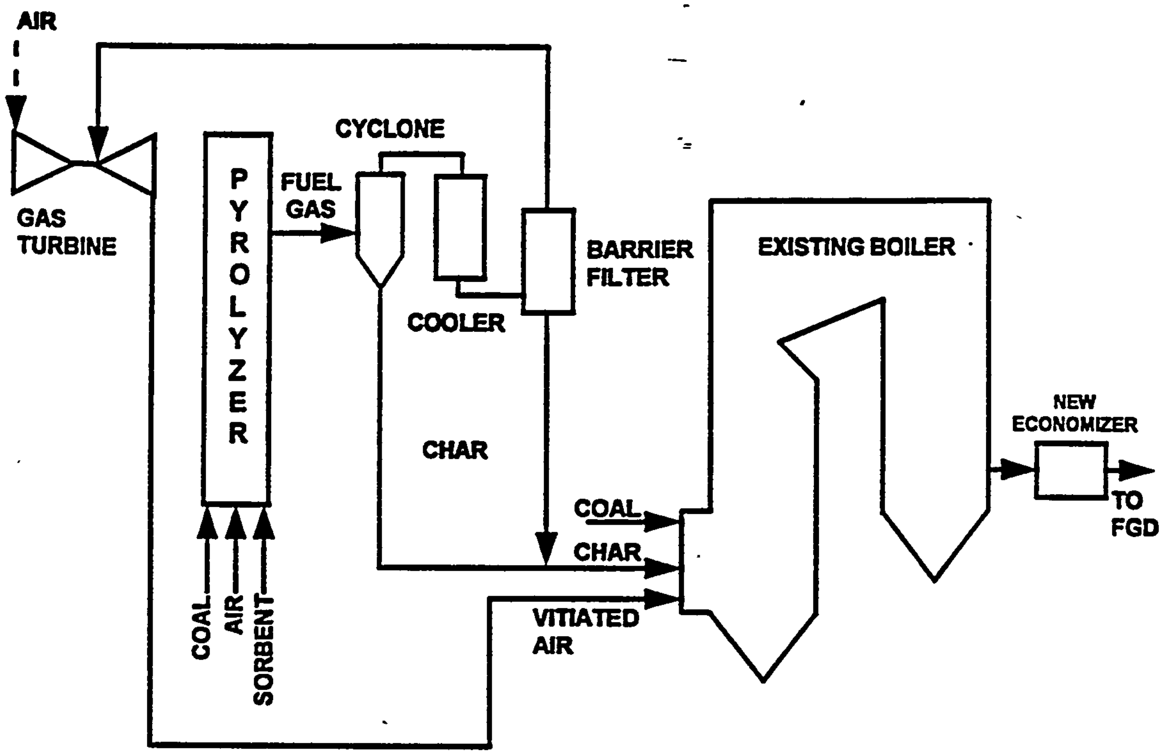


Figure 42 Simpilified HIPPS Repowering Process Flow Diagram

Table 33 Typical Repowering Application

Description	Base Case	HIPPS Repowering
Coal Flow to Pyrolyzer, M lb/h	0.00	61.25
Coal to Boiler, M lb/h	73.02	16.40
Total Coal Flow, M lb/h	73.02	77.65
Pyrogas Flow, M lb/h		130.8
Char Flow, M lb/h		32.6
Coal HHV, M Btu/lb	13.05	13.05
Gas Turbine		
Inlet Temperature, °F		2100
Inlet Pressure, psia		164
Outlet Temperature, °F.		1047
Gross Power, MW		32.6
Steam Turbine		
Inlet Pressure, psia	1815	1815
SH/RH Temperature, °F	1005/990	1005/990
Steam Flow, MM lb/h	0.666	0.508
Exit Pressure, psia	0.728	0.728
Outlet Temperature, °F	91.3	91.3
Condenser Duty, MM Btu/h	481	455
Gross Power, MW	98.93	90.2
Total Gross Power, MW	98.93	122.8
Total Coal LHV, MM Btu/h	921.70	980.4
Total Coal HHV, MM Btu/h	952.93	1,013.3
Auxiliary Power, MW	5.21	6.4
Total Net Power, MW	93.72	116.4
Efficiency – HHV	33.6 percent	39.2 percent
Efficiency – LHV	34.7 percent	40.5 percent

Table 34 Repowering Process Flow Streams

Stream No.		1		2		3		4		5		6		7		8	
		Coal to Pyrolyzer		Air to Pyrolyzer		Sorbent to Pyrolyzer		Char fm Pyrolyzer		Fuel Gas fm Pyrolyzer		Water to Quench		Fuel Gas to GT Comb.		Air to Compressor	
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
	Carbon	73.76%	45,176					75.43%	24,591								
	Hydrogen	4.62%	2,829					0.47%	155								
	Oxygen	4.05%	2,482														
	Nitrogen	1.34%	821					1.32%	430								
	Sulfur	1.39%	850					1.25%	407								
Solids	Ash	9.29%	5,689			3.00%	61	17.64%	5,749								
lb/h	Moisture	5.61%	3,435			3.00%	61					100.00%	20,826				
	CaCO3					92.00%	1,857										
	MgCO3					2.00%	40										
	CaO							0.95%	309								
	MgO							0.06%	19								
	CaS							2.88%	940								
	CaSO4																
	CH4									2.72%	3,560			2.35%	3,560		
	C2H4																
	C2H6																
	C3H8																
	CO									28.16%	36,840			24.29%	36,840		
Gases	H2									1.40%	1,825			1.20%	1,825		
lb/h	CO2			0.05%	47					6.57%	8,593			5.67%	8,593	0.05%	428
	H2O			0.82%	819					2.50%	3,268			15.89%	24,094	0.82%	7,387
	O2			22.95%	23,000											22.95%	207,409
	N2			74.90%	75,054					57.39%	75,082			49.51%	75,082	74.90%	676,831
	H2S									0.02%	27			0.02%	27		
	COS																
	SO2																
	C6H6+																
	Argon			1.28%	1,280					0.98%	1,280			0.84%	1,280	1.28%	11,545
	NH3									0.27%	350			0.23%	350		
	NO2																
	Total Gas, lb/h	100.06%	61,247	100.00%	100,200	100.00%	2,018	100.00%	32,601	100.00%	130,824	100.00%	20,826	100.00%	151,649	100.00%	903,600
					3,445						5,521				6,677		31,063
					29.09						23.70				22.71		29.09
	Pressure, psia		212.49		194.80		212.49		194.80		194.80		253.10		188.90		14.20
	Temperature, °F		70.00		700.79		70.00		1,700.00		1,700.00		96.20		1,000.00		59.00

Table 34 Continued

Stream No.		9		10		11		12		13		14		15		16	
Stream		Bypass Air		Air to GT Combustor		Air to Booster Clr		Air to Booster		Flue Gas fm GT Comb.		V.A. fm GT		Vitiated. Air to Furn		Coal to Pulverizer	
		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr
	Carbon															73.76%	12,097
	Hydrogen															4.62%	758
	Oxygen															4.05%	665
	Nitrogen															1.34%	220
	Sulfur															1.39%	228
Solids	Ash															9.29%	1,523
lb/h	Moisture															5.61%	920
	CaCO3																
	MgCO3																
	CaO																
	MgO																
	CaS																
	CaSO4																
	CH4																
	C2H4																
	C2H6																
	C3H8																
	CO																
Gases	H2																
lb/h	CO2	0.05%	59	0.05%	321	0.05%	47	0.05%	47	9.22%	76,562	8.02%	76,621	8.02%	76,621		
	H2O	0.82%	1,020	0.82%	5,548	0.82%	819	0.82%	819	6.57%	54,515	5.81%	55,535	5.81%	55,535		
	O2	22.95%	28,646	22.95%	155,764	22.95%	23,000	22.95%	23,000	12.63%	104,848	13.98%	133,494	13.98%	133,494		
	N2	74.90%	93,480	74.90%	508,297	74.90%	75,054	74.90%	75,054	70.27%	583,379	70.87%	676,859	70.87%	676,859		
	H2S																
	COS																
	SO2									0.01%	51	0.01%	51	0.01%	51		
	C6H6+																
	Argon	1.28%	1,595	1.28%	8,670	1.28%	1,280	1.28%	1,280	1.20%	9,950	1.21%	11,545	1.21%	11,545		
	NH3																
	NO2									0.11%	944	0.10%	944	0.10%	944		
Total Gas, lb/h		100.00%	124,800	100.00%	678,600	100.00%	100,200	100.00%	100,200	100.00%	830,249	100.00%	955,049	100.00%	955,049	100.06%	16,401
			4,290		23,328		3,445		3,445		28,889		33,179		33,179		
			29.09		29.09		29.09		29.09		28.74		28.78		28.78		
Pressure, psia			174.09		174.09		174.09		172.39		163.99		15.20		15.20		15.20
Temperature, °F			665.11		665.11		665.11		655.11		2,121.00		1,053.16		881.00		64.00

Table 34 Continued

Stream No.		17		18		19		20		21		22		23		24	
		Char to Pulverizer		Air to Pulverizer		CC to Furnace		Ash fm Furnace		Flue Gas to Furnace		Flue Gas to Superhtr		Flue Gas to Back end		Flue Gas to FGD	
Stream		%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	%wt	lb/hr	wt%	lb/hr
	Carbon	75.43%	24,591			29.97%	36,688										
	Hydrogen	0.47%	155			0.75%	912										
	Oxygen					0.54%	665										
	Nitrogen	1.32%	430			0.53%	650										
	Sulfur	1.25%	407			0.52%	635										
Solids lb/h	Ash	17.64%	5,749			5.94%	7,272	87.25%	7,200		73						
	Moisture					0.75%	920										
	CaCO3																
	MgCO3																
	CaO	0.95%	309				309	12.52%	1,033		7						
	MgO	0.06%	19			0.02%	19	0.23%	19		0						
	CaS	2.88%	940			0.77%	940										
	CaSO4																
	CH4																
	C2H4																
	C2H6																
	C3H8																
	CO																
Gases lb/h	H2																
	CO2			0.05%	35	0.03%	35			19.74%	211,084	19.74%	211,084	19.74%	211,084	19.74%	211,084
	H2O			0.82%	600	0.49%	600			6.10%	65,209	6.10%	65,209	6.10%	65,209	6.10%	65,209
	O2			22.95%	16,853	13.77%	16,853			4.19%	44,770	4.19%	44,770	4.19%	44,770	4.19%	44,770
	N2			74.90%	54,994	44.92%	54,994			68.51%	732,503	68.51%	732,503	68.51%	732,503	68.51%	732,503
	H2S																
	COS																
	SO2									0.20%	2,154	0.20%	2,154	0.20%	2,154	0.20%	2,154
	C6H6+																
	Argon			1.28%	938	0.77%	938			1.17%	12,483	1.17%	12,483	1.17%	12,483	1.17%	12,483
	NH3																
	NO2									0.09%	944	0.09%	944	0.09%	944	0.09%	944
Total Gas, lb/h		100.00%	32,601	100.00%	73,420	99.75%	122,431	100.00%	8,252	99.99%	1,069,228	100.00%	1,069,148	100.00%	1,069,148	100.00%	1,069,148
			-		2,524		2,524						36,018		36,018		36,018
			#DIV/0!		29.09		48.51						29.68		29.68		29.68
Pressure, psia			15.20		15.20		15.20		14.70		14.30		14.60		14.60		14.50
Temperature, °F			300.00		67.80		125.30		2,560.00		2,560.00		1,800.00		1,065.00		299.70

The cycle is based on a modified Westinghouse 251B12 gas turbine. A block diagram of the system is shown in Figure 44, and discussion of each subsystem follows. The design goals of the HIPPS repowering system were a little different than those for the greenfields plant, and this situation resulted in some differences in design. One of the main goals for the greenfields plant was an efficiency of greater than 47 percent. In repowering, a primary consideration is the integration of the new equipment with existing systems. Also, the approach taken in the repowering study is that it should be even more near term than the greenfields plant. It should be a system that will bridge the gap between current PC-fired boilers and the optimized HIPPS plant.

Pyrolyzer Coal/Sorbent Preparation and Feeding. A process flow diagram for the pyrolyzer coal/sorbent preparation and feeding system is shown in Figure 45. Coal for the pyrolyzer will be taken off the existing coal handling system from the coal bunker serving Unit #2. It will then be crushed and conveyed to a coal bin. The limestone is recieved on site already sized. It will also be held in a storage bin. Gravimetric feeders are used to proportion the coal and char as they are fed to lockhoppers. The lockhoppers pressurize the coal and sorbent. These feedstocks are then peumatically injected into the pyrolyzer. The coal/sorbent preparation and feeding system is composed of commercially available equipment.

Pyrolyzer. The pyrolyzer subsystem is shown in Figure 46. A jetting bed pyrolyzer is used for the generation of fuel gas and char. The fuel gas goes to the gas turbine and the char is depressurized, cooled and then conveyed to the boiler pulverizers. A circulating fluidized bed pyrolyzer system designed to yield char of suitable size for combustion could also be used. A system of this type is being developed for the greenfields plant, and it would likely be lower cost. The jetting bed pyrolyzer system with char pulverization uses equipment that is either commercial or being demonstrated on a large scale. For this reason, it was used in the study for near term applications.

Char is separated from the fuel gas in much the same manner as for the greenfields plant. The main difference is that approximately 50 percent of the char will come directly from the bed. The char is depressurized in Restrictive Pipe Discharge (RPD) systems and then cooled to about 200 F. It is then transported to the pulverizer system in a conveyor system that is purged with inert gas.

The fuel gas is cooled to around 1000°F to condense the alkalies. To keep the repowering system as simple as possible, water quench cooling is used. The barrier filter will be of the same design as the greenfields plant with the filter elements being either iron aluminide or ceramic.

Char Feed System. The char feed system to the pulverizers is shown in Figure 47. Rotary valves meter the cooled char into a series of chain conveyors that transport the solids to the char surge bin. The rotary valves are controlled to maintain the proper level of material in the RPD system. Although the char will be cooled to well below the ignition temperature, the chain conveyor and bins will be purged with inert gas to prevent the possibilty of explosion and to allow more time for any hot particles to cool before the char enters the pulverizers.

Coal and char are fed from their respective bins with weigh feeders. Two of the three pulverizers at the plant are fed with a mixture of coal and char. The output of one char feeder and one coal feeder are combined to feed each of the pulverizers. Constant speed rotary valves are located in the outlet pipes from each weigh feeder to provide sealing.

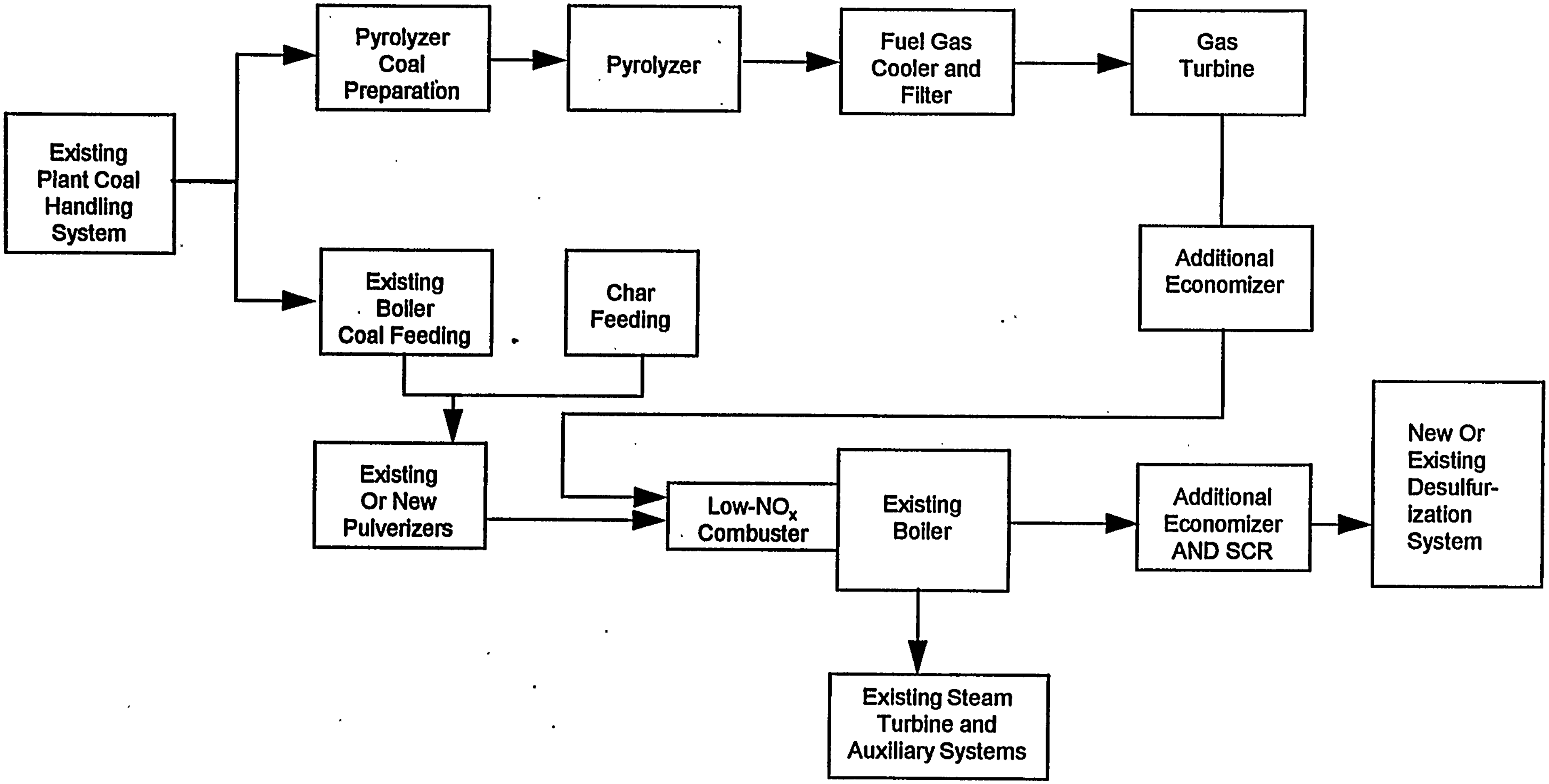


Figure 44 System Block Diagram of HIPPS Repowering

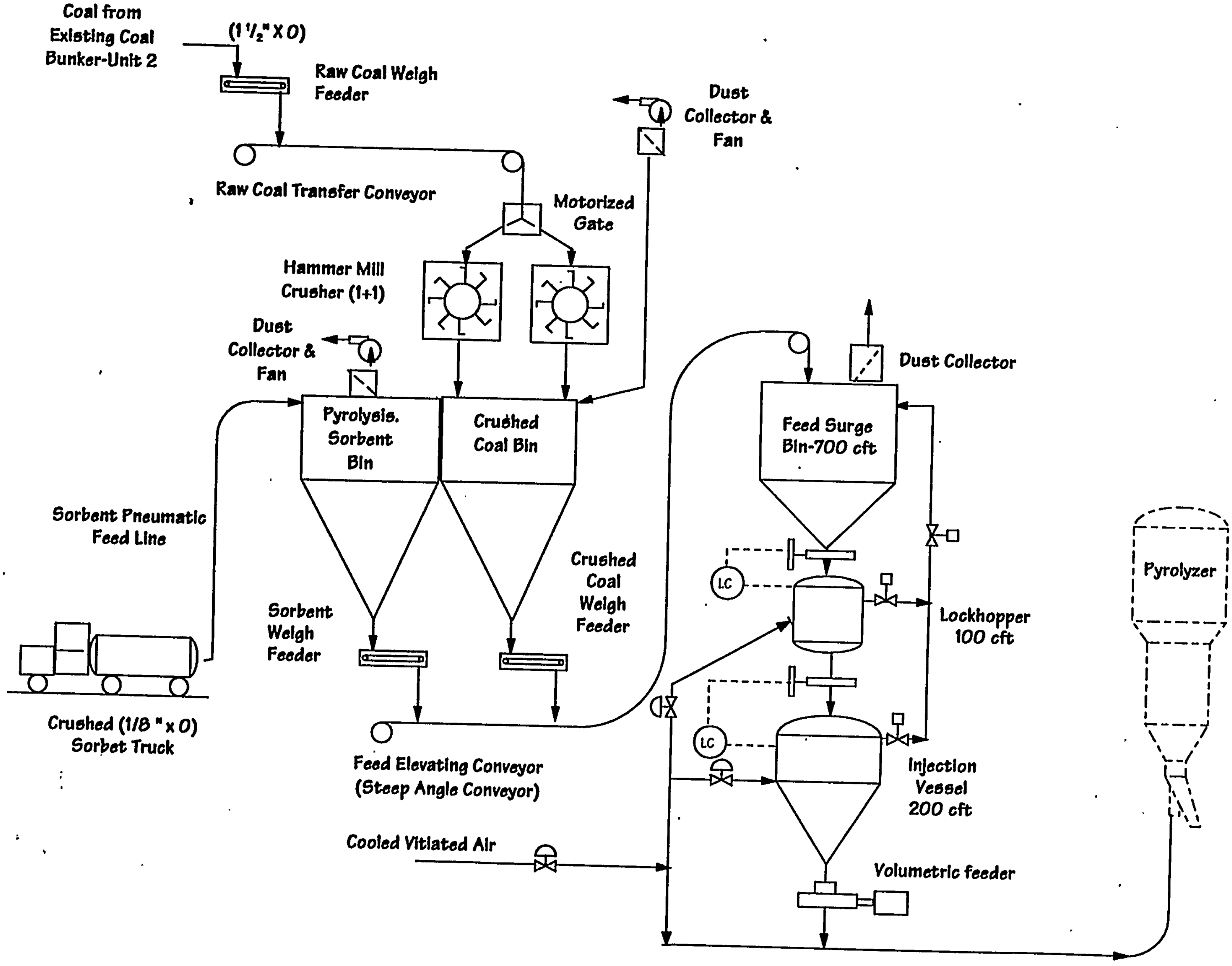


Figure 45 Pyrolyzer Coal/Sorbent Preparation and Feeding

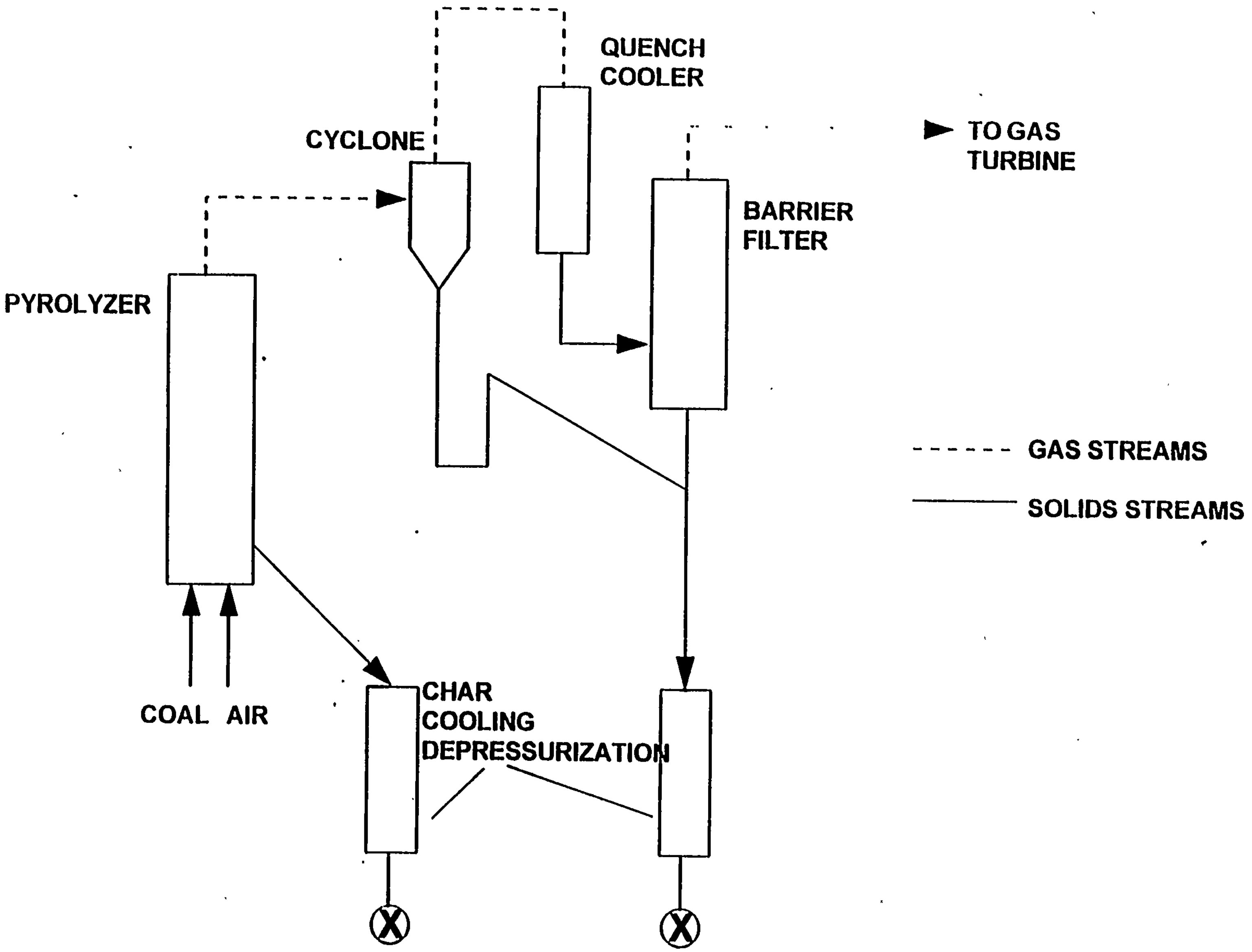
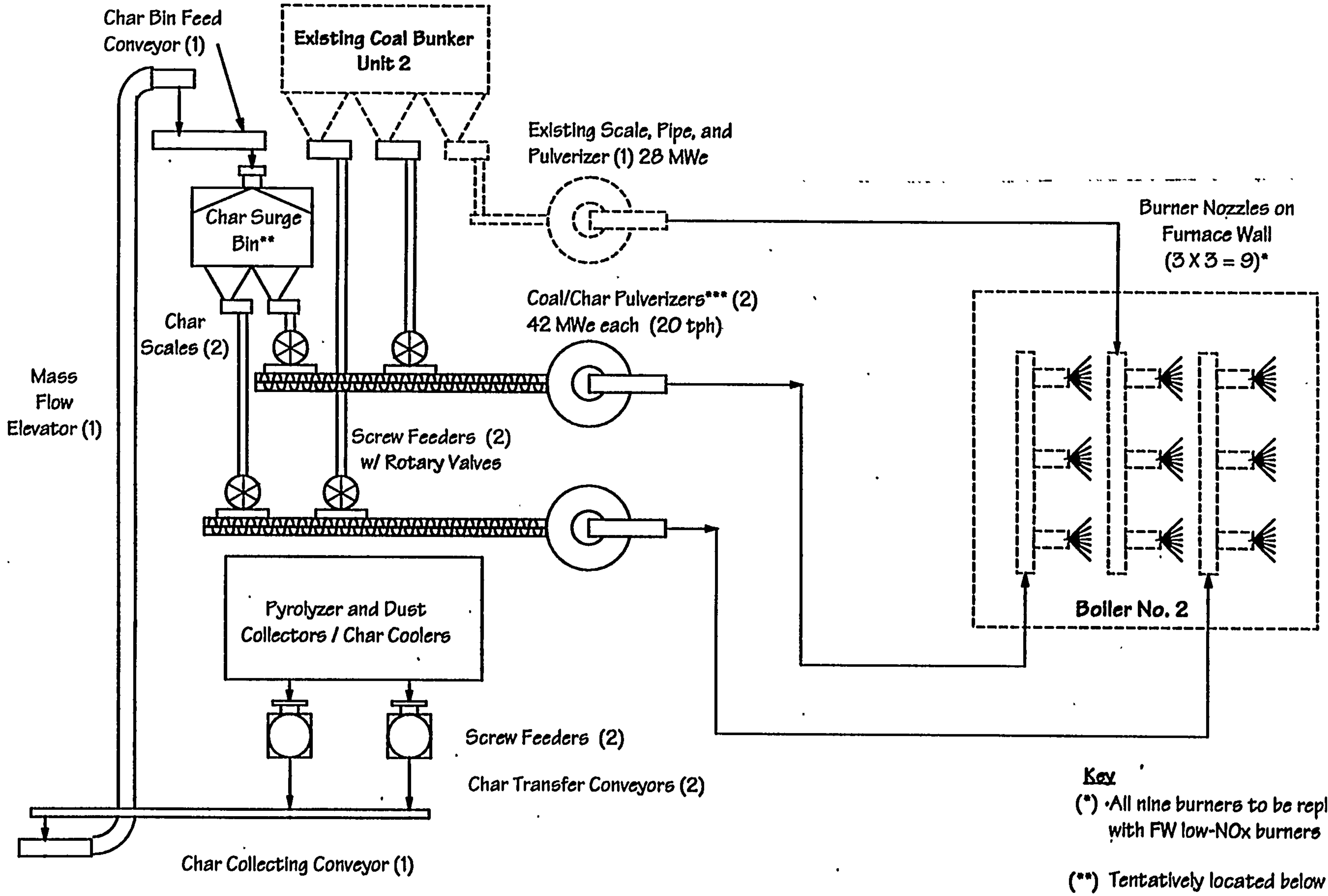


FIGURE 46 PYROLYZER SUBSYSTEM



Key

(*) All nine burners to be replaced with FW low-NOx burners

(**) Tentatively located below coal bunker with top elevation 62 ft

(***) Pulverizers to grind any mixture of coal and char between 0 - 50% char

Figure 47 Coal/Char Feed System to Boiler

The coal and char streams are fed to a common constant speed screw conveyor. The mixture enters the pulverizer through one pipe, and it is possible that existing pulverizers could be used in many applications. At Indian River, it may be necessary to replace the pulverizers because of their age.

Gas Turbine. The gas turbine is a Westinghouse modified 251B12. Other gas turbines are suitable for HIPPS repowering; however, the Westinghouse machine has some features that make it a particularly good match for the HIPPS system and the Indian River boilers. The exhaust gas flow from the gas turbine can be reduced by eliminating two rows of blades in the compressor. Of course, this also reduces the power and efficiency, but it results in a better match with the existing boiler. Another reason for using the Westinghouse machine is that they have developed a combustor that drastically reduces the conversion of fuel gas ammonia to NO_x. The Multi-Annular Swirl Burner (MASB) has been shown limit this conversion to less than 30 percent and in many tests as low as 10 percent [5].

Gas Turbine Exhaust Economizer. The gas turbine exhaust is used for combustion air in the boiler. This stream is at 1045°F which is above the temperature where carbon steel can be used. In order to make use of the existing ducting and windbox and to lower the cost of new ducting, an economizer has been added to cool the gas turbine exhaust stream to 750°F.

Existing Boiler. We believe that the most promising market niche for HIPPS repowering will be units where the existing boiler can be modified and reused. It is also possible to replace the boiler. We have determined costs for both approaches, but the following discussion relates to the modifications necessary to reuse the existing boiler.

Since the gas turbine exhaust is used as combustion air, it is not necessary to have an air heater. The existing air heater is removed and additional economizer surface is used to recover this heat. This added economizer duty replaces heat that was added to the feedwater in the feedwater heaters. Since the steam turbine extraction is eliminated, the main steam flow rate in the boiler is reduced to match the original steam flow rate after the extractions. Although the steam cycle power output is reduced slightly from these modifications, it is more than made up for by the additional power from the gas turbine.

Many of the changes effected by the HIPPS repowering scheme compliment each other. For example, one concern is the effect that the lower oxygen content of the combustion air will have on boiler heat absorption and flue gas velocities. These effects are mitigated somewhat by the lower steam flow required from the boiler. The use of gas turbine exhaust for combustion air lowers the adiabatic flame temperature and therefore the furnace absorption, but less steam generation is required. Also, although some primary superheater pendants will have to be removed to limit flue gas velocity, no superheater tubes need to be added to make up for the reduction in heat transfer surface. Some loops will have to be removed from each of the reheater pendants to decrease this surface area, and elements will need to be removed from the existing economizer.

The changes to the existing boiler are relatively minor consisting mainly of tube removal. No changes are required for the existing enclosure walls, headers, windbox or air ducts. The air heater is removed, and an economizer bank is added in the same location. In oder to achieve the low NO_x emissions required at the site (0.15 lb/MMBtu), an SCR is added behind the boiler, and another economizer bank is located downstream of this device.

Combustors. Because of the significant amount of coal that will be fired with the char, it is possible to use wall burners in the repowering application. It may be possible in some instances to use the existing burners, but in most cases a modification of this system will be required. The effect of lower oxygen combustion air needs to be evaluated for each combustor design. Slagging combustors can be added to the furnace to take advantage of their reduction in ash loadings through the boiler. This approach may lead to somewhat higher allowable flue gas velocities, but further analysis would be required.

The base case design work in the study was done assuming that the wall burners would be replaced with new wall burners. The use of slagging combustors will not have a significant effect on the performance of the plant. This approach will require some modification to the furnace and therefore an increase in cost. Costs were developed for both options.

A more detailed discussion of the repowering design and an economic analysis are contained in Appendix G.

2.8 BACKUP STRATEGIES AND ALTERNATIVE DESIGNS

The backup strategies for individual plant subsystems are discussed in the sections that pertain to these subsystems. We believe that there are sufficient alternative designs and approaches to ensure that the basic concept can be brought to commercialization. The analysis done on this design indicates that it will be economically viable even without further evolution.

Ceramic air heaters were not included in the base case design because we are confident that the proposed design will meet the goals of the project. There is also an alternate design that incorporates ceramic air heaters in the HITAF. The gas turbine air is heated in alloy tubes We completed a conceptual design of this cycle and determined that it could meet the project objectives provided a reliable ceramic air heater was developed. Like our base case concept, the ceramic air heater HIPPS would also have a pyrolyzer to convert the coal into fuel gas and char. The purpose of this conversion process is to provide a fuel for the ceramic air heater that will not cause corrosion or ash deposition problems. In our concept, the fuel gas and char from the pyrolyzer are fired in separate furnaces. Only the products of combustion from the fuel gas firing then pass through the ceramic air heater.

A simplified schematic of the ceramic air heater HIPPS concept is shown in Figure 48. The char is fired in a portion of the HITAF that is basically the same design as the base case HIPPS. Here, the gas turbine air is heated to 1400°F in alloy tubes. The air then goes to the ceramic air heater where it is heated to a temperature that will be determined by the capabilities of this component. The fuel gas is cleaned of alkalies and particulates in the same manner as in the base case HIPPS, and then it is fired in the furnace upstream of the ceramic air heater. Heat is transferred to the steam cycle in the HITAF and in a HRSG in the gas turbine exhaust stream. Details of the ceramic air heater design and the Phase 1 R&D are included in Appendix E.

Both the base case arrangement and the ceramic air heater arrangement can be developed to meet the project objectives. Unless a ceramic air heater is developed to operate up to the gas turbine inlet temperature, this arrangement will have a fuel cost penalty because natural gas will be used for topping combustion. It does not make sense to have a ceramic air heater and use fuel gas in topping combustor because of all the equipment required to include both these functions. The ceramic air heater arrangement does have the advantage of allowing the pyrolyzer to be operated at a lower pressure. Also, there will be no SO_x in the gas turbine exhaust stream which will simplify the FGD system.

If a ceramic air heater could be built to heat the air all the way up to the gas turbine inlet temperature, additional benefits would result. The gas turbine exhaust would not require any SO_x or NO_x removal. The required emissions systems efficiency would be essentially the same, but only one gas stream would have to be treated. Preliminary analyses also indicate that there would be a gain in plant efficiency of about one or two points.

We believe that our concept for a ceramic air heater HIPPS has a better chance of eventual success than other ceramic air heater concepts that have been presented to date. Coal ash management at the temperatures required for these high temperature air heaters is an enormous problem. Various schemes have been proposed by others to keep coal ash off the tubes, but given the quantity of flue gas that will flow through the system, none of these schemes will have the required ash removal efficiency. Our concept will remove 99.99 percent of the ash and virtually all of the alkalies before the fuel is fired. This is done at 1100°F where reliable filtration can be achieved.

Although our concept has the best chance of developing into a ceramic air heater HIPPS, the current state of ceramic air heater development adds a high level of risk to the project schedule. We are going to pursue the development of a ceramic air heater by doing R&D to resolve the technical issues. If this development proceeds at a sufficiently rapid pace, the Phase 3 Prototype Plant could be built with this HIPPS arrangement.

A benefit of our ceramic air heater HIPPS concept is that it does not depend on any particular air heater design. Once a clean fuel is provided, the air heater can essentially be any shape or form. Given the state of ceramic air heater development, this is a particularly important feature. The technical issues and the proposed R&D for ceramic air heaters are included in Sections 3.9 and 4.11.

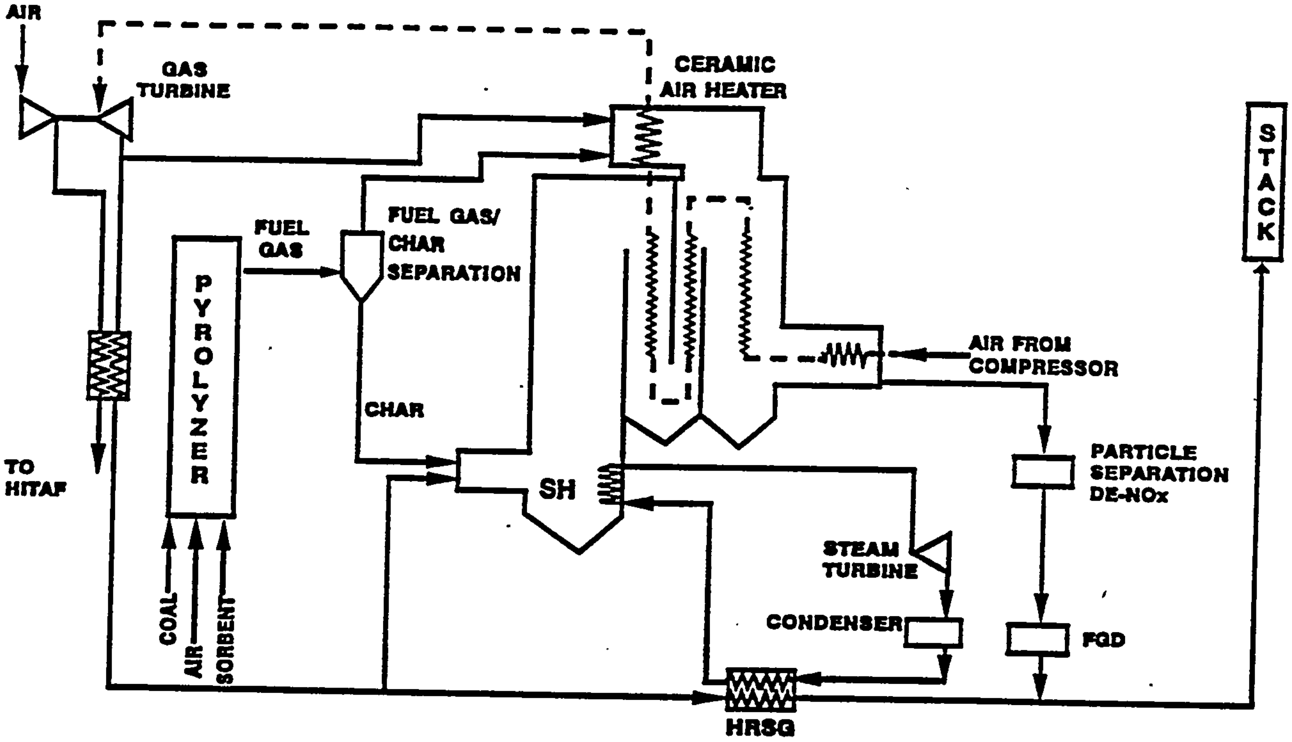


Figure 48 Ceramic Air Heater HIPPS

2.9 COMMERCIAL ACCEPTABILITY OF DESIGN TO POWER PRODUCERS

Advances in control technology have made operation of more sophisticated processes easier and more reliable. Although power producers prefer not to get involved in process activities, the fact is that environmental regulations are already pushing them to more involved processes for emissions control. As the utilities get used to operating plants that are required to meet emissions requirements, they should be receptive to technologies that, although more complicated, offer tangible returns in the form of lower COE.

The HIPPS technology offers a very high efficiency with a plant that uses a fuel that is low priced and should have long-term price stability. If the economic goals of the project are met with a reliable system, there is no inherent reason that the system should not be accepted by power producers. It will have to compete with other concepts that are under development, but at this time, there is no reason to believe that the system will not be able to compete. No systems under development show higher promise for performance, and all have technological issues that need to be resolved.

One of the advantages in accepting the HIPPS plant is a repowering concept that should make economic sense even without externalities (such as siting requirements) as the driving force. As a modular add-on to an existing boiler, the system has lower risk for both the suppliers and the purchasers than systems that are basically greenfields plants that reuse the existing steam turbine. This type of application establishes a user base relatively quickly, and this base would be very beneficial in selling the more advanced plant.

3.0 TECHNICAL ISSUES

3.1 INTRODUCTION

The proposed HIPPS concept has a solid technological foundation. There are no gaps in the basic technologies that could halt progress in the development of the system. The system is new, but it builds off of technologies that are either commercial or being demonstrated on a large scale. For example, the pressurized fluidized bed pyrolyzer is similar in design and operation to the high temperature Winkler process which has been demonstrated at 170 TPD scale. Our process differs in that only partial conversion of the coal is required, but the general design and operation are similar.

Another important technology for the HIPPS plant is the efficient combustion of char. Foster Wheeler has years of experience in burning low grade fuels including the world's largest base of anthracite fired boilers. Testing in Phase 1 of the project has indicated that the char should be easier to burn than anthracite. The TRW combustor, which has been chosen as the base case combustor, will be demonstrated in the Healy Alaska Clean Coal project. Although the coal in that project is bituminous, it is very high in ash.

Work was also done on the development of a HIPPS plant that used a ceramic air heater. This type of a system is not proposed for Phases 2 and 3 of the project because we believe that the state-of-the-art of this technology will not support the development schedule of the project. Basic issues such as mechanical reliability, corrosion resistance, and fabricability need to be resolved to a greater degree. We have been working on these issues in Phase 1 and are including further development as part of Phase 2, but the base case HIPPS plant does not depend on ceramic air heater technology.

Although the basic technology required for the HIPPS plant exists, research needs to be done to develop the design and process information that is required for a commercial plant. The individual components need to be designed and operated in a manner that is complementary to other components and all the components need to be integrated into a system that will operate efficiently and reliably. For example, it is not sufficient that the pyrolyzer just make fuel gas and char. The char must be suitable for combustion in the HITAF, and it must be delivered to the HITAF in a manner that is compatible with the operation of the char combustor. The development of these components and systems for HIPPS will require R&D, but the basic technologies are far enough along that we are confident of success. The following subsections discuss specific technological issues relevant to the development of HIPPS.

Table 35 lists the plant subsystems by number and indicates the general maturity of each technology. The technical issues as related to HIPPS are also listed along with our approach to resolving these issues. The relevant sections of this proposal that discuss these issues and approaches are indicated in the table.

Table 35 Status of HIPPS Technologies

PLANT SUBSYSTEM	MATURITY	ISSUES FOR HIPPS APPLICATION*	DEVELOPMENT APPROACH*
1 Solids Feeds and Removal			
1.1 Coal prep/feeding	Commercial	None	--
1.2 Sorbent prep/feeding	Commercial	None	--
1.3 Ash/slag removal	Commercial	None	--
2 Steam Generator Island			
2.1 High temperature furnace	Mature	Materials	Bench scale tests (3,4)
2.2 Coal/char combustor	Pilot scale demonstration	Char combustion, NO_x, Scale-up and design (2.4)	Bench scale, subsystem and pilot plant tests (3.4, 3.6)
2.3 Heat recovery systems	Commercial	None	--
2.4 Stacks/ducting	Commercial	None	--
2.5 I.D. fan	Commercial	None	--
3 Recuperator	Commercial	None	--
4 High Temperature Piping/Ducting	Commercial	None	--
5 Process Systems			
5.1 Pyrolyzer	Demonstration units	Yields, hydrodynamics, solids characteristics, operating characteristics under HIPPS conditions (2.2)	Bench scale (3.9) and pilot plant Tests (3.2, 3.6)
5.2 Cyclones	Commercial	None	--
5.3 Fuel gas cooler	Demonstration units	None	--
5.4 Barrier filter	Demonstration units	Operation at HIPPS conditions	Pilot plant tests (3.2, 3.6)
5.5 Solids transport	Commercial except for RPD	RPD/Transmission system design and operation (2.3)	Cold test (3.2) pilot plant tests (3.2, 3.6)
5.6 Pyrolyzer compressor	Commercial	None	--
6 Gas Turbine/Topping Combustor	Gas turbine commercial topping combustor demonstration tests	Operation at HIPPS conditions	Engineering Analysis (3.5)
7 Steam Turbine/BFW	Commercial	None	--
8 Emissions Control System			
8.1 Particulate removal	Commercial	None	--
8.2 SO_2 removal	Demonstration units	None	--
8.3 NO_x removal	Demonstration units	Operation at HIPPS conditions	Pilot plant tests (3.6)
10-13 Balance-of-Plant	Commercial	None	--

* Relevant Sections of the proposal are indicated in parenthesis.

3.2 PYROLYZER

Although some of the details of the pyrolyzer design and operation are unique, the general process has been around for almost 70 years. Pilot plants, demonstration units, and commercial plants have used similar technology. In addition to coal gasification experience with this type of reactor, there are many commercial applications of circulating fluidized bed boilers. Foster Wheeler alone has built seven units, and the experience gained with these units can be applied to various aspects of the pyrolyzer.

The earliest commercial application of a fluidized bed gasifier is the Winkler process, which was first used in the 1920s. At least 16 commercial units have been built throughout the world, using coals ranging from lignite to bituminous. A pressurized offspring of the Winkler process was developed in the 1970s—the high-temperature Winkler (HTW) process. Like the HIPPS pyrolyzer, it uses a pressurized circulating fluidized bed. A 130-psig 35-t/d pilot plant was operated at Wachtberg from 1978 to 1985 for over 38,000 hours. A 130-psig 720-t/d demonstration plant built at Berrenrath in 1986 has accumulated over 30,000 operating hours. A 350-psig 170-t/d pilot plant HTW built in Wesseling has operated for over 8000 hours so far. Based on the results of this research, a 300-MW IGCC demonstration plant is being designed.

The Institute of Gas Technology (IGT) developed a fluidized bed gasification process called U-Gas. Work on this process started in 1945, and several pilot plants were built with capacities of up to 18 t/d. The rights to the process for most of the world were sold to Tampella, and a 430-psig, 40 t/d demonstration unit built in Finland was commissioned in 1992. IGT still has the rights to the technology in China, and a 1000 t/d commercial facility was built in Shanghai in 1994. The technology has also been selected for a Clean Coal project. A 190-MWe plant, called the Toms River IGCC Demonstration project, is planned.

Another related technology is the KRW gasifier, which is being used for the Clean Coal Piñon Pine IGCC Power Project. Foster Wheeler is the architect, engineer, and constructor for this project. This project is in the fabrication stage.

In many ways, the HIPPS pyrolyzer is less of a technological risk than the related gasification systems. Since only about 70 percent of the carbon is converted in the HIPPS, temperatures can be lower, reducing the tendency for high-temperature agglomeration. Also, maintaining cycle efficiency with gasifiers requires that only minimal carbon is left in the ash. The recycle and conversion of fines becomes critical in these units. In contrast, the HIPPS burns the char in an atmospheric PC-fired combustor and furnace, where there is much more design flexibility for obtaining good carbon burnout. Also, the heating value of the fuel gas will be higher in the HIPPS system than in air blown full gasification systems.

As discussed in Section 2.3.5, there are two basic aspects to the pyrolyzer design—the coal conversion process and fluidized bed operation. Research on circulating fluidized beds is too widespread to completely address here. Models have been built and tested, and scaling criteria have been developed. Pilot plants and commercial fluidized bed boilers have been built by Foster Wheeler and others. Thus there is a body of both practical and theoretical knowledge to draw from in the design of the HIPPS pyrolyzer.

The second-generation PFB pilot plant test work at FWDC is very applicable to the HIPPS design. Although most of the pyrolyzer tests were run with a jetting fluidized bed, four setpoints were run with a circulating bed arrangement. These runs proved the feasibility of a circulating bed arrangement and provided yield data. These data showed that carbon conversion and other process parameters were very close to those of the jetting bed. Because of this situation, the more extensive range of parameters tested in the jetting bed arrangement can be applied to the circulating bed arrangement.

Some potential technological issues concerning the pyrolyzer operation were resolved during the second-generation PFB pilot plant tests. A major concern before these tests was that tars would be produced that foul and plug equipment in the fuel gas stream. No evidence of tars was found in any of the tests. There was also concern about the degree of sulfur removal that would occur under the conditions in the pyrolyzer, but the tests showed that only 2 to 5 percent of the sulfur in the coal went into the fuel gas.

Although the feasibility of a circulating bed pyrolyzer has been proved, specific design information must be generated for the HIPPS pyrolyzer. The basic difference in approach between the HIPPS concept and other coal conversion systems is that the generated char will be fired in an atmospheric furnace using a PC-fired combustor. The size and combustion characteristics of the char are therefore important, and these requirements affect the design of the pyrolyzer. The coal and sorbent feed will be smaller than that used in the second-generation PFB pilot plant tests, and removal of char from the pyrolyzer must be done in a manner that will result in a narrower range of particle sizes.

As discussed in Section 2.3.5, the primary cyclone will classify the char particles sent to the char combustor. Cyclones are a very mature technology, and there is a high confidence level that the cyclone can be designed to achieve the correct char particle size range. What is less certain is the feedstock sizes needed to achieve the required flow rate of char from the pyrolyzer. A related concern is whether the flow rate of the char leaving the pyrolyzer must be controlled. The Phase 2 RD&T plan addresses these issues, and there are design options depending on the results of those tests. Feedstock size can be changed by pulverizer classifier adjustments or design modifications. If significantly coarser particle sizes are required, various types of crushers are available.

With a given coal feed rate, the amount of solids exiting the primary cyclone with the fuel gas will be affected by particle attrition and particle elutriation from the bed. To some extent, the pyrolyzer will tend toward steady-state operation, where the ratio of char to fuel gas leaving the primary cyclone reflects the generation of these fuels in the pyrolyzer. This tendency exists because the bed level will rise and elutriation will increase if not enough char is leaving the bed. Increased elutriation raises the solids circulation rate, increasing the rate of attrition and the flow rate of solids through the cyclone. Both effects will tend to increase the flow of char leaving the pyrolyzer with the fuel gas. The converse situation will also tend toward the equilibrium situation.

The bed height can vary only over a certain range or performance will suffer. Other means may be necessary to add additional control over the flow rate of char leaving the pyrolyzer. One method would be to size the cyclone for excessive particle carryover and use a solids eductor to reinject char into the pyrolyzer. Another method would be the manipulation of the cyclone efficiency either mechanically or by the injection of gas at strategic locations. There are cyclone type devices that are specifically designed for the classification of solids. A third method would be to remove a stream of solids directly from the bed. This stream would then be cooled and pulverized before being sent to the char combustors. The solids eductor is commercially available although the temperatures in our system are higher than most current applications. If any additional systems are required, they will have an effect on plant capital cost, but probably to a minor degree only.

Another technical issue is the removal of sorbent from the bed. The removal of significant amounts of sorbent as CaS is to be avoided since this material would have to be further processed before disposal. Two approaches are possible. One approach is to size the sorbent fine enough such that it will carry over with the char going to the char combustor. At the conditions in the char combustor, the CaS is not likely to cause a disposal problem. Most likely it will decompose and the sulfur will be released into the flue gas. The fate of the CaS in the char combustor is discussed in more detail in Section 3.4.

Another approach is to remove spent sorbent from the bed in the form of $CaSO_4$. This is the approach taken as the Commercial Plant base case in terms of hardware design; however, no credit was taken for sulfur removal in this stream. With this method, the sorbent is sized such that it will preferentially segregate to the bottom of the riser section where it would be oxidized by air entering the pyrolyzer. If sufficient residence time at temperature is provided in this section of the bed, the sorbent will be removed as $CaSO_4$. According to the modeling results, this type of operation will be feasible, but it will need to be evaluated in the Phase 2 tests. If the oxidizing section proves not to be feasible, we would size the sorbent for more carryover and provide an external fluidized bed to oxidize whatever sorbent needs to be removed from the riser section as CaS.

In summary, there is a high degree of confidence in the basic pyrolyzer technology, but there are several issues that need to be resolved in order to design the pyrolyzer for the HIPPS plant. We have planned a development program for Phase 2 and 3 that addresses these issues. This plan is presented in Section 4.2, 4.6, 4.9 and 4.10. The pyrolyzer testing will proceed in steps, each step increasing the scale and degree of integration of the pyrolyzer and its associated subsystems. The first pilot plant test will be at approximately 600 lb/h of coal input. This test, the Pyrolyzer/Char Transport Test (PCTT), will test a circulating fluidized bed pyrolyzer that is connected to a char transport system. This test will resolve the basic operation and configuration issues and provide design information for the next level of scale and integration which is the Integrated System Test (IST).

The IST pyrolyzer will operate at approximately 6,000 lb/h coal input, and it will fully integrate the pyrolyzer with the char combustor and furnace. During this test program, the pyrolyzer design will be refined as necessary to achieve the necessary operating characteristics. Although the PCTT will be of sufficient scale to determine yields and the basic pyrolyzer configuration, design details such as the design and location of the paste and air injectors may change with scale. The step in scale from the PCTT to the IST will also give a benchmark for the scale up criteria and a start point for scale up to the Prototype Plant. The Prototype Plant Pyrolyzer will have a coal input of approximately 40,000 lb/h.

3.3 CHAR SEPARATION AND TRANSPORT

The char separation and transport system presented as the base case design is one of several arrangements that can be used. It was chosen as a reasonable approach, given the current state of the relevant technologies. There are alternative approaches that involve less technological risk, but may have higher costs. There are also areas where advances in technology could simplify the subsystem and lower costs.

The area of greatest uncertainty in the char transport system is the RPD system. This system provides the function of depressurizing the char collected in the pyrolyzer system. It is described in detail in Section 2.3.5. This type of a system is inexpensive and simple to operate; however, there are no commercial applications yet, and the laboratory tests done so far have used coarser material. These tests have successfully used particle size distributions with average particle sizes down to 132 microns and pressure differentials of 100 psig [6]. The average particle size in the HIPPS stream will be 65 microns. The Institute of Gas Technology (IGT) and the Particulate Solids Research Institute (PSRI) have done prior development work in this area, and they will be working on this project as part of our team. Tests will be run on a cold model of the RPD system to determine its performance and establish the design for the pyrolyzer/char transport test (PCTT). The cold model test will give us information early in the project as to the feasibility of this approach. As previously mentioned, the PCTT will be a pilot plant test that will integrate the operation of the pyrolyzer and the char transport system. The cold model tests of the RPD system and the PCTT are discussed in more detail in Section 4.2.

If the RPD hopper concept is deemed to be unsuitable in either the cold tests or the PCTT, an option is to use a lock-hopper system to drop the pressure. In the present system design, the solids are cooled to 1580°F before they enter the RPD system. If lock-hoppers are used, more cooling of the solids will probably be required. Steam coils would be used to cool down the solids to 1200°F for more reliable valve operation.

Screw coolers are specified as the base case method of controlling the char flow to the char combustors. These devices are sold commercially and have been used with solids in excess of 1700°F. If a means of flow control with less moving parts could be used, reliability would probably be improved. In Phase 2 we will investigate the reliability of in service screw coolers to determine if it is sufficient for the HIPPS plant. The plant is designed with two screw feeders and two pneumatic transport lines for each char combustor, and it will be possible to isolate any of the feeders and lines during operation.

Alternate methods of controlling the char flow are to use a slide valve or a non-mechanical valve to regulate the solids flow into the pneumatic feed line. Slide valves are used in fluidized bed catalytic crackers to control the flow between the reactor vessel and the regenerator vessel. Non-mechanical valves such as J-valves and L-valves have been used in circulating fluidized beds. These alternatives will probably be more mechanically reliable than screw coolers, and they certainly will be less expensive. At this point, a drawback is the lack of an accurate means of directly measuring the solids flow. These devices can be calibrated, but the accuracy of the calibration as conditions change is a concern. The development of instrumentation that measures solids flow in the RPD standpipe or pneumatic transport line would increase the usefulness of these valves.

3.4 CHAR COMBUSTOR DEVELOPMENT ISSUES

The state of development and integration status of the slagging char combustion system has been assessed during Phase 1 of the HIPPS program by comparison of the performance demonstrated to date with the requirements necessary to meet the HIPPS system requirements. During this assessment, a number of development issues were identified that must be addressed prior to successful commercialization of the HIPPS concept. These development issues fall into three general categories, namely: Combustor Performance Issues, Combustor Design Issues and Combustor Operational Issues, as is illustrated in Figure 49.

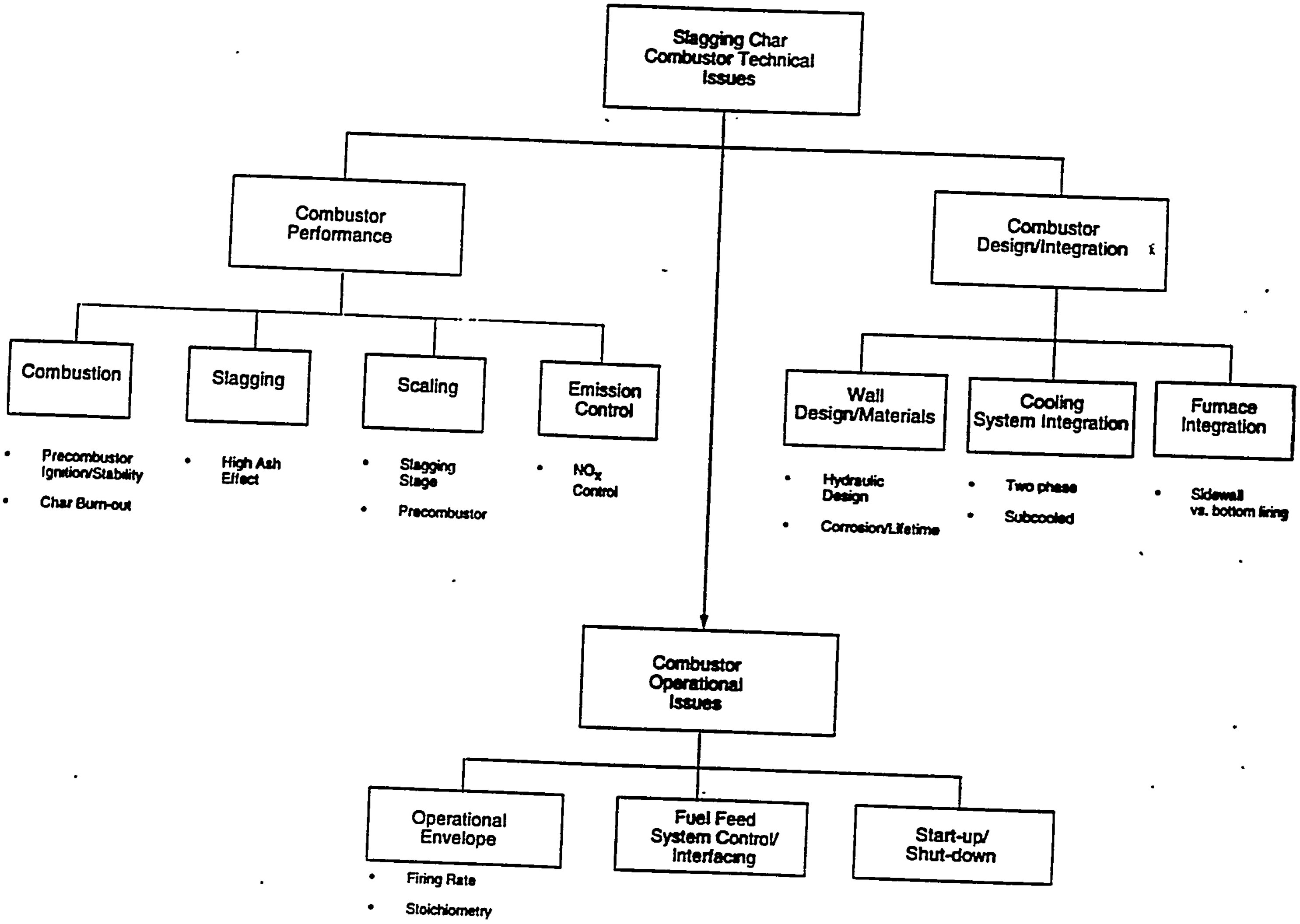


Figure 49 Slagging Char Combustor Technical Issues

Figure 50 illustrates the technology status as it relates to the major issues listed in Figure 49. The assessment includes present status as well as the anticipated status at the conclusion of Phases 2 and 3. It is seen that for all the issues listed, the commercial readiness will be established at the conclusion of Phase 3. Examination of Figure 50 reveals that for some issues, engineering development data is already available whereas for some others, only a feasibility assessment is available to date. The technical risk can be gauged by the present state of readiness and the anticipated level at the conclusion of the Phase 2 development effort.

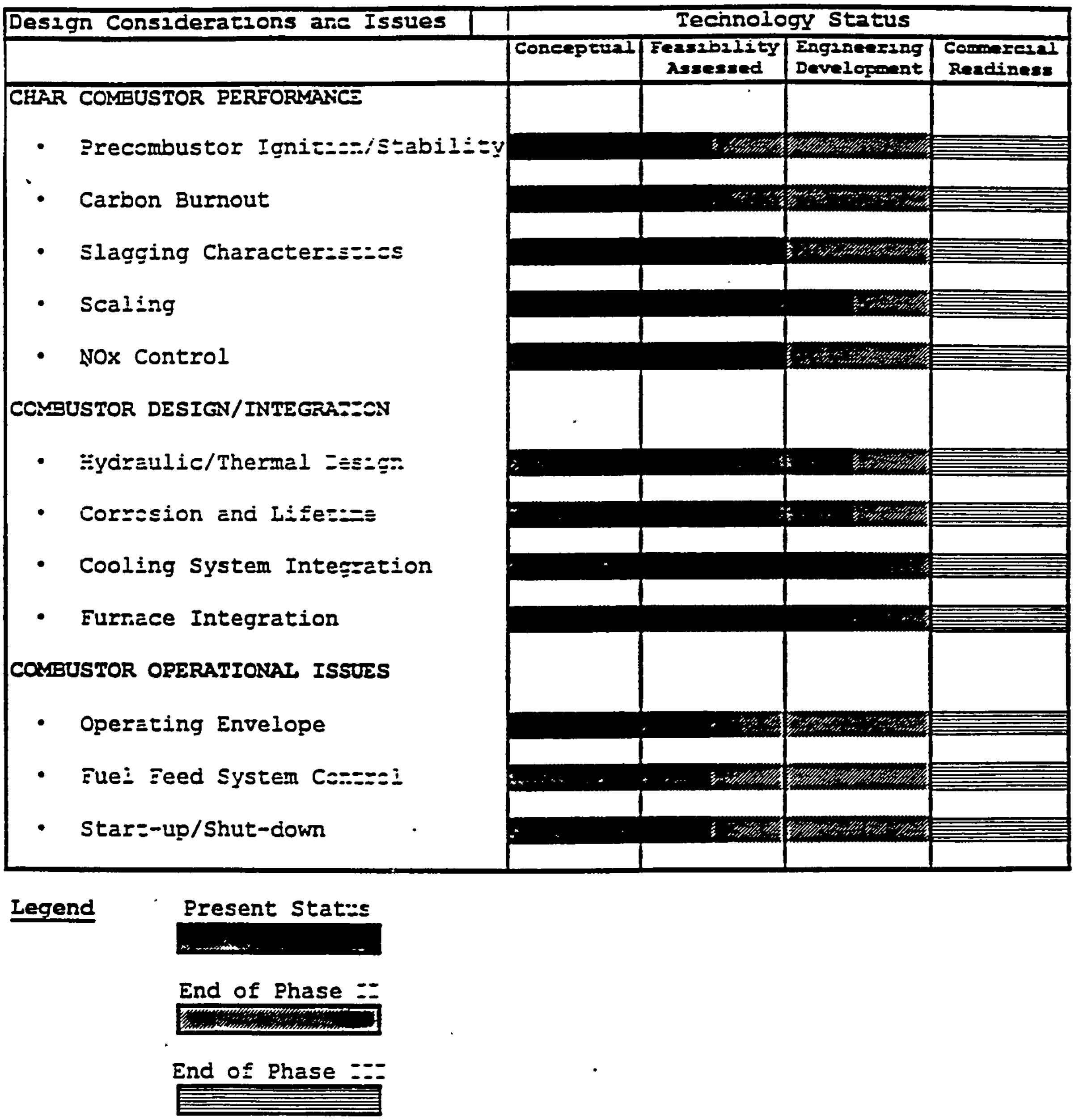


Figure 50 Technology Readiness

As will be discussed later, the Phase 2 RD&T plan for the char combustor includes subscale component testing at the TRW Capistrano Test Site, which will focus on performance issues, and integrated HIPPS system testing to be conducted at the University of Tennessee Space Institute (UTSI), which will focus on operational issues. Design and integration issues will be addressed in support of and as part of the overall system design. A discussion of the key development issues follows.

3.4.1 Combustor Performance Issues

Carbon Burnout

One of the primary performance issues for the char combustor is char burnout, or the minimization of carbon losses, given the low volatile content in the pyrolyzed char. However, unlike naturally occurring low volatile fuels such as anthracite coal, pyrolyzed char tends to have relatively high internal surface areas (200 - 500 m^2/g, based on CO_2 surface area, 50 - 150 m^2/g, based on N_2 surface area), which enhances reactivity. Char characterization tests conducted at Brigham Young University (See Appendix A) and char combustion tests conducted at TRW (See Appendix B) during Phase 1 have both indicated that pyrolyzed Pittsburgh No. 8 char produced by Foster Wheeler was as reactive, or more reactive than its parent coal, following devolatilization.

As a result of its relatively high temperature environment (2800 - 3200°F) and operational flexibility, the TRW slagging combustor is well suited to efficiently burn char with minimum carbon losses. Through the use of a coal-fired precombustor, the combustion air is preheated to temperatures in the range 1800 - 2200°F, enhancing particle heating rates and flame stabilization within the headend of the slagging stage. Toroidal recirculation zones present parameters within the headend also promote flame stabilization. In addition, char combustor operating parameters such as precombustor preheat temperature and combustor stoichiometry can also be adjusted to achieve optimum performance.

NO_x Control

The control of NO_x emissions by combustion under fuel rich conditions relies on precursor and NO destruction through reactions of the type:

$$NO + NH_2 \rightarrow N_2 + H_2O \qquad (3.4.1\text{-}1)$$

For a total fixed nitrogen pool, the destruction rate is maximum when the concentration in amines is comparable to the NO level. NO_x emissions of the order of 0.2 lb NO_2/MMBtu have been demonstrated with the TRW slagging combustor. Data acquired by TRW for different coals and combustor operating conditions has been used to anchor combustor computer models which in turn can be used to predict NO_x emissions and investigate alternate strategies for the control of NO_x.

For the HIPPS char combustor, there are a number of factors that must be considered with regards to NO_x control. First, the overall NO_x emission goal is 0.06 lb NO_2/MMBtu, which is below the demonstrated level of the slagging combustor. To reach this level, either the char must have lower NO_x characteristics than most coals, or an alternate control strategy must be implemented. Second, the char contains very little volatile nitrogen or hydrocarbons, which are usually the principle sources of nitrogen-bound species (HCN, NH_i) that are used to destroy NO under high temperature, fuel-rich conditions. Third, the adiabatic flame temperature for char firing under HIPPS conditions is lower than typical coal-fired slagging combustor conditions, due to the reduced oxygen content in the combustion air, as well as the reduced heating value of the fuel.

Preliminary NO_x emission predictions for the char combustor are presented in the char combustor design section (Section 2.3.2.2). These calculations indicate that total fixed nitrogen compounds are minimized at a combustor stoichiometry of approximately 0.85, at a level of

0.10 - 0.15 lb NO_2/MMBtu. If it is determined that combustor NO_x goals cannot be met through combustion modifications alone, the alternate control strategy is to inject ammonia-type compounds near the combustor exit. NO_x levels as low as 50 ppm have been demonstrated with ammonia injection under fuel rich conditions, for gas temperatures in the 2600 - 2700°F range [7]. The gas environment near the exit of the TRW combustor is ideal for this method of NO_x control, as the flow in this zone is quite uniform in terms of temperature and composition, and the residual swirl from the slagging stage can be used to promote rapid mixing.

Precombustor Ignition and Flame Stability

As mentioned in Section 2.3.2.2, firing pyrolyzed char in the precombustor offers the potential advantages of a higher overall system efficiency, a smaller bottoming cycle, and lower capital costs. However, due to the low volatile content and corresponding high ignition temperature of the char, the issues of precombustor ignition and flame stability must be addressed. Several factors which promote ignition prevail within the precombustor so that satisfactory performance should be obtainable when firing char. These factors include: high air preheat (1125°F), hot refractory surfaces within the precombustor can, and recirculation of hot gases induced by the inlet swirl.

Char combustion laboratory testing was conducted during Phase 1 to gather preliminary data on char ignition and flame stability. In addition, analytical model calculations using TRW's IGNITION program (see description in Section 4.3) have been performed to determine flame temperature profiles and carbon burnout as a function of combustion chamber length and recirculation. Results indicate that reasonable carbon burnout (70 - 80 percent) can be achieved within one chamber diameter. This would lift the combustion air temperature into the 2000 - 2300°F range, provided 35 - 40 percent of the total char is fired in the precombustor. If required, a modest amount of fuel gas (approximately five percent of precombustor enthalpy input) could be used to ensure stable operation. The same model applied to the proposed R&D subscale unit shows comparable performance provided that a finer grind (325 to 400 mesh) is used in that instance.

Slagging Characteristics

There are several issues related to slag properties and slagging characteristics for the proposed char combustor that must be addressed during the Phase 2 development program. First, the ash content in the fuel, 20 to 30 percent, is higher than most coals, as a result of the pyrolysis process. This leads to a relatively high slag flow rate for a given combustor size and thus special consideration must be given to baffle keyslot and slag tap sizing.

Second, spent sorbent from the pyrolyzer is mixed with the char and may affect slag fluid properties. The impact of slag viscosity and fluid temperatures will depend on the type of coal as well as the sorbent loading within the pyrolyzer. For Pittsburgh No. 8 coal at a pyrolyzer Ca/S ratio of approximately 2, the presence of excess calcium increases the slag fluid temperature from 2500 to 2600°F, however, this is still well within the demonstrated slagging combustor operating envelope.

Third, there has been concern that calcium sulfide from the char may still be present within the slag removed from the combustor, thus requiring additional treatment prior to reuse or disposal. Preliminary results from Phase 1 indicate that very little calcium sulfide, if any, can be expected to be recovered with the slag, for the following reasons: (1) during tests conducted at BYU, the rate of calcium sulfide decomposition exceeded the char oxidation rates, thus conditions which yield high carbon burnout will also yield high calcium sulfide decomposition rates, (2) any calcium sulfide that does not decompose either in-flight or along the slagged walls of the combustor will most likely decompose within the slag quench tank in the presence of water, and (3) very little sulfur has been measured in slag recovered from the TRW slagging combustor (less than 1%), even for tests involving sorbent injection within the slagging stage. Subscale char combustor tests will be conducted during Phase 2 to confirm these preliminary results.

Scaling

The issue of scaling relates not so much to the ability to design future commercial scale slagging char combustors, but in ensuring that the subscale test conditions are selected in a way which ensures that the data can be applied with confidence to the design of future commercial units. To this end, a major effort in the modeling and selection of conditions and sizes for subscale R&D testing will be to ensure that the data can be scaled when the physical size of the hardware increases. From the point of view of combustion, selecting finer coal grinds for subscale testing provides the right residence time scale while still dealing with topologies (aspect ratio) representative of future commercial systems. Subscale testing should also be such that the radiative coupling to the walls is representative of large units. From these view points, the use of finer coal grinds is also beneficial. From the NO_x control view point, the kinetic time scale is less favorable at small sizes, but mixing is usually easier to implement. Accordingly this is also an area where application of the subscale data to future commercial systems also requires proper modeling and scaling.

3.4.2 Combustor Design Issues

Wall Design / Material Selection

The baseline char combustor design approach is to retain as many of the design features of the Healy combustor as possible, while still meeting the requirements of the HIPPS system. This represents the minimum risk and minimum cost approach. However, there are two factors specific to the HIPPS char combustor which necessitates that special attention be given to combustor cooling tube design and material selection. First, the sulfur levels within the combustor are elevated, due to the higher sulfur content within the char and spent sorbent. Second, the operating temperatures of the combustor cooling tubes are approximately 50°F above the design temperatures used for the Healy combustor. Both of these factors increase the potential for high temperature sulfidation in the reducing zones within the combustor. This may require selection of a different cooling tube and membrane material than that used at Healy (low alloy steel, ½ Cr, ½ Mo)or selection of a coating material in specific areas of concern. Most likely a higher chromium content (i.e., 2¼ Cr) will be required for the higher operating temperature and pressure of the combustor cooling tubes.

Cooling System Integration

The integration of the combustor cooling system within the HIPPS plant is another issue that must be addressed. The baseline combustor cooling arrangement uses saturated steam drum water and relies on two-phase flow cooling, similar to the Healy combustor cooling system. An alternate sub-cooled cooling circuit integration arrangement could be used, provided this scheme could be accommodated within the overall plant design. In this approach, boiler feedwater is used to cool the combustor. A high circulation rate is maintained within the combustor cooling circuit. This arrangement offers the advantages of lower operating temperatures for the wall design and the possibility of simpler (and accordingly less expensive) tube arrangements for the combustor.

The feasibility of cooling the char combustor with high pressure, high temperature air from the gas turbine compressor must also be addressed. This method of cooling may be attractive for the overall system, particularly for a repowering application where it may be difficult to add air heater surface within the existing boiler. Specific char combustor design issues that must be addressed are the cooling passage design (air velocities, temperature drop and pressure drop) and material issues associated with the use of high pressure, high temperature air.

Furnace Integration

The physical arrangement for the combustor and the topology of the slag recovery section can be modified to accommodate either sidewall firing or bottom firing of the boiler. The baseline configuration is a bottom (or hopper) firing configuration which will be demonstrated as part of the Healy Clean Coal Project. This configuration makes better use of the available floor space and alleviates somewhat the interface problems associated with support of the combustion system and thermal growth. An alternate approach which will be considered is side wall firing, which was successfully demonstrated as part of the Cleveland Pilot Plant installation. This approach simplifies furnace hopper construction, and may reduce the height requirements of the furnace.

Char Feed Splitter

A long duration, six-way coal splitter has been developed for the Healy coal feed system to provide coal to six individual injectors in the headend region of the slagging combustor. The Healy coal feed system is based on dilute pneumatic transport, with a baseline solids to gas ratio for this feed system is approximately 1.25:1. For the HIPPS plant, fuel gas from the pyrolyzer will be used to transport the char to the combustor, at a solids-to-gas ratio of approximately 10:1. In order to operate properly under these conditions, the Healy splitter may require design modifications. This will be investigated during Phase 2 of the HIPPS program.

3.4.3 Combustor Operational Issues

The char combustor plays a critical role in the operation of the HIPPS plant, essentially serving as a link between the topping cycle (pyrolyzer and gas turbine) and the bottoming cycle (high temperature furnace, steam turbine, and heat recovery equipment). The operation of the char combustor is closely tied to that of the pyrolyzer and char feed system. The pyrolyzer affects both char properties (volatile content, heating value, ash content, and particle size) and to some extent, char feed rate. The char feed system affects char feed rate, char temperature, carrier flow rate, and char feed steadiness. In addition, the char combustor operation is also dependent on gas turbine operation, which provides high temperature, vitiated air to the combustor. Finally, the operation of the char combustor must be carefully coordinated with the operation of the boiler and steam turbine systems, in particular during start-up, shut-down, and turn-down operations.

Operating Envelope

Because of its critical role within the HIPPS plant, the char combustor operating envelope must be well-characterized so that appropriate plant operating procedures can be specified.

While operation of the TRW slagging combustor under coal-fired conditions has been well-characterized, additional subscale tests are required to characterize the combustor operating envelope under char-fired conditions. Specifically, operating ranges for the following parameters: combustor firing rate, precombustor and slagging stage stoichiometry, precombustor preheat temperature, and air preheat temperature and oxygen content. Key issues include the determination of char combustor turndown limits, minimum air preheat temperatures and oxygen content, minimum precombustor preheat temperature (for coal-fired operation), and optimum stoichiometry range for both NO_x control and carbon burnout.

Fuel Feed System Control and Operation

As mentioned above, the char combustor performance and operation is closely tied to the design and operation of the char feed system. In order for the combustor to operate properly, the char flow rate must be accurately controlled and measured. Uncontrolled variations in char feed result in combustor stoichiometry and firing rate variations, which in turn may lead to variations in combustion exit temperature, NO_x emissions, heat loads to steam and air circuits, and slagging behavior. Close and coordinated development of the char feed system and char combustor is thus required to ensure steady and controllable system operation.

Combustor Start-Up and Shut-Down

Due to the highly integrated nature of the HIPPS plant, start-up and shut-down procedures require special consideration. Key issues related to the char combustor during start-up and shut-down operations include: combustion air temperatures and oxygen content, cooling water temperature and pressures, char feed rates, fuel properties variations, and ignitor requirements.

3.5 HITAF

The HITAF design is similar to commercial pulverized coal boilers. The tube banks and enclosures are designed and constructed in the same manner as these boilers. The main difference between the HITAF and a commercial boiler is the air heater tube bank. The design of this tube bank is similar to boiler tube banks in terms of mechanical design, heat transfer and fluid flow, and existing data can support the design in these areas. One area that needs some further development is material selection for this air heater. The metal temperatures will be higher than are encountered in boilers, and the corrosion characteristics of candidate materials in the HITAF environment need to be evaluated.

Foster Wheeler has extensive experience in the design and operation of coal-fired boilers. The tubes in these units operate in the 700 to 1200°F range with water/steam on the inside and flue gas/coal ash on the outside. Above 1150°F, the coal ash begins to form an alkali-iron-trisulfate which is molten at 1156°F and causes accelerated corrosion between 1150 and 1350°F. FW has done extensive research into the compatibility of different alloys to this coal ash corrosion mechanism. Above 1350°F, the alkali-iron-trisulfate volatilizes and is not corrosive; however, corrosion by oxidation, sulfidation, and alkali-sulfates become a concern. There is a data bank of materials information on corrosion in alkali-sulfates, but the corrosion tests were performed on turbine alloys or older tubing alloys. There are a number of new high-strength, more corrosion-resistant alloys that have been developed.

The present design results in a metal temperature of around 1500°F. Since future system improvements could be made by increasing the metal temperature, there is a gap in the available materials engineering data. There are a number of stainless steels and superalloys which have different strengths, corrosion resistance, and cost. The present available data do not define the corrosion allowance and maximum usable temperature to permit the optimum materials selection. Therefore, a laboratory test will be performed to obtain these data. The details of that test program are described in Section 4.4.

3.6 GAS TURBINE COMBUSTOR

Combustor Design

Because the air entering the combustor is at 1400°F rather than usual the 700°F for gas turbines, and the fuel contains fuel-bound nitrogen in the form of ammonia, a conventional type of combustor is not suitable. Both emissions and wall-cooling problems preclude the use of a conventional design. Therefore, a combustor that meets the requirements of utilizing the higher temperature air for both wall cooling and combustion is required.

In selecting a combustor design that will withstand the conditions expected in the topping application, the effective utilization of the high temperature air mentioned above could satisfy the wall cooling challenge by maintaining a cooling air layer of substantial thickness. The creation of thick layers of cooling air at the leading edge of each inlet section is easily achieved if the combustor is made up of concentric annular passages. In addition to wall cooling considerations, the burner must inhibit the formation of NO_x from fuel gas that contains fuel-bound nitrogen, have high combustion efficiency, produce an acceptable exhaust temperature pattern, exhibit good stability, and be able to light off at cold plant conditions. The Multi-Annular Swirl Burner (MASB), was chosen as the candidate to meet these requirements. The MASB as shown in Figure 51 is designed to operate in a staged combustion mode to inhibit the formation of NO_x.

The MASB has been designed as a combustor specifically for low-Btu, coal-derived fuel gases containing significant fuel bound nitrogen, primarily in the form of NH_3. Standard Dry Low-NO_x combustors have focused on minimization of thermal NO_x generation. The MASB must minimize Thermal NO_x and also must convert NH_3 to molecular nitrogen.

The MASB approach is to:

- Employ a high-residence-time, fuel-rich zone at an optimized temperature such that NH_3 is converted to N_2 rather than to NO_x.
- Establish strong swirl and strong recirculation in the rich zone for flame stabilization and ensure that the entire rich zone is utilized for this purpose.
- Achieve a rapid quench to fuel lean conditions to minimize the formation of thermal NO_x after the rich zone.

Westinghouse, together with UTSI, has developed significant computer models of the system, both with computational fluid dynamic (CFD) codes and with chemical kinetics codes. Output from this analysis has been factored into the latest designs of the MASB, particularly with respect to the primary (fuel-rich) zone. CFD modeling of the redesigned configuration shown in Figure 52 shows that this new design will have significant recirculation in the primary zone.

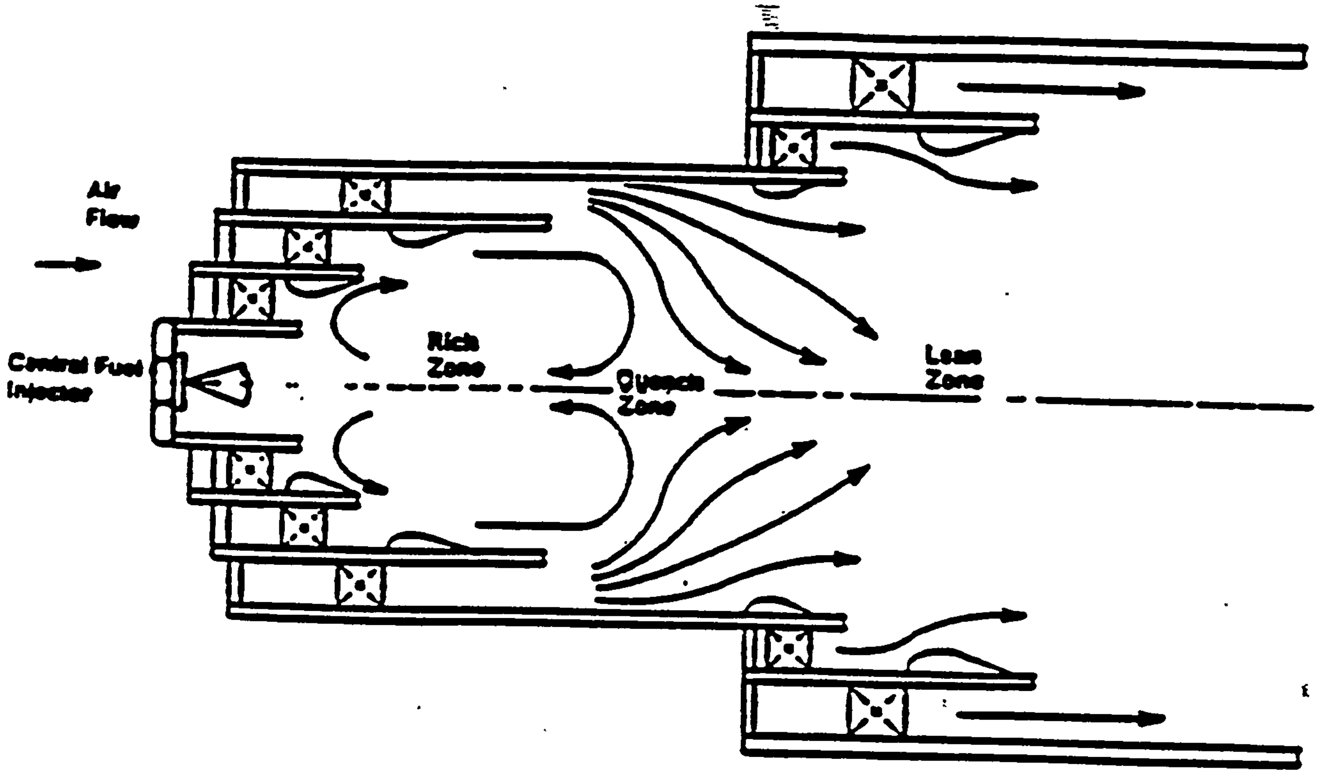


Figure 51 Conceptual Arrangement of the Multi-Annular Swirl Burner Based on J.M. Beer's Patent Design (1989)

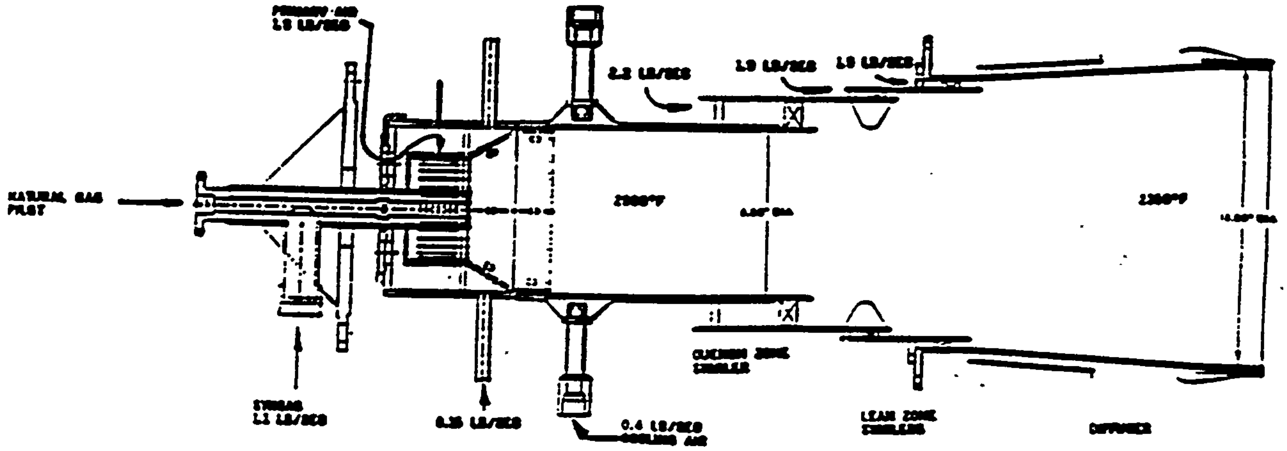


Figure 52 Recent 14-In. MASB Design

The development work being done on the MASB so far has been in support of second-generation PFB systems. The gas turbine combustor conditions for those systems are very similar to the conditions that will be present in HIPPS.

In support of the second-generation PFB development, three syngas tests and one fuel oil/natural gas test were conducted in the 1990-1991 time frame with 12-in. and 14-in. diameter MASBs at UTSI. These tests have confirmed that the MASB can be successfully cooled with 1600°F vitiated air (supplemented with a small amount [5 to 10% of total air flow] of additional cooling air at the hottest locations). The 12-in. (30.5 cm) combustor demonstrated that good temperature patterns could be obtained at 2100°F firing temperature, and the 14-in. test showed that a uniform 2350°F combustor outlet temperature could be obtained without overheating the materials of construction.

Emissions from the 12-in. and 14-in. MASB tests have shown low CO, and no soot or unburned hydrocarbons have been detected. In a "conventional" oil or natural gas fired combustion turbine combustor, Westinghouse would predict that 85 percent of the fuel-bound nitrogen would be selectively converted to NO_x. The tests to date with the 12-in. (30.3 cm) and 14-in. (35.6 cm) MASBs have shown 20 percent to 30 percent conversion of the NH_3 added to the syngas to simulate fuel bound nitrogen to No_x. Results from the MASB testing can be found in reference 5.

3.7 EMISSIONS SYSTEMS

The major components of the emissions control equipment are:

- Fuel gas particulate control by sintered metal candle filters.
- Gas turbine post combustion NO_x control by SCR.
- Fuel gas and char combustion SO_2 control by magnesium-enhanced lime (MEL) scrubbing.
- Char combustion particulate and NO_x control by CeraMem catalytic filters.

Control of NO_x by SCR and control of SO_2 by MEL scrubbing are considered mature technologies with established track records of successful full-scale installations. Still, some technical/economic issues need to be addressed to properly design the proposed SO_2 removal system. One of the advantages of magnesium-enhanced (or magnesium-based) lime processes is their high SO_2 removal efficiency. Most commercially operating MEL installations (such as the Zimmer Generating Station in Moscow, Ohio) have been designed to meet less stringent SO_2 removal level (about 95-96% removal) than that specified for the HIPPS plant (98.7% removal). In magnesium-based processes, SO_2 removal is limited only by the equilibrium concentration of the SO_2 in the clean exit gas stream. Bechtel demonstrated over the last ten years a magnesium-based FGD system at Montana Power Company's Colstrip Station that has consistently achieved low exit SO_2 concentrations (approaching equilibrium) that easily meet the HIPPS requirement (about 40 ppm by weight). Therefore, designing an MEL system to meet HIPPS SO2 removal requirement can be done. The MEL system has to also be properly designed to enhance the settling of the calcium sulfite so it can be dewatered in a cost effective manner before being disposed of. Controlled oxidation of the sulfite within the scrubber has been shown to significantly promote its settling. Another design/economic option to consider is to fully oxidize the sulfite to gypsum (which has enhanced dewatering characteristics) using air sparging within the scrubber. After decholorination and dewatering, the fairly clean, white gypsum can then be sold for use in wallboard plants or in the cement industry.

The Pall GSS sintered metal technology selected for the barrier filter has been commercially proven in the chemical, petroleum, and mineral industries for many years. However, the iron aluminide filter medium suggested for the HIPPS application is a relatively recent development; this medium has been extensively tested in Pall's pilot facility at process conditions not unlike those for HIPPS. In Phase 2, additional testing of this device in an actual HIPPS environment may be needed to further assess its structural reliability.

The CeraMem unit specified for the back-end NO_x and particulate removal for the HITAF flue gas stream. This device can simultaneously remove particulates and simultaneously reduce the nitrogen oxide. In Phase 2, we need to test this device in the HIPPS environment to evaluate the effect of catalyst formulation on NO_x reduction, SO_2 oxidation, and ammonia slip. This will be done in the Integrated System Test (IST) where a combination NO_x and particulate cleanup system will be used in a flue gas stream.

3.8 SYSTEM INTEGRATION AND CONTROL

Specific issues of system integration are discussed in Section 2 where the plant subsystems are described in detail and plant operating procedures are presented. The system integration issue that is particular to the HIPPS plant is the matching of the pyrolyzer operation with the operation of the gas turbine and the char combustor. The pyrolyzer/gas turbine control issues are being addressed in the second-generation PFB projects at Wilsonville and Four Rivers and the IGCC project at Pinon Pine. The fuel gas control systems being developed for these projects will be directly applicable to HIPPS. The integration of the pyrolyzer and the char combustor is unique to the HIPPS concept. The technical issues involving this interface are discussed in Section 3.3 and 3.4 along with alternative designs to overcome potential problems. The basic consideration is to ensure that the flow rate and characteristics of the char from the pyrolyzer are compatible with the char combustor. The testing planned for Phase 2 will thoroughly investigate this issue culminating with an integrated system test of approximately 70 MMBtu/h heat input.

Beyond integration of the new technologies, there is also the issue of overall control of the system. Although the control system has not been developed in detail yet, a general procedure has been established (Section 2.5), and there does not appear to be any aspects of the system that would make it uncontrollable. It is, however, necessary to know the operating characteristics of the various components and subsystems so that the dynamics of the system can be modeled and control algorithms can be written. In Phase 2, a detailed mathematical modeling of the system will be performed. This modeling is discussed in Section 4.7.

3.9 CERAMIC AIR HEATER (ALTERNATIVE DESIGN)

The base case HIPPS that will be developed for a prototype plant in Phase 3 will not include a ceramic air heater. We believe that the current status of these air heaters will not support the required project schedule. If, however, reliable ceramic air heaters were developed, the portion of indirect heating in the HIPPS cycle could be increased. For this reason, research required for the development of ceramic air heaters is included in Phase 2 of the project.

The current status of ceramic air heater development is discussed below. The development of ceramic heat exchangers or air heaters has concentrated on three areas: evaluation of materials, fabrication, and design.

3.9.1 Evaluation of Materials

Material properties are critical for the reliable design and operation of ceramic air heaters and have been the subject of extensive study. The ability to resist thermal shock–induced fracture has been the primary criterion for selection of materials. The fundamental resistance to thermal shock cracking is a function of strength, Poisson's ratio, and thermal conductivity. The resistance to thermal shock is inversely proportional to modulus of elasticity and thermal expansion. Calculation shows, for example, silicon carbide to have nine times the thermal shock resistance of alumina, hence the extensive evaluation of this material for heat exchanger applications.

Corrosion resistance is another critical consideration in the selection of materials for ceramic air heater application. In coal combustion or coal gasification environments, selected ceramic materials are exposed to a combination of hot gases and molten slags simultaneously. Molten slag deposits could induce severe corrosive attack on the selected material and significantly affect the material mechanical properties [8]. Chemical reactions of molten slag with the ceramic could result in uniform material loss as well as selective localized attack or pitting. Loss of material, enlargement of critical surface flaw size, or contamination of grain boundaries by the corrosive elements can result in degradation of the brittle fracture strength, decreased fracture toughness, and reduction of high–temperature creep strength.

Silicon carbide has been considered as a candidate material for use in ceramic air heaters because of its exceptional mechanical and heat conductance properties and its resistance to thermal shock. One of the attractions of silicon carbide is that under sufficiently oxidizing conditions, a protective oxide layer is formed on the surface which effectively inhibits further oxidation [9]. The stability of the silica layer becomes the key to whether or not further attack may occur. In a sufficiently reducing environment, the decomposition and volatilization of any existing oxide layer are followed by the similar loss of the underlying silicon carbide via active oxidation. The conditions for stability of the oxide layer are made increasingly complex by the presence of various sintering aids added to the silicon carbide during processing, as well as by the presence of contaminants in the application environment. In the presence of coal slags, the usually protective silica surface layer can be dissolved, resulting in a nonprotective liquid deposit on the silicon carbide surface. Certain common oxide slag components such as iron oxide, magnesium oxide, and calcium oxide can react with the silicon carbide to form low–melting metal silicides. Attack is usually characterized either by surface recession or intergranular penetration. In general, in the corrosive attack by molten slags, the extent of material loss varies with the relative amount of basic (e.g., Fe_3O_4, CaO, MgO) and acidic (SiO_2, Al_2O_3, TiO_2) components in the slag. The material loss is more pronounced in the case of basic slags. The lower viscosity of the basic slag compared to the acidic slag is partly the cause of the faster rate of corrosive attack.

Recent work on silicon carbide for ceramic heat exchanger applications has involved evaluation of corrosion characteristics and mechanical properties of the material under various conditions [10, 11]. Ceramic coatings on silicon carbide have been evaluated for corrosion protection [12,13]. Coatings, up to 50 mils thick, have been applied by plasma spraying on silicon carbide. A single–layer mullite coating with a vitreous phase ceramic seal coat has shown excellent corrosion resistance. Gradual coating blends from mullite to alumina and mullite to yttria also show promise. Other materials have also been investigated. Silicon carbide whisker-reinforced alumina has been found to be a potential candidate as heat exchanger tube material because the material possesses both high strength and improved thermal shock resistance compared to normal alumina [14]. Exposure tests have indicated that silicon carbide whisker-reinforced alumina has very similar corrosion resistance to pure alumina. A class of silicon carbide particulate-reinforced alumina composite has been evaluated [15]. The composite shows an increase in weight during exposures to dynamic corrosion as a result of the oxidation of the aluminum which is drawn to the surface from the interior of the composite. However, the composite tends to lose a significant amount of its strength at room temperature due to the exposures to dynamic corrosion. The suitability of silicon carbide/silicon carbide composites has been studied for header applications in heat exchangers [16]. The composite possesses an advantage over monolithic materials in that it shows greater tolerance to strain and better room temperature strength. However, the C-ring strength of these composites deteriorates at temperatures greater than 500°C.

3.9.2 Fabrication

Silicon carbide has been fabricated into shapes required for ceramic air heater applications. Some development work may be needed to scale up the fabrication to produce parts having desired dimensions. Fabrication of tubes made of silicon carbide/alumina composites have been investigated. The key aspect in the fabrication area is the development of ceramic joining technologies. Two key joining technologies have been considered: brazing and solid-state joining. Brazing is of interest because of the relative simplicity of the equipment involved and the potential for high-production capability. However, there are several problems peculiar to the brazing technique: potential chemical incompatibility between the brazing alloy and the ceramic and thermal expansion coefficient mismatch. High temperatures and corrosive environments are other concerns in the development of brazing technologies. Silicon carbide-to-silicon carbide joining made by brazing have been investigated [17, 18]. Work has been performed on solid-state joining of silicon carbide. Direct joining of silicon carbide has been attempted by polishing the joined pieces to a mirror-like finish before heating [19] and by microwave joining [20]. A promising joining technology for use in ceramic air heaters is the reaction bonding method [21, 22]. The processing step of this method includes tape–casting thin sheets of silicon carbide and graphite precursor, placing the tape between the ceramic parts to be joined, providing a source of silicon adjacent to the joint, and heating the joint above the melting point of silicon in argon. Molten silicon infiltrates the joint via capillary action, forming a reaction–bonded silicon carbide interlayer and simultaneously joining the ceramic parts. Four-point bend strength and fracture toughness of joined specimens have been evaluated at room and high temperatures. The joint mechanical properties have been found to be comparable to or higher than those reported for bulk silicon carbide for test temperatures up to 1400°C.

3.9.3 Design

In the design of a ceramic air heater, the following features are significant: (1) stress prediction and control, particularly at joints and points of contact; (2) fouling and methods of deposit removal where used in dirty environments; (3) repairability with the capability to selectively replace parts with minimal time out of service; and (4) ability to withstand thermal cycling. Most of the ceramic air heater designs to date use ceramic tubes. The proposed air heater design of this proposed program is an assembly of a number of independent heat exchanger modules. Each module consists of a number of tubes having an integral internal cruciform, and each tube of the module are attached to manifolds on both ends. The Hague design is a multipass shell and tube design [23]. In this design, the heat exchanger is a tube string assembly. Each tube string consists of two ceramic internally enhanced tubes, a metallic internally enhanced tube, adapter hex sleeves, and the spring pack assembly. The tubes are held vertically in compression using the spring pack assembly. Hex sleeves are used to prove interface between the tubes and join the tube string assembly to the heat exchanger frame. To date, all the ceramic air heater designs require further development and testing.

4.0 RESEARCH, DEVELOPMENT AND TEST PLAN FOR PHASE 2

4.1 INTRODUCTION/OVERVIEW

Figure 53 shows the project overview by task and subtask and illustrates the general logic of the HIPPS development. This section of the report describes the activities that are part of Tasks 2, 3, 4 and 5. The Task 2 activities are analytical in nature or are bench scale tests. Tasks 3, 4 and 5 are the design, construction and testing phases of larger scale tests. The logic of the RD&T plan is that the development will proceed in stages of scale and system integration. At the conclusion of the Phase 2 testing, the system will have been demonstrated at sufficient scale and completeness to proceed to the prototype plant.

Table 36 indicates what sections of the RD&T plan relate to the various subtasks that are shown in Figure 53.

Table 36 Organization of RD&T Plan Discussion

Subtasks		Proposal Sections
2.1	Perform Pyrolyzer and HITAF Engineering Analysis	4.7, 4.10
2.2	RPD System Cold Tests	4.2.1
2.3	Perform Pyrolyzer and HITAF Experimentation	4.4, 4.9
2.4	Perform Char Combustor Analysis and Laboratory Experiments	4.3
2.5	Evaluate Emissions Systems	4.6
2.6	Develop Gas Turbine Design and Performance	4.5
2.7	Design Ceramic Air Heater	4.12
2.8	Determine Fabrication and Joining for Ceramic Air Heater	4.12
2.9	Revise Analytical Models	4.7, 4.8, 4.10
2.10	Ceramic Corrosion Test	4.2
3.1	Design Pyrolyzer/Char Transport Test	4.2
3.2	Design Char Combustor Test	4.3
3.3	Design Integrated Test	4.6
4.1	Construct Pyrolyzer/Char Transport Test	4.2
4.2	Construct Char Combustor Test	4.3
4.3	Construct Integrated Test	4.6
5.1	Conduct Pyrolyzer/Char Transport Test	4.2
5.2	Conduct Char Combustor Test	4.3
5.3	Conduct Integrated Test	4.6

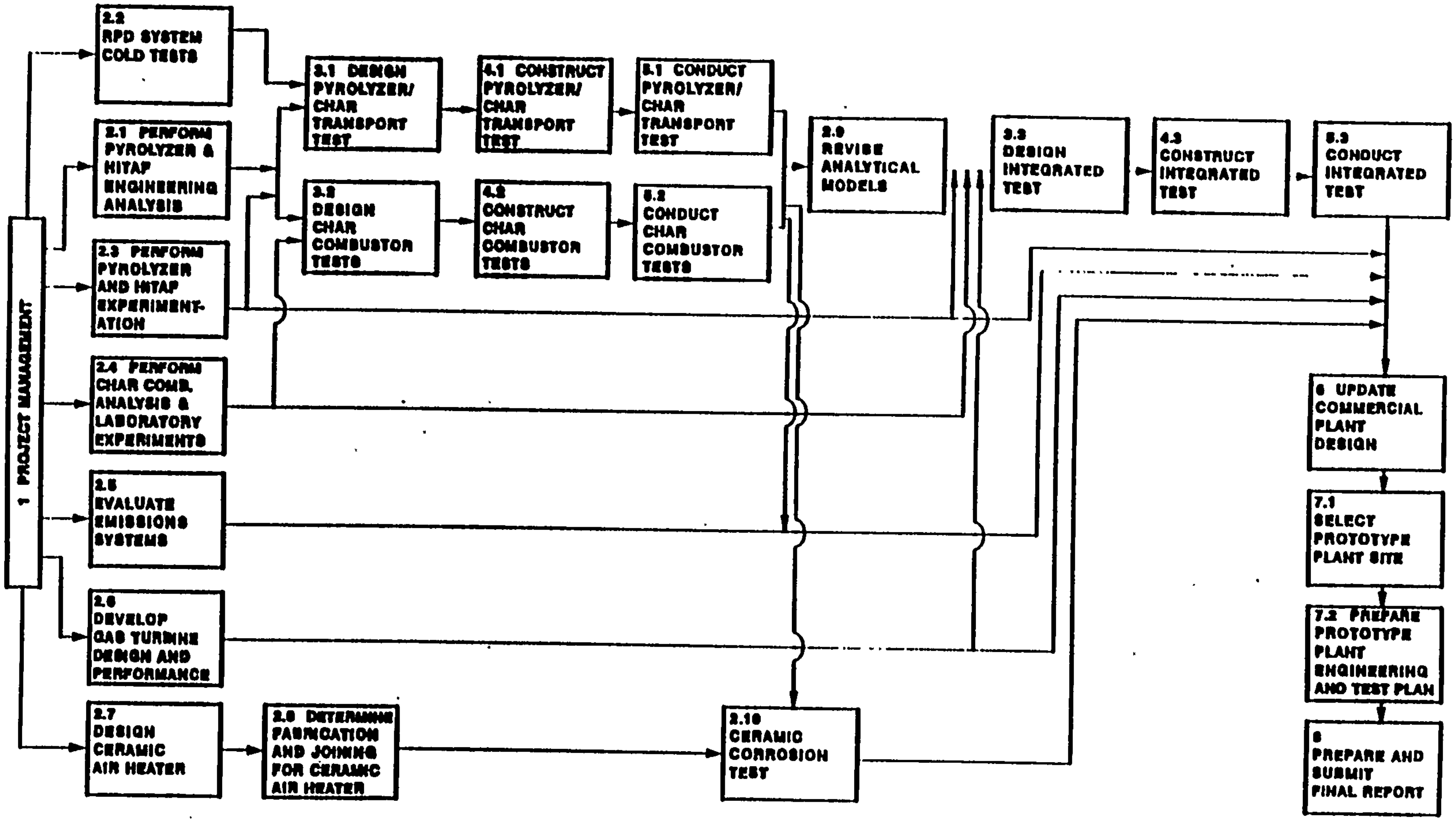


Figure 53 Phase 2 Project Overview (by task/subtask) for Phase 1

4.2 PYROLYZER/CHAR TRANSPORT

4.2.1 Char Depressurization Test

Rationale and Objectives

The objective of this work is to conduct cold-flow model testing with actual solids in a Restricted Pipe Discharge (RDP) System depressurization system simulating the actual depressurization system to be used in the plant. The average particle size of the material which will be depressurized in the plant is expected to be approximately 50 microns. The RPD system has been operated primarily with solids larger than 100 microns. Therefore, to ensure that the RPD system will operate satisfactorily, testing with the actual material to be depressurized is recommended.

The RPD system is a novel depressurization system which can be used in place of traditional lockhoppers. A lockhopper system has some disadvantages: (1) it discharges solids intermittently in batches instead of continuously; and (2) it requires several expensive, high-pressure valves to seal the full system pressure under severe operating conditions when solids are present. The valves must continuously cycle under conditions when gas and solids are both present, and wear out frequently.

A recent alternative to lockhoppers has been developed: the Restricted Pipe Discharge System (RPD system). This method of depressurizing solids utilizes the relative velocity between gas and solids to dissipate the pressure in the discharge line. With the RPD system, the solids are discharged continuously, and only one "working" valve is required. The pressure drop across this valve is only a few inches of water instead of full system pressure. In addition, the RPD system can be used to depressurize and simultaneously transfer solids to another location in the plant. Also, the depressurization can be conducted in a vertical upflow mode. This means that the RPD system does not need to be located below the depressurization vessel, but can be located at its side. The latter feature can lower the height of reactor vessels above grade relative to reactors utilizing a lockhopper system.

Data Requirements and Approach

A flowsheet of the char separation and transport system which will be used in the plant is shown in Figure 54. Char from the pyrolyzer second stage cyclone are collected in the hopper of the barrier filter vessel. These solids will be depressurized via a RPD system before being fed into a pneumatic conveying line for transport into other sections of the plant.

A flowsheet of the test facility is given in Figure 55. It consists of a 3-ft diameter pressure vessel which will simulate the barrier-filter pressure vessel. Solids will be transferred through a 2-in. diameter depressurization line via gravity into an 18-in. diameter disengaging vessel. The depressurized excess gas is vented at this point. The solids will flow out of the vessel into a screw feeder which will set the solids flow rate in the system, and will be collected in a 4-ft diameter receiver vessel.

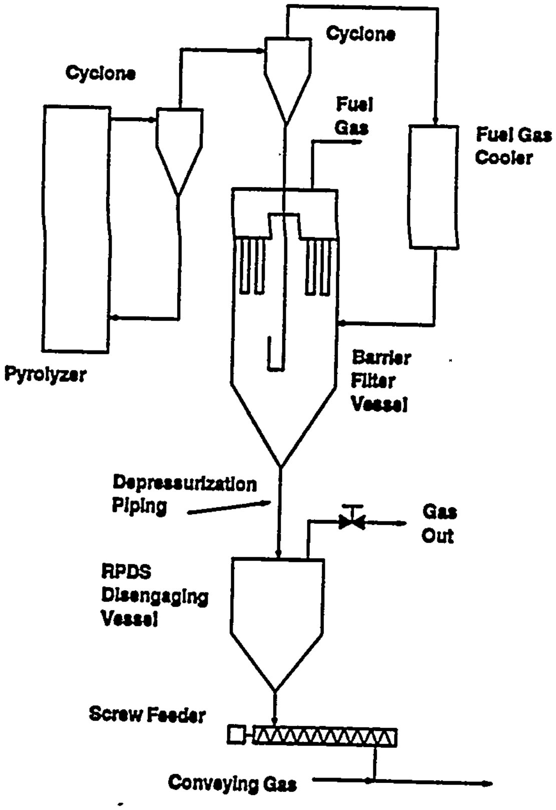


Figure 54 Schematic Drawing of Char Separation and Transport System

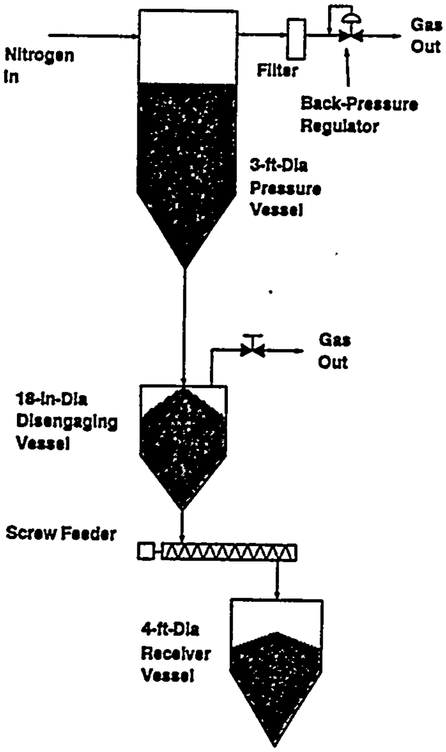


Figure 55 Schematic Drawing of RPDS Test Unit

The existing facility will require minor modifications to simulate the actual configuration which will be used in the plant. Specifically, a screw feeder will be added to the existing facility. In addition, the pipe length between the pressure vessel and the disengaging vessel will be adjusted in order to match the distance between the barrier filter vessel and the disengaging vessel in the plant.

To ensure that the RPD system will operate satisfactorily with the material used in the plant approximately 1500 pounds of the material will be shipped to IGT by FWDC. Tests to determine how the RPD system will operate with the test material will be conducted at three solids flow rates (bracketing the actual solid velocity which will be used in the plant) and at several system pressures bracketing the operating pressure expected in the plant.

During each test, the following data will be obtained:

(1) The solids flow rate in the depressurization line and the gas flow rate out of the disengaging vessel.
(2) The pressure profile in the depressurization piping.
(3) Pressures in the pressure vessel and disengaging vessel.

The testing will be used to determine (1) if the solids will flow smoothly as they are being depressurized, (2) if the pressure profile in the depressurization line is stable during the depressurizing, and (3) the amount of gas used to depressurize the solids as a function of solids flow rate and system pressure.

The data obtained from the testing will then be used to fine-tune an existing mathematical model of the RPD system. Specifically, the particle size of the solids used in the model will be adjusted until the pressure profile and gas losses are predicted by the mathematical model. This will define the "effective" particle size of the test solids. The "effective" particle size will then be used in the model at the actual conditions in the plant to predict actual gas losses. This information can then be used to design valves and gas-flow meters for the RPD system used in the plant.

Upon completion of the testing, the data will be analyzed and a final report issued. The final report will contain a description of the test unit and operating procedure, as well as descriptions of any operating problems experienced with the solids. The results of the testing will also be reported in detail using graphs, charts, and tables to elucidate the data. The most significant findings and conclusions of the RPD system testing will also be summarized in the report.

The test work will be conducted in an existing Restricted Pipe Discharge System depressurization test facility located at the Institute of Gas Technology's Energy Development Center in Chicago. The facility has the capability to conduct the testing at the system pressure equivalent to the pressure used in the actual plant, and at a scale large enough so that the data can be used for evaluation and design. The facility will be available for conducting the testing during the proposed test period.

Schedule

The char depressurization test will be done at the start of Phase 2 so that the information will be available for the Pyrolyzer/Char Transport Test (PCTT). Char from the FWDC second-generation PFB tests will be screened to provide the proper size distribution for the tests.

4.2.2 Pyrolyzer/Char Transport Test

Rationale and Objectives

The main objective of the PCTT is to obtain design information that will be used for the design of the larger scale Integrated System Test (IST) Facility. The IST Facility will then provide the design information required for the Prototype Plant. Because the existing Second-Generation PFB pilot plant facility can be used for the PCTT, this information can be obtained early in the project at a reasonable cost. This test will yield information on basic process parameters and practical equipment design. Because this test is smaller scale than the Integrated System Test, design modifications can be made at lower cost. This situation will allow us to optimize the subsystem before the char combustor is added in the IST. Table 37 summarizes the technical issues that will be addressed in the PCTT and how the information will be obtained and used.

Data Requirements

The data requirements required to address the critical issues are listed in Table 37. We will take sufficient data and do sufficient sample analysis to quantify the process yields and characterize the char. Also, measurements will be taken of transport system parameters to verify correlations and establish design parameters.

Approach

A process flow diagram of the system is shown in Figure 56. Flow stream conditions for the base case operation are listed in Table 38. The pyrolyzer will use paste fed coal and sorbent with particle size distributions that are representative of the larger size plants. The pyrolyzer will be run as a circulating fluidized bed. The fuel gas will then go directly to the barrier filter vessel. In the larger pilot plant and commercial plants, the fuel gas will go through a secondary cyclone and cooler before it enters the barrier filter vessel. This equipment has been omitted because of space limitations. We believe that the secondary cyclone and fuel gas cooler can first be introduced in the Integrated System Test. Once we determine the fuel gas composition at temperature, the gas composition at lower temperatures can be reliably calculated with thermodynamic models.

The restrictive pipe discharge (RPD) system below the barrier filter will have all the components that are present in the commercial plant. The solids pressure will be reduced from 206 PSIA to approximately 17 PSIA. A screw feeder will be used to feed solids into the transport line. It will be controlled to maintain a level setting in the surge hopper. Nitrogen will be used as the transport gas.

The transport gas will be separated from the solids in the disengaging vessel. The solids will fall into the weigh hopper. This hopper will be on weigh cells so the solids flow rate will be measured on a continuous basis except for the dump periods.

An arrangement drawing of the PCTT Facility is shown in Figure 57. The shaded components will be added to the existing pilot plant. The existing pyrolyzer, coal and sorbent feed system and barrier filter will be used. Existing systems (not shown) will also be used to cool, filter and incinerate the fuel gas. As shown in Figure 57, a new cyclone and solids recirculation system will be added to the pyrolyzer. The surge hopper, RPD system and screw feeder will be added below the existing barrier filter vessel.

Table 37 Summary of Pyrolyzer/Char Transport Test

<table>
<tr><th>Technical Issues</th><th>Measurements</th><th colspan="3">Scale-Up</th></tr>
<tr><td>• Pyrolyzer Heat Material Balance Including:
— Sulfur to H_2S
— NH_3
— Heating Value
— Effect of Ca/S
— Effect of Feedstocks</td><td>Solids and Gas
— Flow rate
— Temperature
— Pressure
— Particle size
— Composition</td><td colspan="3">Use specific test yield factors information and approach-to-equilibrium as input to the computer model.</td></tr>
<tr><td rowspan="2">• Fluidized Bed Hydrodynamics</td><td rowspan="2">Solids and Gas
— Flow rate
— Temperature
— Pressure
— Particle size</td><td colspan="3">Use fluidized bed scaling laws to set superficial velocity, bed diameter, and particle size for test.</td></tr>
<tr><td><u>Parameter</u>
D (ft)
d_p (ft)
U_g
U^2_o / gL
r_S / r_F
U_o / U_{MF}</td><td><u>Pyrolyzer Test</u>
0.768
7.09×10^{-4}
8.20
2.734
171
586</td><td><u>Integrated Test</u>
1.92
8.92×10^{-4}
13.0
2.734
171
586</td></tr>
<tr><td>• Attrition</td><td>Particle Size Distribution</td><td colspan="3">With same feedstocks and representative bed conditions, attrition should be representative.</td></tr>
<tr><td>• Char Combustion Characteristics</td><td>Char Supply for Combustor Tests</td><td colspan="3">With same feedstocks and representative bed conditions, char should be representative.</td></tr>
<tr><td>• Fuel Gas Alkalies</td><td>Gas Sample Drawn at Temperature and Condensed</td><td colspan="3">With same feedstocks and representative bed conditions, fuel gas alkali content should be representative. Gaseous-phase alkalies at lower temperatures will be determined by thermodynamic equilibrium model.</td></tr>
<tr><td>• Transport Gas Requirement</td><td>Solids and Gas
— Flow rate
— Temperature
— Pressure</td><td colspan="3">Particulate Solids Research Institute saltation velocity correlation used to extrapolate gas-flow requirement to higher solids flow rates and pipe diameters.</td></tr>
<tr><td>• Transport Pipe Erosion</td><td>Post-Test Inspection</td><td colspan="3">Establish wear rate per hour and compare with longer-term laboratory test data.</td></tr>
</table>

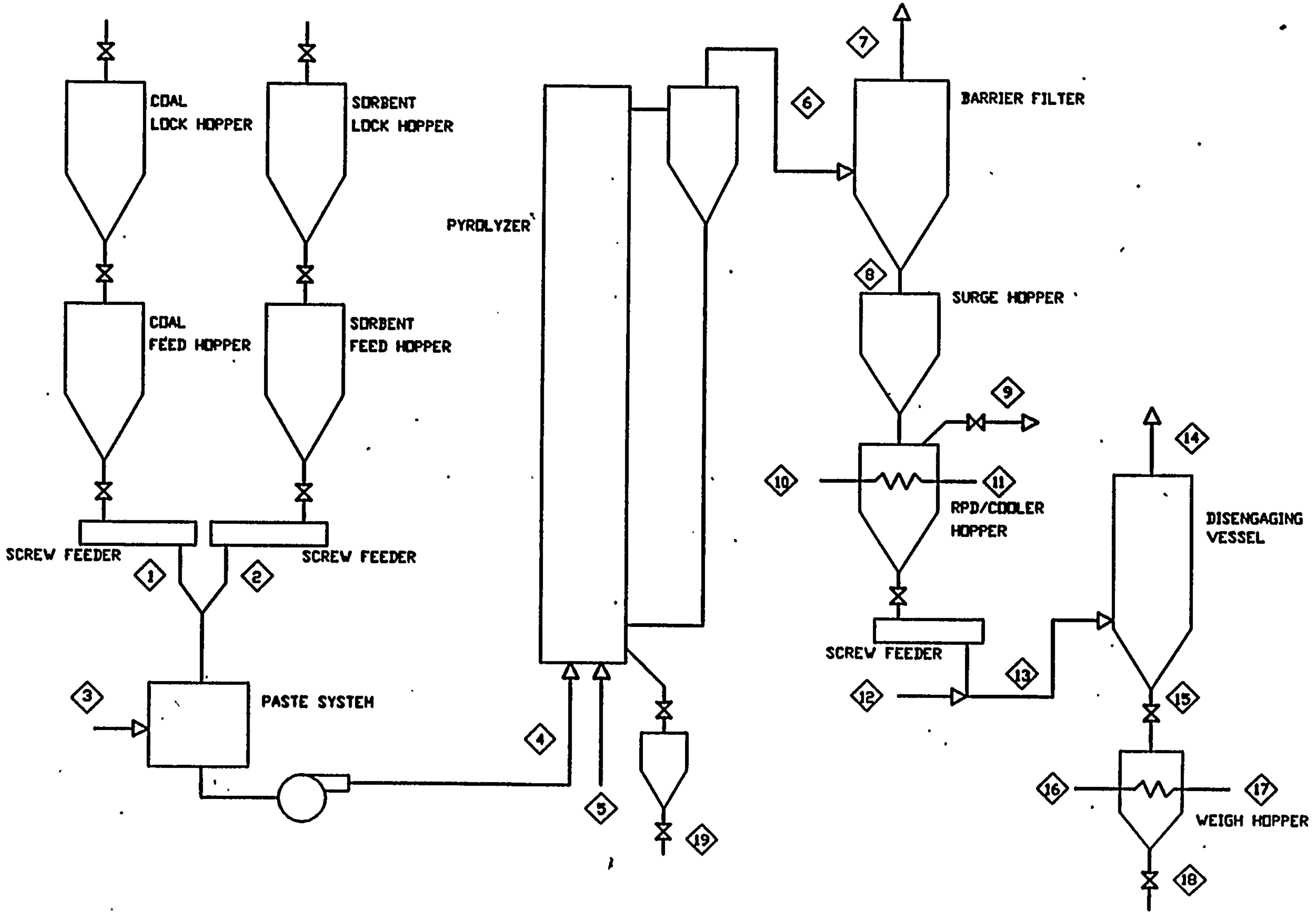


Figure 56 Pyrolyzer/Char Transport Process Flow Schematic

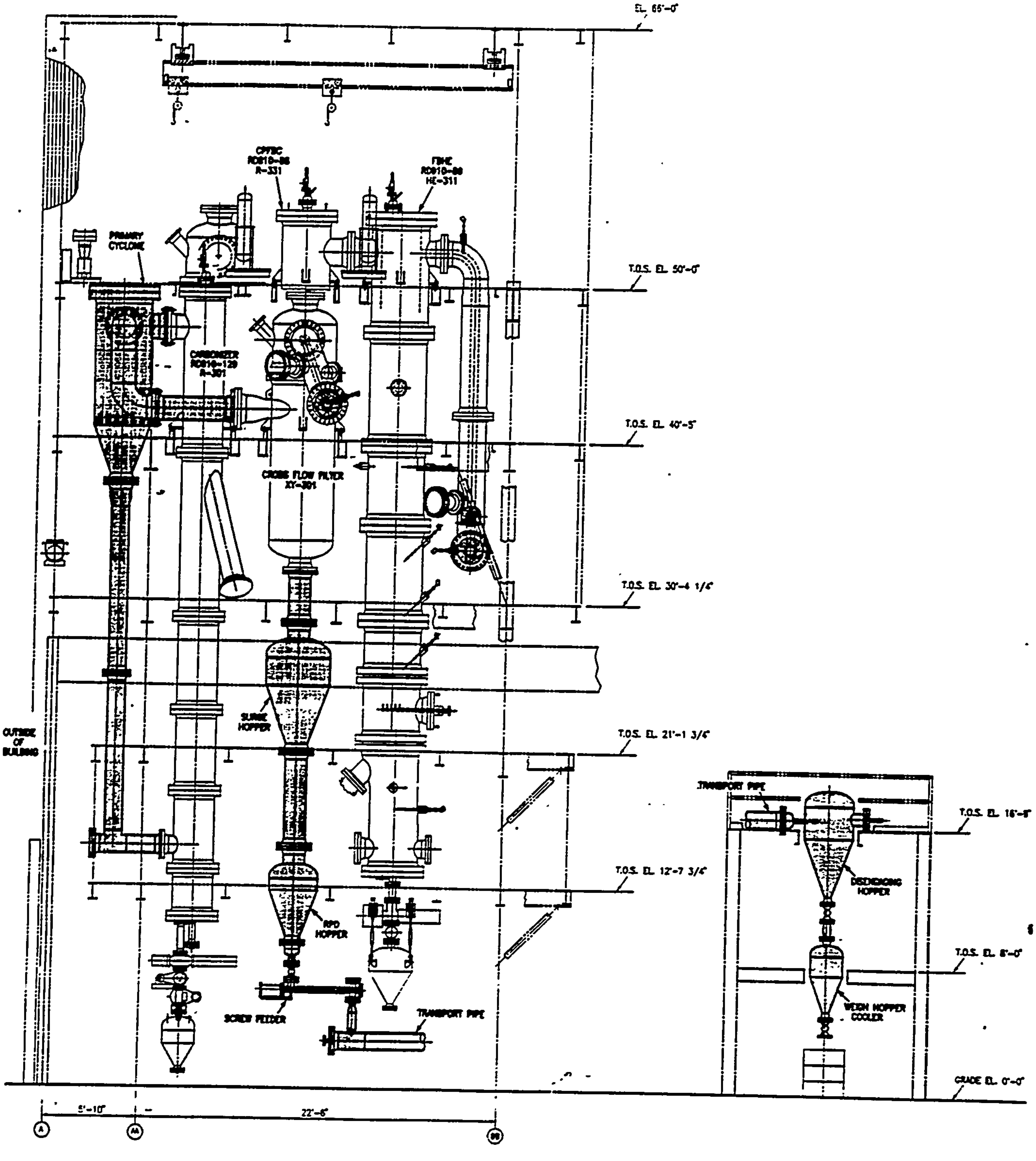


Figure 57 Pyrolyzer/Char Transport Pilot Plant

Table 38 Pyrolyzer/Char Transport Test Flow Parameters

Stream No.	Component	Pressure (psig)	Temperature (°F)	Flow Rate (lb/h)
1	Coal	0	amb.	600
2	Limestone	0	amb.	61
3	Water	0	amb.	193
4	Coal/Limestone/Water	250	amb.	854
5	Air	250	410	1600
6	FG/Char/Sorbent			
	Fuel Gas	224	1700	2200
	Char/Sorbent	224	1700	254
7	Fuel Gas	224	1700	1970
8	Char/Sorbent	204	1700	243
9	Fuel Gas	0	1700	230
10	Water	100	70	1360
11	Water	100	140	1360
12	Nitrogen	1	amb.	15
13	Char/Sorbent/Nitrogen	1	400	258
14	Nitrogen	0	400	15
15	Char/Sorbent	0	400	243
16	Water	100	70	260
17	Water	100	140	260
18	Char/Sorbent	0	150	243
19	Spent Sorbent	0	350	11

The char transport line will consist of about 30 feet of pipe that will run from the screw feeder to the disengaging vessel. The disengaging vessel, weigh hopper and associated structural steel will all be new.

The test information will be used to provide the design information needed to design the Integrated Test Facility. Based on throughputs, the test will be 1/10 scale of the Integrated Test Facility. However, the geometric scale of the pyrolyzer will be about 3/8 based on the bed diameters.

Both the chemical process conditions and the hydrodynamics of the circulating fluidized bed need to be considered in the scale up of the test data. In order to duplicate the chemical process as much as possible, the same feedstocks, bed temperatures and pressures will be used. Because of the smaller scale, the heat losses and the nitrogen purges will be a greater proportion of the throughput in the PCTT. These factors will be accounted for in the computer model described in Section 2.3.5. The model will be run with input data obtained from the PCTT.

Because of the need to match process conditions and other functional requirements, pilot plants rarely meet the strict criteria for hydrodynamic modeling. In our test program the effects of any dissimilarity in this area are minimized by progressing in relatively modest steps of scale from the PCTT to the IST and then to the Prototype Plant. This progression of scale and component development is shown in Table 39.

Table 39 Pyrolyzer Scale Progression

Description	PCTT	IST	Prototype Plant	Commercial Plant
Coal Flow Per Pyrolyzer (lb/h)	600	6,100	40,000	75,600
Bed Diameter (ft)	0.77	1.67	4.66	5.83
Scale of Commercial Plant *	1/8	1/4	3/4	1
Scale of Next Largest Test *	3/8	3/8	3/4	—
Bed Height to Diameter Ratio	52	24	11	9
* Based on bed diameter				

Glicksman [24] has determined the following simplified set of dimensionless numbers can be used in modelling circulating fluidized beds. The simplification basically relaxes the need for exact matching of Reynolds Numbers under certain conditions:

$$\frac{U_o^2}{gL},\ \frac{\rho_S}{\rho_F},\ \frac{U_o}{U_{MF}},\ \textit{geometric similarity} \qquad (3.2.2\text{-}1)$$

where:

U_o = superficial velocity, ft/sec
g = acceleration of gravity, ft/sec^2
L = characteristic length, ft
ρ_S = solids particle density, lb/ft^3
ρ_F = gas density, lb/ft^3
U_{MF} = minimum fluidization velocity, ft/sec

One compromise that needs to be made in a pyrolyzer pilot plant is in the area of geometric similarity. In order to achieve sufficient gas residence time, the pilot plant height to diameter ratio will be higher than what would result from strict geometric similarity. As can be seen in Table 39 there is a progression of height to diameter ratios that will approach the commercial plant ratio as the scale of our tests increase.

Although it is not possible to match all the dimensionless numbers and still meet the process requirements, some manipulation of the superficial velocity and particle diameter can bring the numbers into closer agreement. The parameters listed in Table 37 are based on bed diameter as the characteristic length. This choice of superficial velocity and mean particle size will bring all the dimensionless numbers in line except for the Reynolds Number. At Reynolds Numbers below 10 and above 1000, tests by Glicksman have indicated that virtually no error is introduced by not matching the Reynolds Number. Although we are above the lower Reynolds Number limit, we still are in a range where the effect of Reynolds Number on particle drag force is small.

In the area of char transport, the PCTT will mainly provide functional design information. It will be our first hot test of the RPD system, and it will yield information on the reliability and controllability of the char depressurization and transport system. If there are problems with the operation of the system, modifications will be made and tested. These modifications could involve changes in shape or aeration to enhance solids flow in different parts of the system. Although the tests will not be a lot of hours in terms of material wear, there should be sufficient time for any severe erosion problem areas to surface.

As part of the PCTT, ceramic specimens will be exposed to the flue gas from the fuel gas incinerator. The results of this exposure will be compared with the laboratory tests that were done in Phase 1.

Making and testing design changes will be less expensive in the PCTT than in the IST because of the smaller scale. Although problems may develop in the IST that will not surface in the smaller scale tests, the PCTT will serve to establish the basic system design and significantly reduce the chance of problems in the IST. The effects of scale up on operational parameters such as saltation velocity and pressure drop will be accounted for by comparing the test operation to established correlations. The effects of changes such as flow rates and diameters will be assessed in this manner.

A detailed test plan will be prepared for the facility preparation, hardware installation and test activities for the PCTT. In addition to shakedown operation, there will be 6 test runs each of 5 days duration. At least two different coals and sorbents will be used as feed stocks, and the size distribution of the feed stocks will be varied. Although the test activities for the entire test program will be planned up front, the nature of the testing dictates that the results of each test run be reviewed immediately after the run and the test procedure for the next run be modified if necessary. A Fisher Provox distributed control system including a data archiving system will be used to provide the test information quickly. Software is already in place to provide heat and material balances for the pyrolyzer. Some of the inputs to the heat and material balance program are from laboratory analysis of solids and gas samples. These analyses are all done in the FWDC chemical laboratory so the results can be obtained in a timely manner.

Resource Requirements and Availability

The test facility was used as a pilot plant for the Second-Generation PFB DOE project. Testing for this project has been completed. Modifications to the pilot plant will not preclude its use for further second-generation PFB tests should the need arise. Some vessels from the pilot plant will be removed in order to accommodate the PCTT, but they can be reinstalled if necessary. The changes to the facility should not require a new operating permit. FWDC personnel have participated in the design and testing of this facility and these experienced personnel will provide staffing for the PCTT.

Schedule

Construction of the PCTT will start around July 1996. The start of testing will be around December 1996. The design and construction of the Integrated System Test (IST) will start before the completion of the PCTT and the char combustor test. Much of the design of the IST will not depend on results from these tests. By getting an early start on the design and fabrication of this equipment, we will make efficient use of the allotted program time.

4.3 CHAR COMBUSTOR RESEARCH, DEVELOPMENT AND TEST PLAN FOR PHASE 2

As described in Section 3.4, there are several uncertainties related to the design and performance of the commercial-scale char-fired combustor. These uncertainties will be addressed through a comprehensive engineering research and development program conducted during the proposed Phase 2 effort. Table 40 presents a summary of the issues and the proposed technical approach for addressing and resolving each of the issues. Additional details on the approach and the planned research and development activities, including analytical modeling, engineering analysis, experimental research, component development tests, and integrated subsystem tests are described below.

4.3.1 Data Requirements and Priorities

The major issues which need to be addressed during the Phase 2 effort can be divided into three categories: performance issues, design issues, and operational issues. The data required to resolve each of the issues is described below:

Performance Data Requirements

The major char combustor performance issues that need to be addressed through experimental and analytical work during Phase 2 include: 1) combustion issues such as ignition, flame stability, and carbon burnout, 2) NO_x control, and 3) slag effects which include slagging behavior (i.e., the slag coverage on the combustor chamber walls including slag fouling and/or slag accumulation), slag recovery, and slag tapping. In order to address, and resolve, these issues, it is necessary to obtain test data to evaluate, and optimize, the char combustor performance as a function of preheat temperatures, operating equivalence ratios, char grind size and volatile content, load, gas/oil ignitor throughput, char flow split ratio between the precombustor and main stage, and char injection velocity. In addition, test data is needed to evaluate the impact of hardware configuration changes, including burner configuration, combustion chamber length, precombustor throat configuration, and char injector configuration, on the overall char combustor performance characteristics. Other information will also be obtained during the experimental effort including combustor heat loads and pressure drop data.

Scaling of the performance data to the commercial scale size is also an issue. In order to address this, the size of the test hardware, and selection of test conditions, oxidant and fuel compositions, and test configurations should be such that the performance data can be scaled with confidence to the demonstration and commercial scale size. In the case of the char combustor development, the minimum representative scale is approximately 40 MMBtu/hr, which enables subscale testing to be performed with the same basic hardware geometry and topology (aspect ratio) while simulating combustion characteristics through the use of finer char grinds. In addition, the testing should be performed over a wide range of firing rates, and operating conditions, in order to accurately determine the scaling parameters.

Table 40 Summary of Issues and Technical Approach

Technical Issue	Required Data	Proposed Approach
Performance Issues ■ Carbon burnout ■ NO_x control ■ Precombustor ignition and flame stability ■ Slagging characteristics ■ Scaling	■ Combustor performance parameters (carbon losses, NO_x emissions, slag recovery, cooling loads, pressure drop) as a function of firing rate, stoichiometry, preheat temperatures, particle size, volatile content, injection velocity, and combustor geometry	■ Perform preliminary analytical modeling at subscale and commercial sizes ■ Conduct subscale char combustor tests at 30-40 MMBtu/h ■ Refine analytical models based on subscale results ■ Perform detailed modeling calculations for prototype and commercial-scale char combustors
Design Issues ■ Wall design/material selection	■ High temperature corrosion and lifetime data for candidate materials	■ Review existing material database ■ Install test coupons in subscale combustor ■ Perform bench-scale testing of materials
■ Cooling system integration	■ Combustor cooling system parameters (materials, number of circuits, water flow rates, power requirements, topology, capital costs) as a function of cooling water temperature and pressure	■ Conduct system-level trade-off analysis of cooling options ■ Perform combustor design analyses and develop design specifications and costs for each option
■ Furnace integration	■ Floor space availability/Combustor footprint requirements ■ Interface specifications for furnace and slag removal system	■ Develop preliminary physical layouts of combustor and furnace ■ Perform engineering analyses to determine optimum combustor support method
■ Char feed splitter	■ Data on char splitter flow stability, flow accumulation, flow control range, and flow distribution	■ Perform splitter cold flow tests as a function of various splitter geometries
Operational Issues ■ Operating envelope ■ Fuel feed system control and operation ■ Combustor start-up and shut-down	■ Operating limits for the following parameters: firing rate, stoichiometry, combustion air temperature, precombustor coal and/or char fraction, char volatile content, ash content and particle size, feed rate variability, char/fuel gas temperatures, and combustor transport ratios ■ Start-up, turn-down, and shut-down operating procedures	■ Determine char combustor operating envelope during sub-scale tests at 30-40 MMBtu/h at TRW ■ Determine preliminary operating procedures during sub-scale tests at TRW ■ Obtain data on char feed flow and control, consistency of char composition and grind site during subscale pyrolyzer tests at FWDC ■ Perform integrated pyrolyzer/char combustor tests at UTSI

Design Data Requirements

The basic char combustor design approach is to retain as many of the design features of the Healy coal-fired combustor as practical while still meeting the requirements of the HIPPS system. Since the operating range and performance requirements for the commercial-scale char-fired combustor are similar to those previously demonstrated with the TRW coal-fired combustor, it is anticipated that there will not be major modifications to the basic coal-fired combustor design in terms of size (combustor diameter and length), tube and membrane sizing, and the basic configuration. Therefore, the major design issues which need to be addressed during the Phase 2 program are 1) material selection for operation with high cooling water temperatures (660°F) in a fuel-rich, high sulfur environment, 2) site-specific integration issues including interfacing with the furnace and cooling water system, and 3) design of a char feed splitter (to split the char flow into six discrete injectors on the headend of the slagging stage) for operation under dense-phase flow conditions.

In order to address the material uncertainties, empirical data is needed on the performance characteristics (erosion/corrosion behavior) and lifetime of candidate materials of construction, operating at high metal surface temperatures, within the char combustor environment.

The data needed to address the integration issues includes specification of the plant cooling system design such as temperatures, pressures and accessibility at various locations within the system, power requirements and capital costs, and the specific system drainability requirements. Data on the overall plant layout for the commercial HIPPS plant, including floor space availability and interface issues, as well as the design of the combustor support system, accounting for thermal growth, is required in order to determine the optimum physical arrangement for the combustor and the topology of the slag recovery section.

In order to complete the design of the dense-phase char feed splitter, empirical data on the impact of various splitter configurations on char flow split characteristics, including flow stability, flow accumulation, flow control range and flow distribution, is required.

Operational Data Requirements

In order to resolve the uncertainties related to the operation of the integrated pyrolyzer/char combustor system, it is necessary to define, and optimize, the subsystem(s), and integrated system, control and operation and to determine the integrated system operating envelope. The data needed to define the integrated system control and operation is test data on system start-up/shutdown and turndown characteristics, and char feed system operation and control requirements and capabilities. Char feed characteristics, including consistency of the char composition in terms of volatile content, ash content, and grind size, stability and control of the char flowrate, must be optimized based on the char combustor performance characteristics. Definition of the component and integrated system operating envelope requires test data on turndown, firing rate, preheat temperatures, stoichiometry, as a function of the critical performance parameters including ignition, flame stability, carbon burnout, NO_x control and slagging behavior and slag recovery.

In summary, experimental and analytical data is required in order to determine:

- The char combustor performance characteristics as a function of scale, operating conditions, and hardware configuration.
- The integrated pyrolyzer/char combustor control and operational characteristics and definition of the system operating envelope.
- The performance (i.e., erosion and corrosion behavior) and lifetime of potential combustor construction materials during operation at high metal temperatures.
- The impact of various char feed splitter designs and char injector configurations on the char flow stability, control range, and char/air distribution and mixing in the headend of the slagging stage.

4.3.2 Rationale and Approach

The rationale and approach for addressing the performance, design, and operational issues is illustrated in Figure 58 and described below.

Approach to Addressing Performance Issues

The primary approach to address, and resolve, the performance issues and uncertainties is to perform comprehensive analytical modeling, in combination with subscale char combustor development testing. In addition, cold flow modeling, laboratory-scale testing and engineering analysis will be performed in support these activities.

The approach to addressing and resolving the performance uncertainties related to the commercial scale combustor is a four step process: 1) perform preliminary analytical modeling of char combustor performance at both subscale and commercial scale sizes, 2) conduct subscale char combustor tests to obtain empirical performance data, 3) refine the analytical model incorporating results from the subscale performance tests, and 4) perform final analytical modeling of the commercial-scale char combustor performance.

In order to ensure that the subscale performance data can be scaled with confidence to the demonstration and commercial-scale size, the combustion characteristics (i.e., residence time, radiative coupling, recirculation and turbulence levels, and kinetics) as well as test conditions, oxidant and fuel compositions, and test configurations, during the subscale tests must be representative of the commercial scale. In the case of the char combustor development, the minimum representative scale is approximately 40 MMBtu/hr, which enables subscale testing to be performed with the same basic hardware geometry and topology (aspect ratio) while simulating combustion characteristics through the use of finer char grinds. This scaling methodology was demonstrated during the design verification test of the coal-fired precombustor performed on the Healy Clean Coal Program. A finer grind char (70% passing through 325 mesh) is planned for the 40 MM Btu/hr testing to simulate the performance of the full scale commercial combustor firing a nominal 70% through 200 mesh coal grind. The smaller grind size char will enable simulation of particle residence time (for combustion performance), and cyclonic efficiency (for slag recovery performance) on the smaller combustor.

Scaling will be addressed through analytical modeling. The models used will be quasi one-dimensional models which have been developed by TRW and validated with coal-fired data. The computer programs model the precombustor and slagging stage combustion processes based on inputs of geometry and operating conditions, and provide outputs on various performance parameters. As stated previously, the performance models will be verified for char with data from the char-fired subscale component tests.

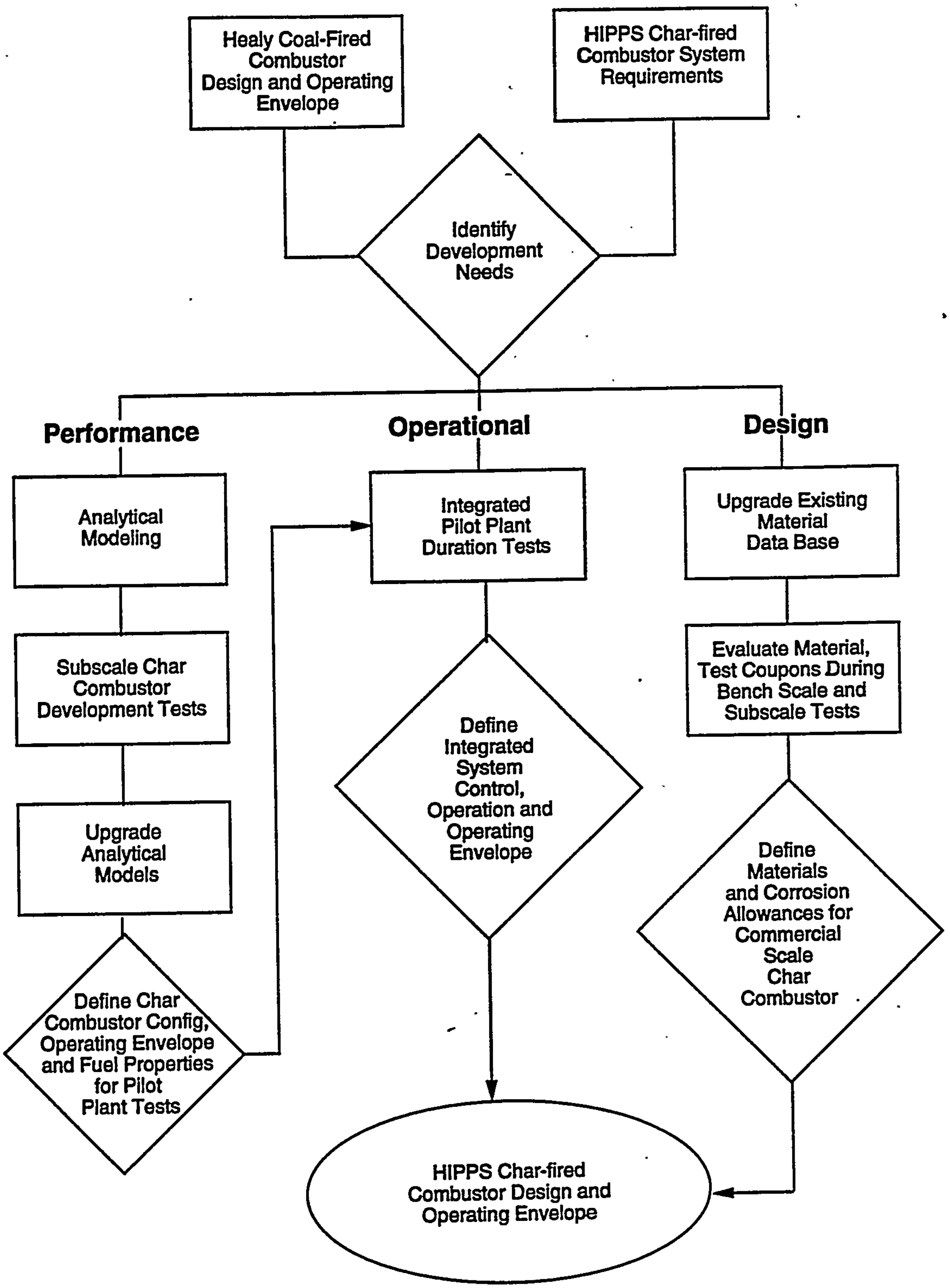


Figure 58 Approach for Resolving Performance, Operational and Design Issues

Approach to Resolving Design Issues

The design uncertainties related to the commercial-scale char combustor can be divided into two basic categories: material issues and integration issues. The approach to resolving the design uncertainties addresses each of these categories individually and entails a combination of analytical and cold flow modeling, engineering analysis, and subscale test activities:

- Material issues will be addressed through a combination of engineering analysis and bench and sub-scale testing. The approach will be a four step process: 1) upgrade the existing material data base in order to evaluate candidate materials of construction in terms of material properties, performance (i.e., erosion/corrosion characteristics) and lifetime in similar operating and gas environments, 2) during subscale combustor development tests, install test coupons of candidate materials, designed to operate at high metal surface temperatures (i.e., increased metal thickness), in order to evaluate material properties (i.e., erosion/corrosion) under actual char-fired operating conditions and, concurrently, perform gas sampling to determine the gas composition in the near-wall zone of the char combustor (i.e., fuel-rich or lean), 3) perform bench-scale testing of selected materials (based on performance during subscale hot-fire test activities) in a simulated char combustor environment (representative of the near-wall conditions) for long duration in order to obtain lifetime data on corrosion behavior as a function of operating time, 4) utilize erosion/corrosion data (i.e., mils/year) from the bench-scale and subscale tests to select materials and specify corrosion allowances for the tubes/membranes of the prototype and commercial-scale char combustor.

- Integration issues will be addressed during the preliminary design of the commercial char combustor utilizing a combination of cold flow modeling and engineering analysis. The primary integration issues relate to the cooling system and furnace interfaces. As the site specific plant design develops, engineering analysis of various integration approaches will be performed in order to select the optimum integration approach in terms of meeting interface requirements and minimizing cost. One additional interface/design issue is the dense-phase char feed splitter for the slagging stage. The approach to addressing the design uncertainties related to the splitter will be to utilize the cold flow model of the char combustor to provide data on the uniformity, stability and control of the char distribution in the headend of the slagging stage as a function of various splitter geometries and char injector configurations.

Approach to Resolving Operational Issues

The approach to resolving the operational issues involves both component development tests and integrated subsystem tests: 1) determine the operating envelope of the char-fired combustor during the subscale char combustor development tests performed at TRW. In addition, obtain test data on the char combustor operational and control requirements related to start-up, shut-down, and turndown; 2) obtain data on the char feed flow and control characteristics, as well as consistency of char composition and grind size, during the subscale pyrolyzer development tests performed at Foster Wheeler, 3) utilize the data from the subscale component development tests to define the initial operating envelope and operation/control requirements for integrated subsystem tests, 4) perform integrated subsystem tests, pyrolyzer and char combustor, at UTSI to verify, and optimize, the integrated system control and operation and to define the integrated system operating envelope.

4.3.3 Engineering Analysis and Modeling Activities

As described above, engineering analysis and modeling activities will be utilized, in conjunction with hot-fire testing, to address the design, performance, and operational uncertainties related to the commercial scale char-fired combustor. This section will provide details on these activities, including descriptions of the analytical and cold flow models.

Analytical Modeling Activities

The primary objectives of the analytical modeling activities are:

- Characterize the baseline performance of the char combustor at the subscale, prototype scale and commercial scale size.

- Parametric evaluation of the impact of geometric variations (i.e., slagging stage headend volume, baffle diameter) and configuration (i.e., char injection pattern) on the baseline char combustor performance; Define the optimum char combustor internal dimensions and configuration at the prototype and commercial scale.

- Define the baseline char combustor operating envelope; Characterize operation and performance over the expected operating envelope.

All of the models used are TRW proprietary codes. Basic descriptions of the models, including specifications of input and output parameters, are provided in Table 41. All of the models are fully developed and will only require minor, if any, modifications to adapt them to this application. The models have been validated with data from coal-fired tests, and char-fired test data, available from the subscale char combustor development tests, is required to validate the models for this application.

TRW's Coal Combustor Engineering Program (CCEP) models the aerodynamic and combustion processes within the slagging stage of the combustor. The model can be described as quasi 1-dimensional with multiple combustion zones. The program models slagging stage aerodynamics, particle trajectories (both char and residual ash particles), gas recirculation and mixing zones, particle heating and devolatilization, in-flight char oxidation, wall combustion, radiant and convective wall heat fluxes, and slag flow. The slagging stage model is divided into two major areas (indicated in Figure 58): the headend and mixing zone regions. In the headend region, fuel particle trajectories are determined based on fuel injection parameters and the combustor flow field. The oxidizer flow entering the slagging stage from the precombustor is assumed to be fully reacted, although this assumption can be relaxed. Both in-flight and wall combustion rates are determined. Gas temperatures and compositions are determined across the flow field according to the level of mixing and combustion.

In the mixing region, gas mixing, particle radial drift, and char oxidation are determined as a function of axial distance. As in the headend region, both in-flight and wall combustion rates are calculated.

Table 41 Summary of TRW-Proprietary Codes

MODEL	INPUT PARAMETERS	OUTPUT PARAMETERS	DESCRIPTION
CCEP2	-geometry -fuel properties -process flows	-carbon burnout -gas temperatures -gas compositions -heat flux distribution -slag temperature -slag recovery -pressure drop	models slagging stage aerodynamics, particle trajectories, mixing, combustion, slag flow
COMBUSTOR	-geometry -fuel properties -process flows	-gas temperatures -gas compositions -heat flux distribution -slag temperature -slag recovery -pressure drop	simplified CCEP2 model; no combustion kinetics (assumes local equilibrium)
IGNITION	-fuel properties -process flows	-particle evolution -char oxidation -gas temp and composition as function of distance/time	geometry fixed: swirl burner/can; models particle evolution, and char oxidation kinetics
NOX	-geometry -fuel properties -process flows -carbon/volatile release in 10 zones	-NO and precursors concentration profiles - output NO_x	models kinetics of formation and destruction of NO and precursors
HEAT AND MATL	-furnace/boiler req -fuel properties	heat and material balance for combustion system including auxillaries (coal feed, limestone feed)	

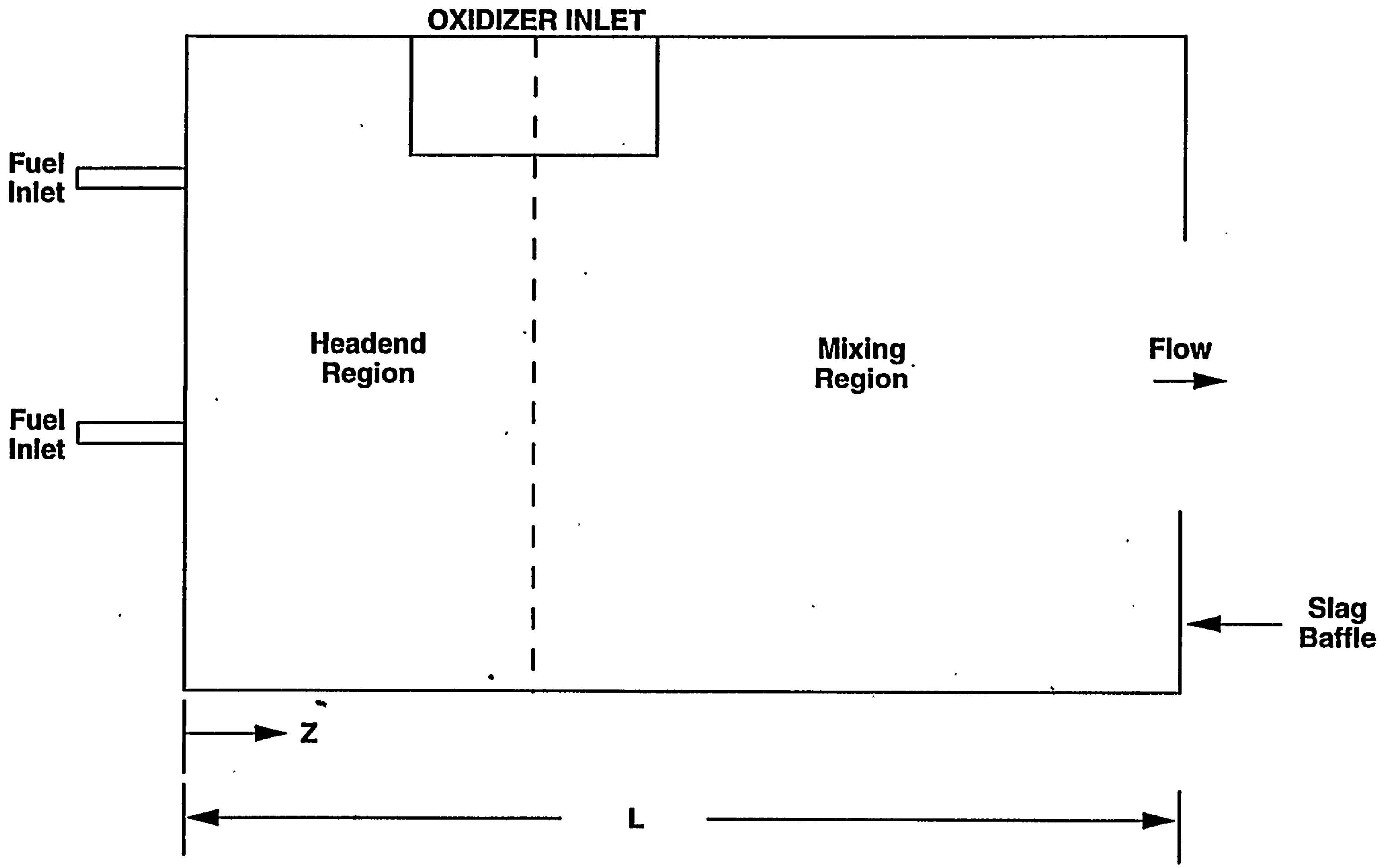


Figure 59 Char Combustor Analytical Model Geometry and Zone Definition

The CCEP model, and COMBUSTOR model (which is a simplified version of the CCEP model that does not include combustion kinetics), have been utilized to date to provide the baseline presented in Section 2.3.2.2. During Phase 2, the models will be utilized to further characterize the performance of the slagging stage of the char combustor and to provide additional definition of the design and operating envelope. In order to characterize the baseline performance, the following parameters will be determined: sectional and overall carbon burnout, gas temperatures and compositions, flow velocities, SO_2 and particulates at the combustor exit, combustor heat flux distribution and overall cooling load, slag recovery, and pressure drop. In addition, parametric calculations will be performed to characterize the char combustor performance as a function of operating conditions and geometry. Key operating parameters which will be varied include: air preheat temperatures and oxygen content, precombustor exit temperature, slagging stage stoichiometry, char particle size, char composition and heating value, and ash content and composition. Geometric variations will include: chamber diameter, chamber length, air inlet dimensions, headend dimensions, slag baffle and slag tap dimensions, char injector configuration, and slag recovery section and exhaust section dimensions. The data will be utilized to define the dimensions, configuration, operating envelope and performance characteristics of the slagging stage of the prototype and commercial scale combustor, as well as to define the initial operating conditions and configuration of the subscale development hardware. As mentioned previously, the COMBUSTOR model will be validated for this application with data from the subscale char combustor development tests.

The IGNITION model will be utilized to characterize the performance of the precombustor of the commercial scale and subscale char combustor. The program models the geometry of the swirl burner and combustion chamber of the precombustor. Based on the input fuel properties and process flow conditions, the program solves 52 simultaneous equations for particle evolution, char oxidation kinetics and devolatilization, surface kinetics and pore diffusion, etc. Program outputs include particle evolution and gas temperatures/compositions as a function of location and/or time.

Parametric calculations using the IGNITION model will be performed in order to characterize the precombustor performance as a function of the configuration and operating conditions. Key operating parameters which will be varied include air preheat temperature and oxygen content, combustion chamber stoichiometry, char composition and particle size, char thermal input, and clean fuel thermal input. Configuration variations include swirl burner inlet geometry, baffle diameter and shape, and combustion chamber diameter and length. The program output will be utilized to define the dimensions, configuration, operating envelope and performance characteristics of the precombustor for the prototype and commercial scale combustor, as well as the initial operating conditions and configuration of the subscale development and pilot plant hardware. The IGNITION model will be validated with data from the subscale development tests performed at TRW.

The NO_x computer program models the NO_x production and destruction mechanisms in the precombustor and slagging stage of the combustor. The model follows the Wendt and Fenimore kinetic model where the major species being tracked are NO, NH_i (amines), and HCN. NO is produced through the Zeldovich mechanism (thermal NO_x) as well as by oxidation of amines by OH and O. Destruction of NO is by reaction with amines and hydrocarbons. The amines production mechanism is through oxidation of HCN by O and OH. Destruction is by oxidation into NO by O and OH, by reaction with hydrocarbons to give HCN, and reaction with NO to give molecular nitrogen. HCN is evolved very rapidly during combustion of hydrocarbons and char. In addition, HCN can be produced from amines by reaction with hydrocarbons as well as NO with hydrocarbons. HCN destruction is by oxidation by OH and O into amines. The model simultaneously solves for the evolution of NO, NH_i, and HCN using the Runge-Kutta algorithm and provides concentration data in 10 zones in the combustor, as well as at the combustor exit.

The precombustor is divided into three major zones: the combustion can, followed by the transition region (unmixed) and the mixing region, which is very lean and for which combustion is either quenched or assumed completed. All precursors are oxidized to NO in this mixing zone. The slagging stage is divided into 8 zones, including the headend core (1 zone), headend recirculation (three zones), downstream core (one zone), downstream wall (two zones), mixing layer (two zones), and slag recovery section (one zone). These zones are the same as the CCEP model.

The NO_x model will be utilized to predict the NO_x output from the prototype and commercial scale combustors as a function of geometry, operating conditions, and fuel properties. This data will be utilized to define the optimum dimensions, configuration, and operating conditions for the commercial char combustor, as well as defining optimum char properties (i.e., volatile content and grind size), to achieve low NO_x emission levels. In addition, the program will be used to characterize the NO_x emission levels over the entire operating envelope. The NO_x model will be validated for this application with data from the subscale char combustor development tests.

The HEAT AND MATERIAL BALANCE model is a simple program which uses the specified furnace input requirements and fuel properties to provide a heat and material balance for the combustion system including auxiliary systems such as the coal and limestone feed systems.

In addition to the TRW-developed computer models, several standard commercially available models will be utilized to support the design of the prototype and commercial scale combustors including ANSYS, NASTRAN and SINDA. These programs will be utilized to evaluate the thermal and stress properties as a function of various materials of construction, design configurations, and cooling water properties.

Cold Flow Modeling Activities

The primary objective of the cold flow modeling activities performed during Phase 2 will be to characterize, and optimize, the dense-phase char feed splitter design and injector configuration for the multiport injector of the combustion subsystem. The splitter must reliably and stably split the char flow into six individual streams feeding the six char injectors located in the headend of the combustor. Coal flow splitters utilized previously are not amenable to this application since they are based on dilute phase, not dense phase, transport.

An existing plexiglass model of the combustor will be utilized to evaluate various dense-phase char flow splitter and injector concepts. The model is available to support the project and requires only minor modifications in order to accomplish the proposed cold-flow modeling activities.

The testing will focus on characterization of the flow distribution and mixing in the headend region of the slagging stage as a function of splitter geometry, char injector configuration and operating conditions. Key combustor flow parameters, such as swirl number and injector-to-freestream momentum ratios, will be maintained during testing in order to preserve the major flow and mixing patterns within the combustor. Key char feed system parameters will be preserved including geometrical similarity, solids-to-gas ratio, and saltation velocity margin. Tests will include qualitative flow visualization as well as detailed measurements of concentration or velocity profiles at selected locations.

Mixing patterns will be evaluated by using CO_2 as a tracer gas mixed with one or several of the flow streams. Flow tufts, water injection, and/or small particles (i.e., talcum powder) will be utilized for flow visualization. The talcum powder will be utilized to simulate the char particles and will be injected through the individual char injectors in order to characterize particle trajectories and fuel / oxidizing mixing as a function of geometry and operating conditions. The tests will characterize mixing of the flow from the char injectors with the primary swirling flow in the slagging stage. Parameters varied will include the char splitter geometry, char injector geometry (i.e., diameter) and configuration (axial and radial pattern on the headend), injection momentum ratio, headend length and swirl damper position.

Performance parameters evaluated for the splitter design will include split control range and accuracy, flow stability, solids accumulation, and pressure drop. The performance parameters evaluated for the char injector configuration (i.e., injector axial and radial locations) will be the char distribution and air/char mixing patterns in the slagging stage.

The cold flow results will be used to define the optimal char splitter/injector configuration for the subscale char combustor development tests, and ultimately, for the design of the demonstration and commercial-scale char combustor.

Engineering Analysis Activities

The primary objectives of the engineering analysis activities are to provide engineering support during the preliminary design of the prototype and commercial-scale combustors including the following activities

- Select materials of construction and specify corrosion allowances for the tubes/membranes of the prototype and commercial-scale combustors based on data obtained from a literature search, thermal and stress analysis, and experimental tests.
- Evaluate several options for integration of the combustor into the plant; in particular, the plant cooling system and furnace.
- Evaluate alternative char combustor designs and configurations based on thermal/stress analysis results and experimental test data.

4.3.4 Experimental Research and Test Activities

As described in Section 4.3.2 herein, hot-fire test data will be utilized, in conjunction with the engineering analysis and modeling activities described above, to address and resolve the design, performance, and operational uncertainties related to the commercial-scale char-fired combustor. Hot-fire test activities include laboratory-scale experimental research, subscale char combustor development testing, and integrated subscale pilot plant testing. The primary objective of the hot-fire test activities is to obtain empirical data on the char combustor, and integrated subsystem, performance and operating characteristics in order to upgrade the performance models being used for the design of the demonstration and commercial-scale HIPPS system. This approach is illustrated in Figure 60.

The hot-fire test activities have been divided into three separate tasks in order to reduce costs, simplify operations and minimize hardware/configuration changes during the integrated pilot plant testing. The basic approach to the hot-fire testing is as follows:

- Basic char ignition and combustion kinetics issues will be addressed during laboratory scale testing.
- The subscale char combustor development tests will be the cornerstone of the char combustor development effort. Specifically, these tests, performed with a workhorse, modular combustor, will focus on defining and optimizing the combustor geometry and configuration, as well as characterizing the char combustor performance over a wide operating envelope in order to support the scaling analysis activities. In addition, these tests will provide a definition of the optimal char characteristics (i.e., grind size and volatile content) required to achieve the performance goals for the char combustor. This data, in conjunction with data from the subscale pyrolyzer and char feed system characterization tests, being conducted separately at Foster Wheeler, will provide definition of the design and baseline operating conditions for the integrated pyrolyzer and char combustor.
- The integrated pilot plant tests will provide verification of the integrated pyrolyzer/char combustor design as well as defining the integrated system operating envelope, long duration operating characteristics, and providing some preliminary lifetime data.

This three phase approach to the hot-fire test activities minimizes overall project risk by confirming the basic hardware design, geometry, and configuration, the optimal char characteristics and the preliminary operating envelope prior to the integrated system pilot plant test program. This section will provide details on the three phases of the hot-fire test activities.

4.3.4.1 Experimental Research Activities

As stated previously, these activities will be performed using an existing, laboratory-scale, modular, 0.5 MMBtu/hr burner which was installed and checked out at TRW's M1-J facility during Phase 1 of the HIPPS program. The focus of the Phase 2 experimental research activities will be to evaluate the impact of char composition and grind size on ignition and combustion kinetics. In order to accomplish this objective, approximately 50 hours of test time will be accumulated on the burner during an approximately 3 month duration. The following sections describe the specific test objectives, test configuration and test plan for these activities.

Test Objective. The primary objective of the experimental research activity is to provide test data on basic char combustion kinetics as a function of char composition and grind size. During Phase 2, the activity will focus on providing a relative comparison of the ignition characteristics, flame stability and combustion kinetics for several different char compositions (i.e., volatile content) and grind sizes. The data from this activity will be utilized to define the required char compositions and grind sizes that should be utilized during, or produced during, the subscale char combustor and pyrolyzer component development tests.

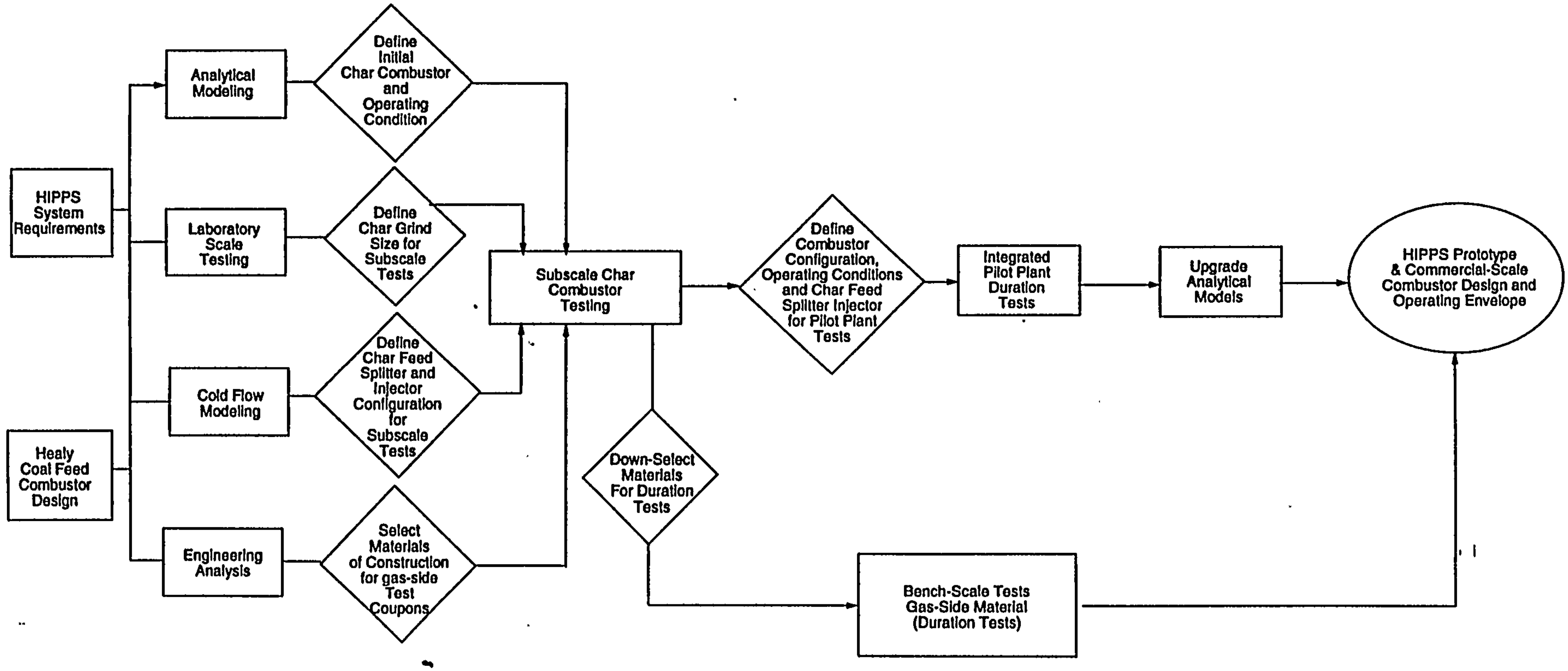


Figure 60 Overall Test Program Logic

Test Configuration.

The test hardware is comprised of a swirl burner assembly, combustion chamber assembly, secondary air injection and combustion assembly, water tempering section, and a bag house. The burner assembly, which consists of a swirl chamber, baffle, char injector and pilot, is designed to simulate the basic swirl burner configuration of the precombustor assembly. Downstream of the baffle is the combustion chamber, which is simply a long, refractory-lined duct, with diagnostic ports around the circumference and along the length. The combustor is essentially a plug flow device. The ports enable measurements of gas temperatures and compositions at various locations along the combustion chamber axial length. The secondary air injection completes the combustion process and the water tempering section reduces the gas temperature prior to entering the baghouse. Test support equipment includes a 2000 gallon cooling water tank and pump, air fan and compressor, air preheater, exhaust stack, data acquisition system and gas analysis equipment.

Test Plan and Procedure.

A detailed test plan and test procedure will be prepared for the test activities at M1-J. The test plan will contain, at a minimum, the specific test objectives, the test configuration, the operating conditions and test duration, instrumentation and data acquisition requirements, consumable storage requirements, health and safety requirements and hazard communication/environmental affairs.

Key parameters varied during the test activities will include char volatile content, char grind size, burner throat configuration and operating conditions. Performance parameters include gas temperatures and compositions as a function of axial length and visual observations of flame characteristics.

Subscale Char Combustor Development Tests

As described previously, the char combustor development test activities will be performed utilizing an existing TRW-owned, workhorse, modular, 40 MMBtu/hr combustor, appropriately modified for the specific needs of the HIPPS program. The combustor will be integrated into an existing test cell at TRW's Fossil Energy Test Site (FETS) located in San Clemente, California.

The total duration of the hardware refurbishment and upgrade, facility modification, hardware installation, and the test activities is approximately 18 months including periods of time for hardware modifications, as required. Approximately 70 tests will be conducted during this time period. A summary of the test objectives, test configuration and test plans/procedures is contained in the following sections.

Test Objectives.

The primary objectives of the char combustor development tests are to verify and optimize the char combustor performance and operational characteristics, and define the combustor operating envelope. Specific objectives include:

- Obtain test data to verify and optimize the char combustor key performance parameters including combustion characteristics such as ignition, flame stability, and carbon burn-out, NO_x control, and slagging behavior and slag recovery.

- Obtain test data to characterize the char combustor operating envelope including firing rate, air preheat, stoichiometric ratio, and turndown. Characterize the performance over a wide range of loads in order to verify the minimum and maximum firing rate of the subscale combustor.

Test Configuration.

The test series will be performed with an existing TRW-owned, modular, 40 MMBtu/hr combustor, appropriately modified to burn char. The combustion system includes a char-fired precombustor, a char-fired slagging stage, a slag recovery section, a slag tank, a windbox, and a boiler simulator. A schematic of the test set-up is shown in Figure 61. A photograph of the test cell is shown in Figure 62.

The combustor is a scaled-down version of the char combustor described in Section 2.3.2.2. Preheated air, at approximately 1100°F, enters the precombustor, where it is burned with typically 20% of the total char fuel input. The combustion products are then mixed with additional preheated air to produce an oxygen rich, high temperature gas at the inlet to the slagging stage. The gases enter the slagging stage tangentially, where they are burned with the remainder of the char, which is injected through a multiple port injector in the headend. The slagging stage is operated fuel rich at equivalence ratios varying from 0.7 to 0.9.

The molten ash droplets are centrifuged to the walls of the slagging stage, forming a self-replenishing slag layer. A concentric baffle separates the slagging stage from the slag recovery section. Slag flows to the slag recovery section via a key-hole slot in the baffle and drops by gravity into a water-filled slag tank.

Additional air is added in the windbox at the inlet of the boiler simulator to complete combustion and raise the equivalence ratio to 1.2. Downstream of the boiler simulator, the combustion gases are quenched and proceed through a knock-out chamber, venturi scrubber and cyclone scrubber prior to being exhausted to the atmosphere through a stack.

The test hardware is modular in construction consisting of several flanged components bolted together: Precombustor assembly, headend plate, air inlet section, chamber section spools, slag recovery section, dipper skirt and slag tank. The hardware is constructed from carbon steel and is designed for operation with low pressure, low temperature cooling water. The existing hardware will be refurbished in support of the test program. Refurbishment will include a new precombustor assembly with adjustable length combustion chamber, a multiport headend assembly, and a new slag tank.

Facility support equipment includes the existing boiler simulator, the knock-out chamber, venturi scrubber, cyclone scrubber, exhaust stack, cooling water system (cooling towers, pumps), air fans and heaters, nitrogen system, char loading, storage and transport system, and oil tank and transport system, instrumentation and data acquisition equipment, and emission monitoring equipment.

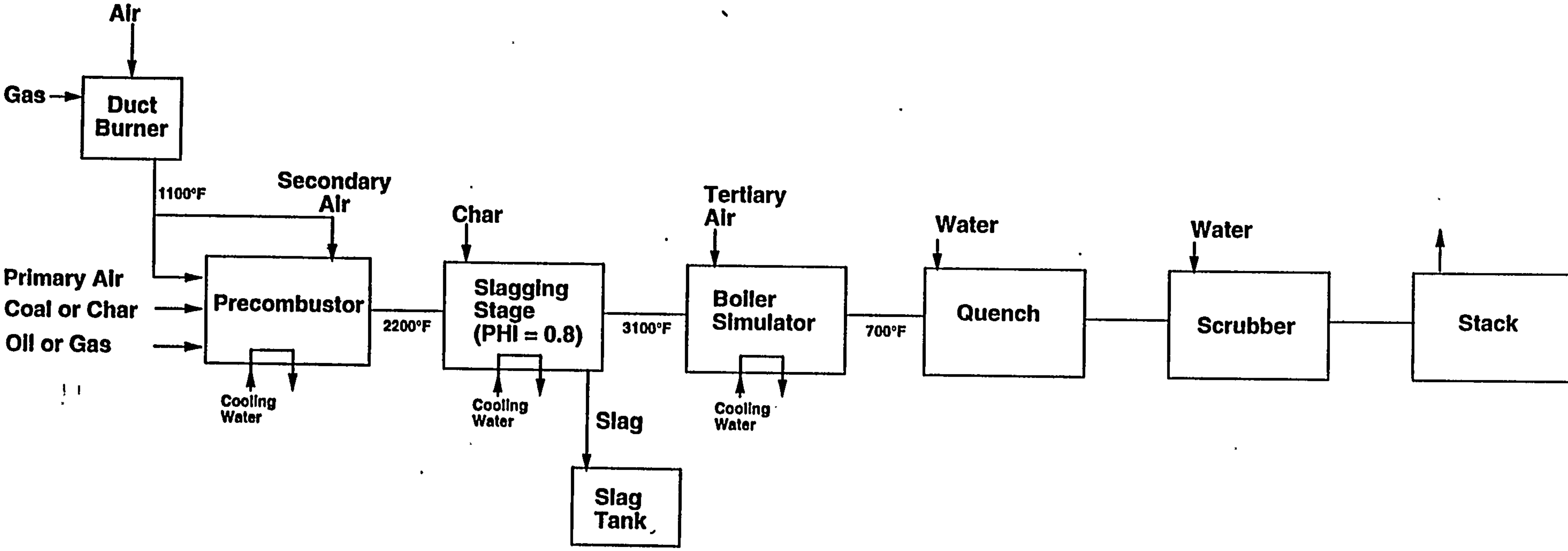


Figure 61 Schematic of Test Set-up for Char Combustor Development Testing at TRW

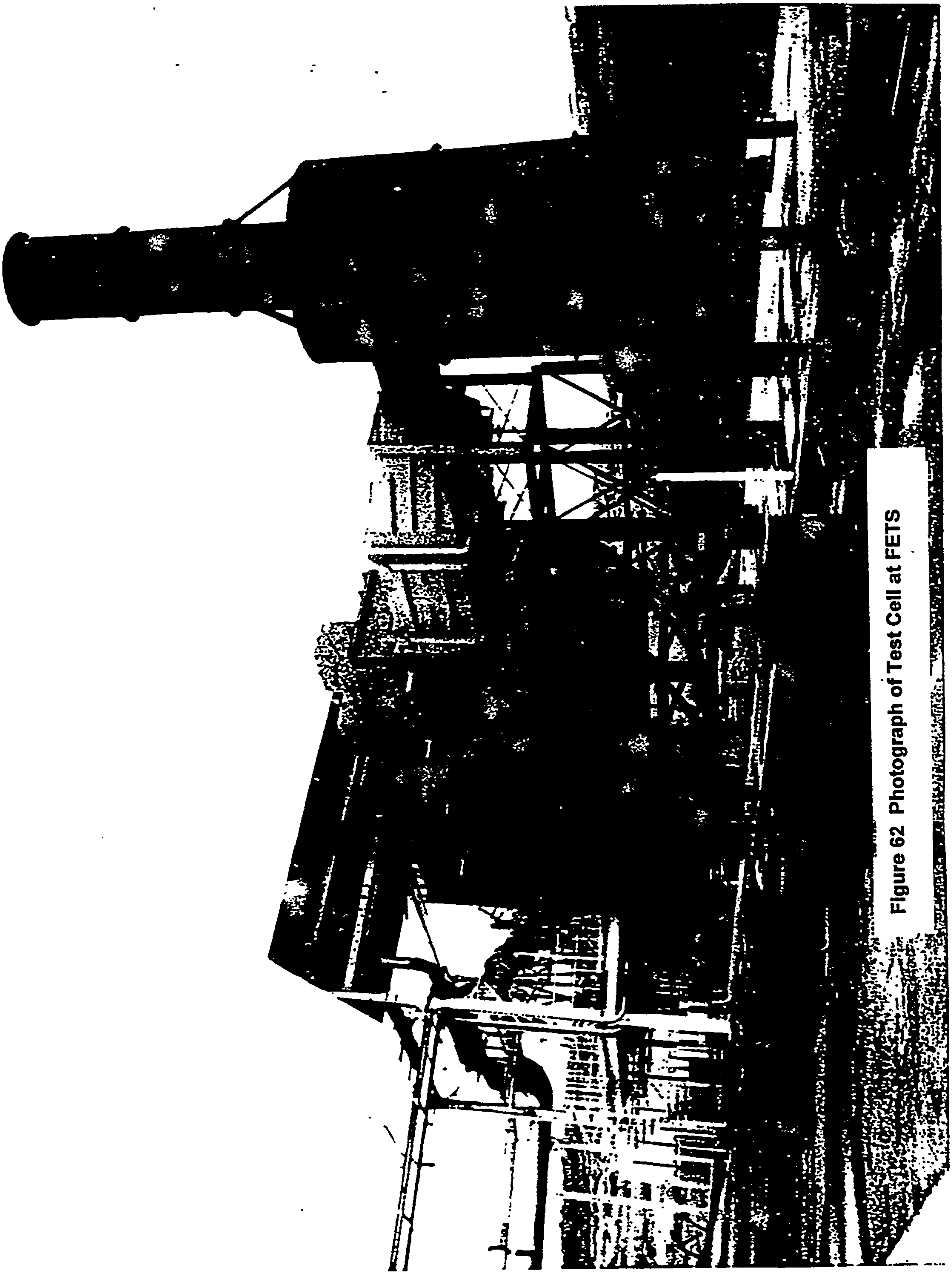


Figure 62 Photograph of Test Cell at FETS

Modifications will be made to all of these systems, as required, in support of the test activities. The majority of the modifications are associated with integrating the existing facility support equipment into the new test stand location at the backend of the boiler simulator.

Test Plan and Procedure.

A detailed test plan and test procedure will be prepared for the facility preparation, hardware installation and test activities at FETS. The test plan will contain, at a minimum, the specific test objectives, the test configuration, the operating conditions and test duration, instrumentation and data acquisition requirements, consumable storage requirements, health and safety requirements and hazard communication/environmental affairs.

The tests will be conducted with two types of char. The preliminary tests will utilize a char type that is representative, in terms of char composition and reactivity, of that produced in the Foster Wheeler pyrolyzer and has been ground to two different nominal grind sizes. The specific grind sizes will be selected based on the laboratory-scale test results as well as analytical modeling. The second set of tests will utilize char that has been produced in the Foster Wheeler pyrolyzer during the subscale development tests per the specifications developed during the combustor laboratory-scale experiments.

The test logic for the subscale char combustor development tests is shown in Figure 63 Subsequent to the integration of the hardware into the test facility, a functional checkout of all systems will be performed in order to confirm the system readiness for test. This will be followed by the basic test series which is comprised of five phases: 1) Baseline Performance with Coal, 2) Baseline Performance with Char in the Slagging Stage and Coal in the Precombustor, 3) Baseline Performance with Char in the Precombustor, 4) Performance Optimization, and 5) Performance Verification with FWDC Char.

The first three phases will focus on evaluating the baseline performance of the char combustor and the last two phases will focus on optimizing the performance. The first phase, Baseline Performance with Coal, is a short duration test series (~ 1.5 weeks) designed to verify that the integrated combustor/facility are operating correctly and that the performance of the combustor is consistent with earlier coal-fired tests. The next two phases are designed to provide a low risk sequential approach to evaluating the combustor performance during char combustion. Initially, the combustor is operated with coal in the precombustor and char in the slagging stage. This test sequence provides the opportunity to evaluate the impact of char on the slagging stage performance separate from that on the precombustor performance. Subsequent to this test phase, both the precombustor and slagging stage will be operated with char. Based on the results of this test phase, hardware modifications will be implemented on the subscale test hardware in order to address any performance issues identified during these early test phases, and the fourth phase of the test series will be initiated: Performance Optimization. Whereas the previous phases will focus on characterizing the baseline performance of the char combustor, this phase will focus on optimizing the performance characteristics in terms of ignition and flame stability, carbon burnout, slagging behavior and slag recovery, and NO_x control. The final phase of the test series will characterize the performance of the char combustor over the entire operating envelope using the char produced in the Foster Wheeler pyrolyzer per the char specifications developed during the laboratory scale test activities.

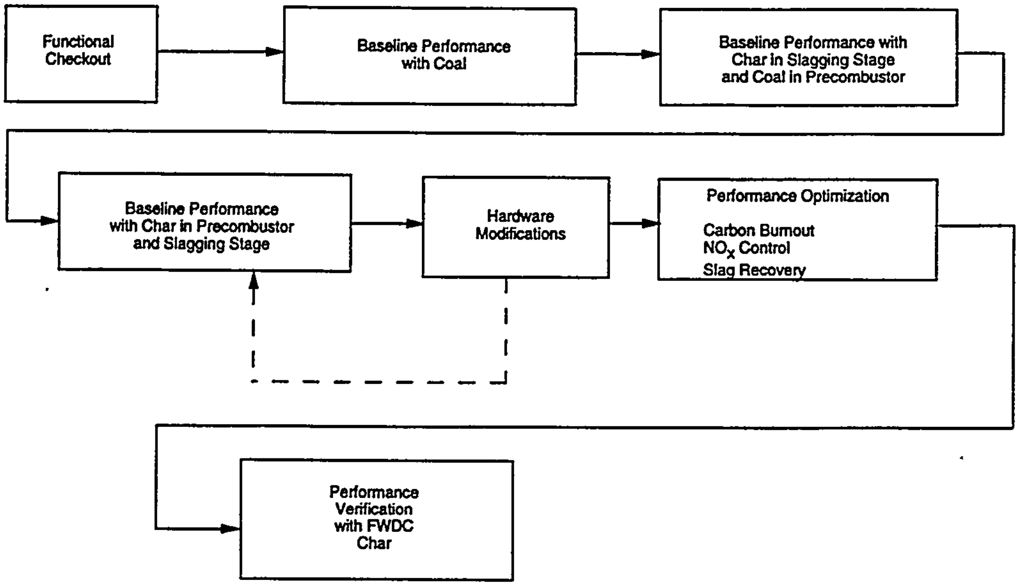


Figure 63 Test Logic For Char Combustor Development Tests at TRW

Tests will be conducted over a wide range of operating conditions and hardware configurations in order to define the optimum hardware configuration and operating conditions required to achieve the performance goals of the combustion system in terms of stable char ignition and flame characteristics, carbon burnout, slagging behavior and slag recovery, and NO_x emission levels. Operating parameters which will be varied include preheat temperatures, equivalence ratios, char grind size and volatile content, gas/oil ignitor throughput, char flow split ratio between PC and main stage, and char injection velocity. Hardware variations include burner configuration, combustion chamber length, PC throat configuration, and char injector configuration. In addition, in order to address scaling issues, the char combustor performance will be characterized over a range of firing rates.

On-line diagnostics will include: 1) calorimetry to determine heat flux as a function of axial location and overall heat loss, 2) gas sampling (CO, CO_2, O_2, and NO_x) both within the combustor and at the exhaust stack, and 3) optic ports for visual observations of ignition and flame stability as well as slag flow characteristics. Post-test diagnostics will include slag and flyash analysis for carbon content and sulfur compounds, slag weight measurements, and visual observations of the slag flow behavior such as bare regions or regions of slag accumulation or fouling. In addition, visual observations of the slag flow into the tank as well as slag particle sizes in the slag tank can provide insight into the slag tapping and slag rejection behavior.

Performance evaluation criteria will include:

(1) Carbon burnout as a function of load, char particle size and stoichiometry. The carbon burnout will be determined both on-line and off-line. During the test, the stack gas composition will provide an indication of the carbon conversion efficiency. Post-test, the slag and flash will be collected and analyzed for carbon content.

(2) Ignition and flame stability as a function of char particle size, preheat temperatures, stoichiometry, clean fuel assist and burner configuration (i.e., throat contour). The ignition and flame stability will be determined qualitatively by visual observations (via a pinhole camera in the headend region) of the flame characteristics during ignition and sustained combustion. In addition, fluctuations, or lack thereof, in the heat flux profile along the axial length of the combustor can be used as further indications of flame movement within the combustion zone.

(3) NO_x control as a function of stoichiometry, preheat temperatures, and NO_x reduction additives. The NO_x will be measured in the combustor as well as at the exhaust stack using a chemiluminescent analyzer.

(4) Slagging behavior, including slag coverage on the chamber walls and slag tapping, will be evaluated qualitatively based on on-line heat flux measurements as a function of axial location, in combination with post test observations of slag characteristics (i.e., color, density, and thickness of the slag coating on the chamber walls or any regions without slag coverage; size, color, and density of the slag particles in the slag tank). Although neither of these techniques is a very precise indication of slag flow characteristics, it does provide a reasonable estimate of regions where slag is freezing, fouling or regions with excessive accumulation or operating without slag coverage.

4.3.5 Data Utilization

As shown in the test logic diagrams presented in Figures 60 and 63, the laboratory-scale and subscale test activities directly support the planning for the integrated pilot plant tests as well as the design of the demonstration and commercial scale char combustion systems. The data utilization for each specific activity was described above in Sections 4.3.3 and 4.3.4 and will only be briefly summarized here.

Standard data reduction and analysis activities will be performed following each test including issuance of a test brief describing the test conditions and test results to all project personnel and tabulation of all test data into standard data format sheets. In addition time history and cross correlation plots will be provided for key parameters such as stoichiometry, cooling load, and NO_x levels. The test briefs, tables and plots will be reviewed by the project manager on a bi-weekly basis and, as appropriate, the future test activities will be modified based on these test results.

Anticipated Results from Laboratory-Scale Test Activities.

As described previously, the test results from the M1-J activities will be utilized to characterize, on a relative basis, the flame stability and combustion kinetics as a function of char volatile content and grind size. These results will then be utilized to 1) define the requisite char properties that must be produced by the pyrolyzer during the pyrolyzer and char feed system characterization tests performed at Foster Wheeler and 2) provide a preliminary definition of the initial char composition for the subscale char combustor development tests.

Anticipated Results from Subscale Combustor Development.

The subscale char combustor development tests will provide empirical data on the combustor performance in terms of carbon burnout, slagging behavior and slag removal, precombustor ignition and flame stability, and NO_x control, for a range of operating conditions which bracket the operating envelope. This data will be used to: 1) define the baseline combustor configuration and operating conditions, as well as the start-up and shut-down requirements, for the integrated pilot plant tests that will be conducted at UTSI, and 2) upgrade the analytical models utilized to define the geometry and performance of the demonstration and commercial scale char combustors.

Anticipated Results from Analytical and Cold Flow Modeling Activities.

The analytical modeling results will be used to characterize the baseline performance of the char combustor at the subscale, prototype scale and commercial scale size and evaluate the impact of scale, geometric variations, and configuration on baseline char combustor performance. Ultimately, this data will be used to define the optimum char combustor internal dimensions and configuration at the prototype and commercial scale and to characterize operation and performance over the expected operating envelope.

The cold flow modeling activities will be used to characterize mixing in the headend region of the slagging stage as a function of char splitter and injector geometry. Ultimately this data will be utilized to define the char splitter design and injector configuration for the subscale char combustor development activities

Anticipated Results from Engineering Analysis Activities.

The data obtained from the engineering analysis activities will be used to select materials of construction and specify corrosion allowances for the tubes/membranes of the prototype and commercial-scale combustors, evaluate several options for integration of the combustor into the plant; in particular, the plant cooling system and furnace, and evaluate alternative char combustor designs and configurations based on thermal/stress analysis results and experimental test data. The primary focus of the engineering analysis activities will be to utilize the data obtained from the analytical and experimental activities in order to define the prototype and commercial-scale char combustor design (material selection, tube sizes, membrane sizes), geometry (chamber diameter, length), configuration and integration specifications, as well as specifying the optimum operating envelope. The engineering analysis will include evaluating the quality of the data, identifying trends, providing plots of performance parameters as a function of time and dependent variables, and bracketing the operating and design envelope. This data will form the basis for the preliminary design of the char combustor.

In summary, the two test programs, in conjunction with the analytical/cold flow modeling and engineering analysis activities, will provide definition and confirmation of the optimum char characteristics (volatile content and char size), char combustor geometry and operating conditions for achieving the performance goals for carbon burnout, slag recovery and NO_x control. These results will be utilized to upgrade the design and operating envelope, as well as performance predictions, for the commercial scale char fired combustor.

4.4 HITAF

Rationale and Objectives

As discussed in Section 3.5, high-temperature corrosion information is lacking for many alloys that could possibly be used for heating the gas turbine air beyond 1400°F. Most coal ash corrosion testing in the past has been performed with metal temperatures below 1350°F. At temperatures between 1150 and 1350°F, corrosion is mainly caused by alkali-iron-trisulfate in the coal ash. Since the HITAF air heater operates at metal temperatures above 1350°F, different corrosion mechanisms are important. The fireside wastage mechanism above 1350°F is caused by oxidation, sulfidation, and alkali-sulfates. There is a data bank of materials information on corrosion in alkali-sulfates, but the corrosion tests were performed on turbine alloys or older tubing alloys. There are a number of new higher-strength, more corrosion-resistant alloys that have been developed.

The present design results in a metal temperature of around 1500°F. Cycle improvements could be achieved by going to higher air temperatures in the HITAF, but there is a gap in the available materials engineering data. There are a number of stainless steels and superalloys which have different strengths, corrosion resistance, and cost. The present available data do not define the corrosion allowance and maximum usable temperature to permit the optimum materials selection. Therefore, it is proposed that a laboratory test be performed to obtain these data.

Data Requirements and Approach

The alloys planned for testing include some of the ORNL-ASME Section VIII, Division 1, alloys with allowable stresses to 1650°F. These include 800HT, RA 330, Alloy X, 253 MA, 556, 230, and 617. In addition, RA 85A and 50 Cr-50 Ni will be used because of their improved corrosion resistance from high Si and Cr levels. Reference alloys to be included in the tests for comparison shall include Types 304 and 310 stainless steel.

Exposure testing will be carried out in 100-hour cycles for a total duration of 1000 hours. Ash generated from a char-sorbent mixture created during the FWDC second-generation PFBC pilot plant pyrolyzer tests with Pittsburgh No. 8, Illinois No. 6, and Eagle Butte coals will be used for exposure testing. Semiqualitative analyses of the char-sorbent mixture taken from the PFBC after ashing are listed in Table 42. (All elements are listed in their highest oxide state.) All tests will be conducted in a synthesized representative flue gas.

Tests will be conducted on flat 1-in. by 2-in. specimens. A mixture of the designated ash and camphor dissolved in alcohol will be coated on the specimen. (The camphor and alcohol will be used as binders to glue the ash to the specimen. When heated, this binder evaporates, leaving no residue.) The specimens will be placed on ceramic fiberboard, and the board then will be placed in a furnace. A nitrogen purge will be supplied as the specimens are heated up. At testing temperature, the purge will be switched off and a flow of simulated flue gas started. Specimens will be exposed to simulated air heater conditions for 100-hour cycles for a total duration of 1000 hours. At the end of each 100-hour exposure cycle, the furnace will be purged with nitrogen and slowly cooled down. After a testing cycle is complete, the specimens will be scraped to remove the old ash layer and the ash replenished for additional 100-hour cycles. Thickness data will be obtained in the scraped condition for each alloy at each 100-hour cycle. At the end of the 1000-hour exposure, metallurgical examination will be performed to evaluate the metal wastage and subsurface penetration, and the damage mechanism will be characterized.

Table 42 Semiqualitative Ash Analysis of Char-Sorbent Mixture (wt%)

Coal Component	Parent Coal		
	Pittsburgh No. 8	Eagle Butte	Illinois No. 6
SiO_2	20.1	0.4	40.5
Al_2O_3	10.4	0.4	17.7
TiO_2	0.4	nil	0.9
Fe_2O_3	12.1	0.3	15.1
CaO	31.8	91.1	13.1
MgO	9.7	4.8	1.2
Na_2O	0.4	1.3	0.8
K_2O	0.8	nil	1.9
SO_3	12.1	3.4	7.1
P_2O_5	0.1	nil	0.1
Base/Acid	1.77	121.87	0.54

The total metal loss, including wastage and penetration, will be plotted as a function of temperature and type of ash for each alloy. These data will be used to establish the corrosion allowance needed for each alloy. The corrosion data will be combined with mechanical property and cost data to establish the optimum alloy and its upper temperature limit for air heater application.

Resource Requirements and Availability

The tests will be performed with an existing test rig at the FWDC Livingston, New Jersey facility. Similar tests have been performed using this test rig, including the ceramic corrosion tests done in Phase 1.

Schedule

The timing of these tests is not critical so scheduling will not be a problem.

4.5 GAS TURBINE COMBUSTOR

As discussed in Section 3.6, the MASB has been tested on the Second-Generation PFB project. The combustor has been tested at 1600°F air inlet temperature which is more severe than HIPPS which is only 1400°F. Further testing is planned for the Four Rivers Modernization Project which will also have an inlet temperature of 1400°F. That project will use a Westinghouse 251 gas turbine which is the turbine we plan to use in the Prototype Plant.

The HIPPS cycle conditions that relate to the gas turbine will be evaluated. This will be done by comparing the HIPPS conditions to data from the previous tests. Based on this analysis, gas turbine cost and performance will be estimated for the Prototype Plant and the Commercial Plant. The performance will be established for both full load and reduced load.

System transient operation will be evaluated with a dynamic mathematical model which is discussed in Section 4.7. Various plant operating conditions will be simulated with this model. The operation of the gas turbine trip system under these conditions will be evaluated. If design changes are necessary, they will be incorporated in the model, and it will be run to evaluate these changes.

4.6. INTEGRATED SYSTEM TEST

Rationale and Objectives

The culmination of the Phase 2 testing will be a pilot plant that includes the critical components working as a system. Specifically, the plant will include the pyrolyzer and associated coal and sorbent feed systems, fuel gas/char separation and char transport system, char combustor, and HITAF furnace. The configuration of all system components will be the same as the proposed prototype plant and the operating conditions, including fuel and oxidizer compositions, will be representative of prototype and commercial operation. The pilot plant will be of sufficient scale (approximately 70 MMBtu/h plant heat input) to demonstrate the technology as well as provide design information for the prototype plant. The scale also is a logical step in the progression from the Pyrolyzer/Char Transport Test (PCTT) to the prototype plant. The progression of scale is shown in Table 39 of Section 4.2.2.

In addition to providing design information for specific components, the IST will demonstrate the system enough to greatly reduce the risk of the prototype plant.

Objectives of the IST are to obtain process and equipment information that will be required to design the Prototype Plant. The information will consist of process data, component operating characteristics and system operating characteristics. The test will address the pyrolyzer and char transport system issues that were addressed in the PCTT but a larger scale. These issues are pyrolyzer yields, fluidized bed hydrodynamics, char combustion characteristics, fuel gas alkalies and transport gas requirements. The PCTT will provide reliable information in these areas, but the increased scale of the IST will increase the accuracy of the data and reduce the amount of scale up that will be required for the Prototype Plant. The IST will have a coal input of approximately 6,000 lb/h which provides two steps of approximately equal scale up from the PCTT to the Prototype Plant.

For the char combustion subsystem, the integrated system tests will provide verification of the integrated pyrolyzer/char combustor design as well as defining the integrated system operating envelope. Specific objectives include: (1) verify the char combustor design in terms of configuration (in particular, the char feed splitter and injector configuration), and interface/integration requirements, (2) verify that the char transport system flow and control characteristics, as well as the consistency of the char composition and grind size, are adequate to provide stable char combustor operation and performance, and (3) optimize the integrated pyrolyzer/char combustor system control and operation, and operating envelope.

A major objective of the IST, is to operate the pyrolyzer, char separation system, char transport system and char combustor as an integrated system. These systems will contain all of the equipment that will be present in the Prototype Plant. The operating characteristics will be determined by operating the IST under conditions that will simulate operation at full and partial loads. Sufficient measurements and samples will be taken to quantify and characterize the important flow streams. Of particular importance, will be the analysis of the waste streams. Because the systems will be operated together, the waste streams will be more representative of Prototype Plant and Commercial Plant operation than the previous tests.

The IST will be the first pilot plant test that will include a simulation of the HITAF furnace. One of the objectives of the IST will be to characterize the ash deposits that will form at various temperature locations in the HITAF. This information will be used to assess the corrosion potential and ash removal equipment that will be required in the larger plants.

Another objective of the IST is to provide specific equipment design information. The PCTT should provide enough functional information to decide on the basic design and arrangement of the subsystems, but there will likely be some design modifications that result from the IST. Scaling laws for certain design details are not well developed, and there may be some adjustment in design that will occur at each step in scale up. Some of these areas may be the location of air and fuel injectors in the pyrolyzer or the location of overfire air in the furnace.

Data Requirements

A process flow diagram of the IST is shown in Figure 64, and the parameters for the base case operation are listed in Table 43. The purpose of this test is to obtain both process data and functional design information for the system. For the pyrolyzer subsystem, the IST will be a step up in scale from 600 to 6,000 lb/h coal input to the pyrolyzer. As discussed in Section 4.2.2, the main process scaling issues are the higher proportion of heat loss and nitrogen injection that will occur at smaller scale testing. These effects are accounted for by using the pyrolyzer computer model in conjunction with the pilot plant test data. The larger scale of the IST compared with the PCTT will increase the accuracy of our yield predictions by bringing the actual data closer to what will occur in the Prototype Plant.

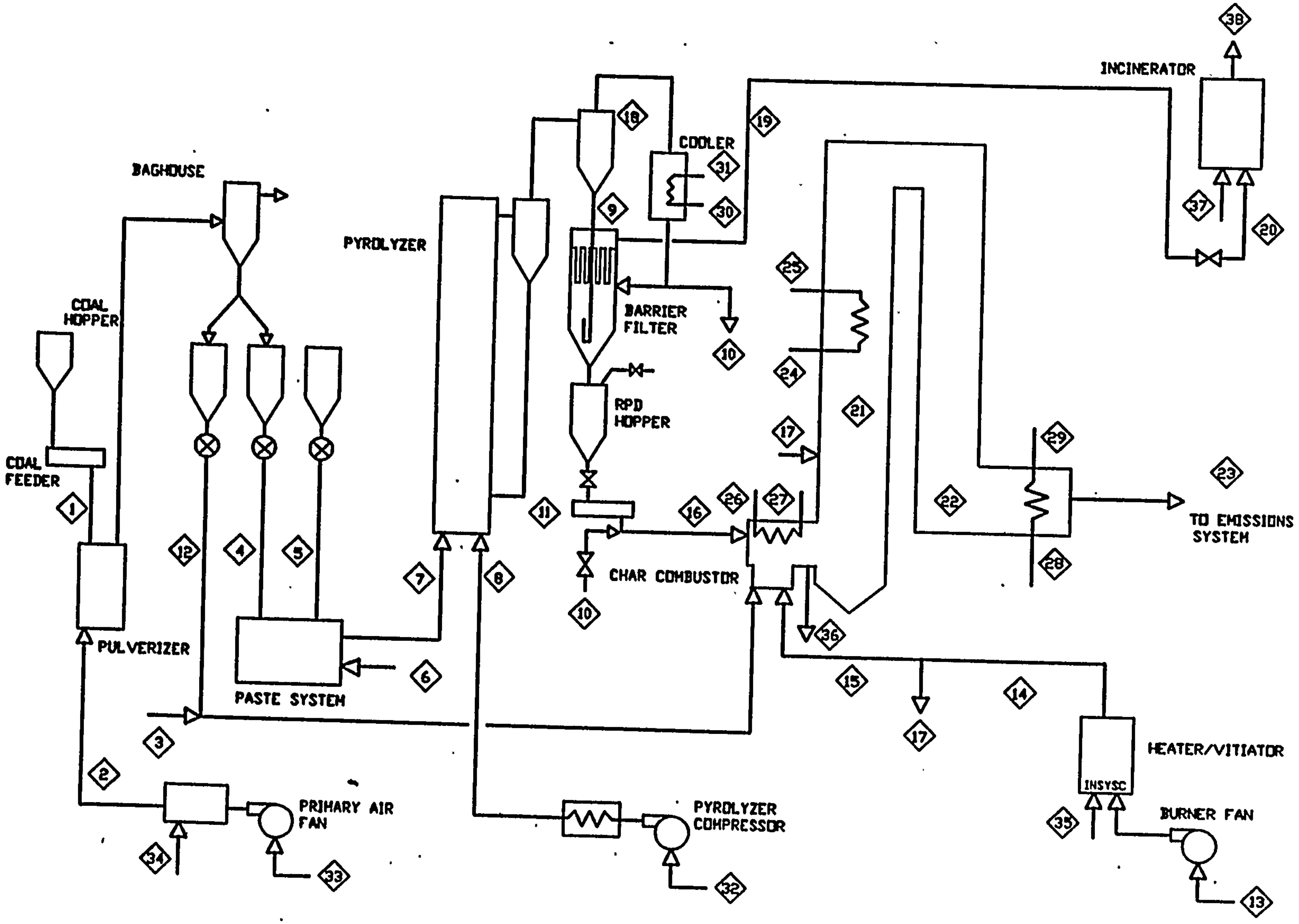


Figure 64 Schematic of Integrated System Test

Table 43 Integrated Pilot Plant Process Flow Parameters

Stream No.	Component	Pressure (psig)	Temperature (°F)	Flow Rate (lb/h)
1	Coal	0	Amb.	6,653
2	Air	5	700	30,225
3	Air	4	Amb.	900
4	Coal	244	Amb.	6,075
5	Sorbent	244	Amb.	618
6	Water	244	Amb.	1,970
7	Coal/Sorbent/Water	244	Amb.	8,663
8	Air	250	410	16,243
9	Char/Sorbent	224	1700	2,151
10	Fuel Gas	214	1200	151
11	Char/Sorbent	4	1450	2,572
12	Coal	4	Amb.	578
13	Air	0	Amb.	35,310
14	Air	3	1120	35,775
15	Air	3	1120	23,850
16	Char/Sorbent/FG	3	1450	2,723
17	Air	3	1120	11,925
18	FG/Char/Sorbent			
	Fuel Gas	224	1700	22,317
	Char/Sorbent	224	1700	421
19	Fuel Gas	204	1200	22,166
20	Fuel Gas	3	1200	22,166
21	Flue Gas	0	3385	39,226

Table 43 (Cont'd) Integrated Pilot Plant Process Flow Parameters

Stream No.	Component	Pressure (psig)	Temperature (°F)	Flow Rate (lb/h)
22	Flue Gas	0	1175	39,226
23	Flue Gas	0	350	39,226
24	Water	150	94	22,890
25	Steam	150	366	22,890
26	Water	730	340	103,700
27	Water	630	380	103,700
28	Water	150	94	35,000
29	Water	150	335	35,000
30	Steam	150	366	22,890
31	Steam	150	694	22,890
32	Air	0	Amb.	16,243
33	Air	0	Amb.	30,000
34	Natural Gas	5	Amb.	225
35	Natural Gas	5	Amb.	465
36	Slag	0	150	750
37	Air	1	Amb.	40,000
38	Flue Gas	0	2590	62,166

For the char combustor, the IST will provide verification of the combustor performance with direct char feed from the char transport system. In particular, the tests will evaluate, and optimize, the char combustor performance with respect to char feed stability, char composition and grind consistency, and char and fuel gas temperature. This will be the first opportunity to evaluate combustion characteristics (ignition, flame stability, and carbon burnout) with a hot (600°F) char. The IST will be run at conditions that will simulate partial load and transient operation. Any changes in char throughput and characteristics under these operating conditions will be measured, and the performance of the char combustor will be correlated with these conditions and data.

The measurements that will be taken during the IST are indicated in Table 44. There will be online measurements and samples that will be taken and analyzed. The data obtained will be sufficient to determine the heat and material balances around the pyrolyzer, char combustor and the complete IST. The chemical composition of critical streams will be determined such as the fuel gas, char, slag and spent sorbent from the pyrolyzer oxidizer section. Also, the alkali content of the fuel gas will be determined before and after cooling with an alkali monitoring system such as the FOAM system developed under DOE sponsored research.

Table 44 Integrated System Test (IST) Measurements

Stream No.	Component	Pressure	Temper-ature	Flow Rate	Sample	Sample Analysis
1	Coal			X	X	Ultimate, Proximate, Physical
2	Air	X	X			
3	Air		X	X		
4	Coal			X	X	Particulate
5	Sorbent			X	X	Chemical, Particulate
6	Water			X		
7	Coal/Sorbent/Water	X	X	X	X	Composition, Physical
8	Air	X	X			
9	Char/Sorbent	X	X		X	Ultimate, Particulate
10	Fuel Gas		X	X	X	Composition, Particulate, Alkali
11	Char/Sorbent		X	X	X	Ultimate, Particulate, TGA
12	Coal			X		
13	Air		X	X		
14	Air	X	X		X	Composition
15	Air		X			
16	Char/Sorbent/FG		X			
17	Air			X		
18	FG/Char/Sorbent	X	X		X	Composition, Particulate, Alkali
19	Fuel Gas	X	X	X	X	Composition, Particulate, Alkali

Table 44 (cont) Integrated System Test (IST) Measurements

Stream No.	Component	Pressure	Temper-ature	Flow Rate	Sample	Sample Analysis
20	Fuel Gas	X				
21	Flue Gas	X	X	X		
22	Flue Gas		X			
23	Flue Gas		X		X	Particulate, NO_x, SO_2
24	Water	X	X	X		
25	Steam		X			
26	Water	X	X	X		
27	Water	X	X			
28	Water	X	X	X		
29	Water		X			
30	Steam	X	X	X		
31	Steam		X			
32	Air		X	X		
33	Air		X	X		
34	Natural Gas			X		
35	Natural Gas			X		
36	Slag		X	X	X	Chemical, Physical
37	Air		X	X		
38	Flue Gas		X		X	Particulate, NO_x, SO_2

Approach

The existing DOE test facility at the University of Tennessee Space Institute (UTSI) will be modified for these tests. This facility, the coal-fired flow facility (CFFF), is very well suited for the IST, and considerable cost savings will result from its use. Much of the coal and sorbent preparation and handling will be done with existing facilities. The existing furnace will be used, and downstream flue gas cooling and cleanup will be accomplished with existing equipment. At the test site, there is also sufficient space between the existing coal preparation equipment and the furnace for the pyrolyzer, char transport system, and char combustor which will be added. The existing char combustor used in the previous TRW tests will also be used in the IST.

Various other systems at the U.S. DOE facility will also be used. Among these are the compressed air systems, fired air heaters, boilers, fans, instrumentation and controls. By using this facility, the IST will only cost a fraction of what it would at a greenfields facility. The layout of the UTSI facility is shown in Figure 65. This drawing also includes the location of the equipment that will be added for the IST.

Over 700 hours of IST operation are planned, including shakedown and testing. The main objective of the test runs will be to demonstrate the operation of HIPPS as a system. For this reason, the test matrix will not be extensive. Evaluation of process parameters such as different feedstocks or pyrolyzer conditions will be done in the smaller scale component tests. The emphasis in the IST will be in controlling the operation of the system at full load, partial loads and the transients between these loads. A detailed test plan will be developed in Phase 2. This plan will establish the IST operating parameters that will represent full and partial load operation.

In summary, the IST will be a test of sufficient scale and completeness to yield design information required for the Prototype Plant. It will be enough like the Prototype Plant in critical aspects to demonstrate the technology as a system. This demonstration will be important in obtaining the final commitments and financing required for the Prototype Plant.

As described previously, the IST will provide empirical data on the integrated system operation, control and performance at both full and 50 percent load. This data will be used to: (1) verify the integrated system design, configuration and interface/integration requirements for the Prototype Plant, (2) define the operating envelope as well as start-up, shut-down, turn-down requirements for the prototype plant, and (3) upgrade the analytical models utilized to define the geometry and performance of the prototype and commercial scale pyrolyzer and char combustor subsystems.

Resource Requirements and Availability

The CFFF will be reserved for use as the IST if we are successful in obtaining this contract. The program for which it was originally built has been completed. We do not anticipate any major permitting problems since the site has been permitted for similar operation.

Schedule

The design of the IST will start mid-1996. Operation is planned for mid-1998. Prototype plant design activities will start before the completion of the IST, but since the Phase 2 design will be a preliminary design this should not be a problem. All of the IST testing will be completed before the detailed engineering is done in Phase 3.

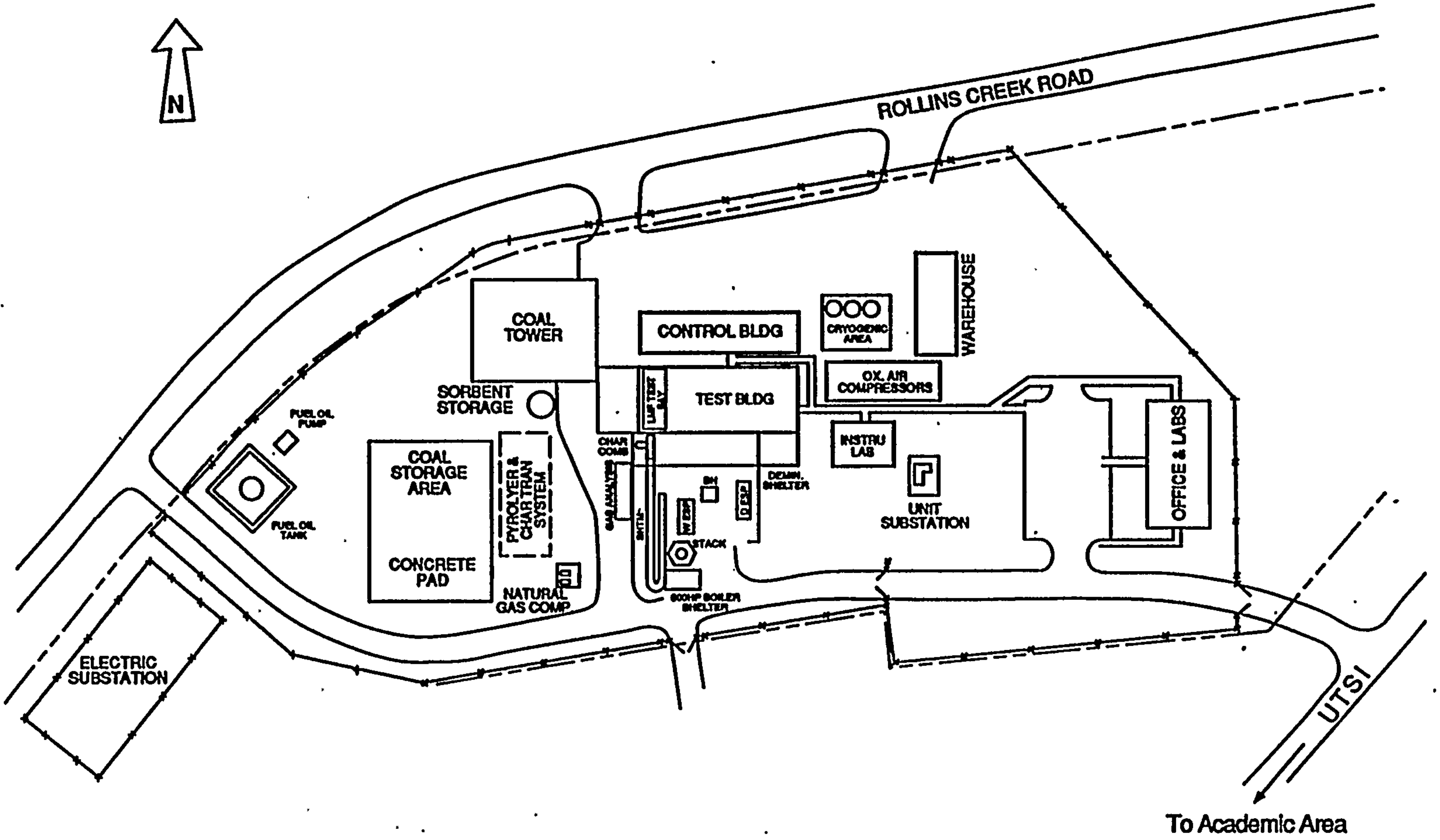


Figure 65 Layout of the UTSI Facility — CFFF Site Plan

4.7 DYNAMIC MATHEMATICAL MODEL

Rationale and Objective

In order to establish operating procedures for the prototype and commercial plants, it is necessary that dynamic or transient response of individual HIPPS components are known. These responses then need to be integrated to assure that the HIPPS system operates in a stable and safe manner when subjected to planned and unplanned (upset) transient events. A dynamic mathematical model for the HIPPS system would allow evaluation of alternate operating procedures and control strategies.

The objective of this element of the RD&T Plan is to develop a dynamic (transient) mathematical model of the HIPPS plant to optimize its operating characteristics.

Data Requirements

The dynamic mathematical model should be sufficiently detailed to predict plant response to planned events such as start-up, shutdown and load changes. The model should also predict response of key plant parameters to upset events such as load rejection. The model should identify behavior of process parameters (e.g. flow, temperature, pressure, etc.) during transients to uncover any unsafe or otherwise undesirable plant conditions. The model should also inexpensively and quickly allow evaluation of alternate plant configuration or control strategies to mitigate any concerns.

Another level of dynamic modeling would include pollutant formation and control. The model should be able to predict that plant emissions remain within prescribed limits during transient events.

Approach

The first step in preparing the plant dynamic model is to develop dynamic response characteristics of individual components. We intend to use a commercially available software PC-TRAX which is modular in structure and has a number of standard component modules in its library such as gas and steam turbines, HRSG, valves, pipes, ducts, etc. Dynamic response characteristics of plant components that are unique to HIPPS will have to be developed. These include the slagging combustor, pyrolyzer, topping combustor and the air heater. Dynamic modules for these unique components will be developed using analytical correlations available in the literature and supplemented by any test data for similar components.

We will develop the dynamic model for the prototype plant to be built and tested in Phase 3. Initially, only a simplified model will be developed to evaluate gross plant response to dynamic events. (The simplified model will not address plant emissions.) The custom-developed modules for unique components will be integrated with conventional components from the PC-TRAX library to assemble a system model for the prototype plant. The model will be tested and exercised to provide preliminary predictions on component and plant response.

The next step is to validate the component or subsystem mathematical models, using data from component and subsystem testing planned in Phase 2. The individual component or subsystem testing modules will be modified to reflect results of Phase 2 tests. At this point, the model will further be expanded to include formation and control of pollutants (e.g. SO_x, NO_x, etc.) The model will be at a level of maturity where all planned and unplanned events can be mathematically simulated.

The model will then be exercised to assist in the Prototype Plant Engineering Design and Test Plan. The plant design will be evaluated for its dynamic characteristics to determine optimum operating procedures and uncover any unsafe conditions. Several planned and unplanned events will be simulated. The results from this model will be extremely valuable in design of the prototype plant and in preparation of a test plan.

The model will also be upgraded to the commercial plant size and exercised to assist in its design.

Resource Requirements and Availability

We plan to use PC-TRAX software for preparation of the dynamic model. We have a license to use the software for development and delivery of such models from the software owner. We have engineers at Foster Wheeler who have or are currently using their software for other similar applications.

Schedule

We propose to develop dynamic models of unique HIPPS components and integrate them into a PC-TRAX system model in 12 months. The model will then be validated based on component and subsystem tests and pollutant formation and control included over a period of 8 months. The model will then be used to support the prototype and commercial plant designs in concert with the schedule for these activities.

4.8 RELIABILITY, AVAILABILITY AND MAINTAINABILITY MODEL

Rationale and Objectives

The HIPPS commercial plant will be a combination of electrical and mechanical components that are subject to random failures as well as wear. A high efficiency unit such as HIPPS will be high on any utility's priorities to keep on-line to the maximum extent possible. In other words, it is important that the HIPPS commercial plant has very high availability to make it attractive to utilities. Effort should be expended to ensure that any weak links in the plant design are identified and mitigated.

The objective of this element of the RD&T plan is to examine reliability, availability, and maintainability (RAM) characteristics of the commercial-size HIPPS plant and remediate any factors that have the potential of reducing reliability and availability of the plant.

Data Requirements

It is necessary to quantify the reliability and availability of the commercial plant with quantitative assessment of contributions of individual components or subsystems to the system reliability and availability. This data will identify components and subsystems that should receive further attention to improve plant RAM characteristics.

Approach

RAM techniques have been applied in the electric utility industry for over two decades and have reached a mature state, with standard and generally accepted definitions of terminology and methodology. The North American Electric Reliability Council (NERC) has a historical data base on the performance of power plants and their components for all present-day methods of power generation, ranging from fossil and nuclear base-load steam plants to load-leveling units such as pumped storage. The Council publishes Generating Availability Data Summary reports, which include annual and 10-year performance of various types of generating units and their components. EPRI has developed assessment methodologies for advanced generation technologies, such as gasification combined cycles, and has developed computer programs such as UNIRAM for RAM assessment. DOE also has available various RAM evaluation programs.

The approach taken for the RAM assessment is to use utility-accepted RAM methodology and EPRI's UNIRAM or equivalent computer code, with component data from the NERC data summary and EPRI data bases supplemented by engineering estimates for new components, to determine the RAM indices for the baseline plant. In addition to overall plant RAM measures, component ranking will be established to determine components that have the greatest impact on plant reliability.

The availability of a complex system such as a HIPPS plant is a function of the reliability and maintainability of the components and subsystems and their functional configuration. An availability model relates the availability of the total system to the performance and arrangement of its components. EPRI's UNIRAM program allows RAM modeling of a complex system such as HIPPS, including partial-capacity states of components. The UNIRAM program will calculate plant performance indices, including equivalent availability, effectiveness, availability, forced outage rate, and equivalent forced outage rate.

The plant will be divided into subsystems based on capacity throughputs and designed redundancy. A fault tree will be constructed for each subsystem, the level of detail being components for which reliability and availability data are available. Input to the UNIRAM model will include number and capacity of subsystems, arrangement of subsystems and their inter-relationship in the plant, and data on failure frequency and restoration time for each component.

Resource Requirements and Availability

The proposed model analysis will require UNIRAM or an equivalent computer software. Arrangements will be made with EPRI for access to the UNIRAM code for this work. Foster Wheeler engineers have used UNIRAM and other RAM programs for reliability and availability of complex power and process plants.

Foster Wheeler is a subscriber to the North American Reliability Council (NERC) database and receives the Generating Availability Data Summary reports. Data in these reports will be modified to reflect any plant-specific factors prior to use in UNIRAM.

Schedule

This work will be performed almost concurrently with the HIPPS commercial plant design update so that any significant results from the RAM evaluation can be incorporated into the plant design. The duration of this effort is expected to be nine months.

4.9 CALCIUM SULFIDE CONVERSION AND PARTICLE ATTRITION

Rationale and Objectives

As discussed in Section 3.2, two technical issues concerning the pyrolyzer are the conversion of calcium sulfide to calcium sulfate and the particle attrition rate. These issues will be investigated in both the PCTT and IST tests, however, the amount of feedstocks that can be reasonably tested at this scale is limited. The objective of the test program discussed in this section is to establish an economical means of determining design parameters for alternative feedstocks.

Approach and Data Requirements

A bench scale test rig will be developed that will include a small circulating fluidized bed. A schematic diagram of the test rig is shown in Figure 66. The rig will be electrically heated to control the bed temperature. The bed will be capable of being fluidized with either air or syntheized gas. Tests will be run to establish procedures and tests parameters that will yield calcium sulfide to calcium sulfate conversion data and attrition data that can be correlated to the data from the pilot plant tests.

Both the design of the test rig and the testing procedure will be developed as part of the Phase 2 effort. It is anticipated, however, that there will be two separate test procedures using the same rig. The basic test for calcuim sulfide to calcium sulfate conversion will be done in a bubbling bed mode that will simulate the operation of the pyrolyzer oxidizer section. A specific quantity of sorbent of predetermined size distriution will be put in the bed and a synteisized fuel gas will used to fluidize the bed at elevated temperature. This gas will contain SO2 which will form calcium sulfide on the particles. After a period of this type of operation which will be determined with initial test runs, air will be used to fluidize the bed and samples will be taken at established time intervals to determine the extent of the chemical conversion.

A similar test will be run to evaluate the attrition characteristics of sorbent. The main difference will be that after the calcium sulfate is formed, the rig will be operated as a circulating bed with an inert gas as the fluidizing medium. This operation will be for a specified length of time and particle size analyses before and after the test will be used to establish an attrition correlation factor.

The purpose of both the calcium sulfate conversion tests and the attrition tests will be to establish a test procedure that can be correlated to pilot plant and then to commercial plant operation. Once this correlation is established for a few sorbents, it can be used to develop information on other feedstocks without the expense of pilot plant operation.

Resource Requirements and Availability

This test rig will be part of a combustion laboratory that is being built at the FWDC Livingston, New Jersey facility. This laboratory will contain equipment for crushing and screening coal and sorbents. It will also have a FTIR for analysis of gas composition and a pressurized TGA. FWDC personnel with experience in the area of fluidized beds will participate in this testing.

Schedule

The test rig development will start in the second quarter of Phase 2. Testing will then be done during the next two quarters to establish a preliminary base of data for the feedstocks that will be used in the pilot plant tests. Then, as data is available from the PCTT and the IST, the test rig data and the pilot plant data will be reviewed to determine relevant correlations. Based on this review, the test rig and/or the test procedure will be modified to improve the usefulness of of the laboratory data.

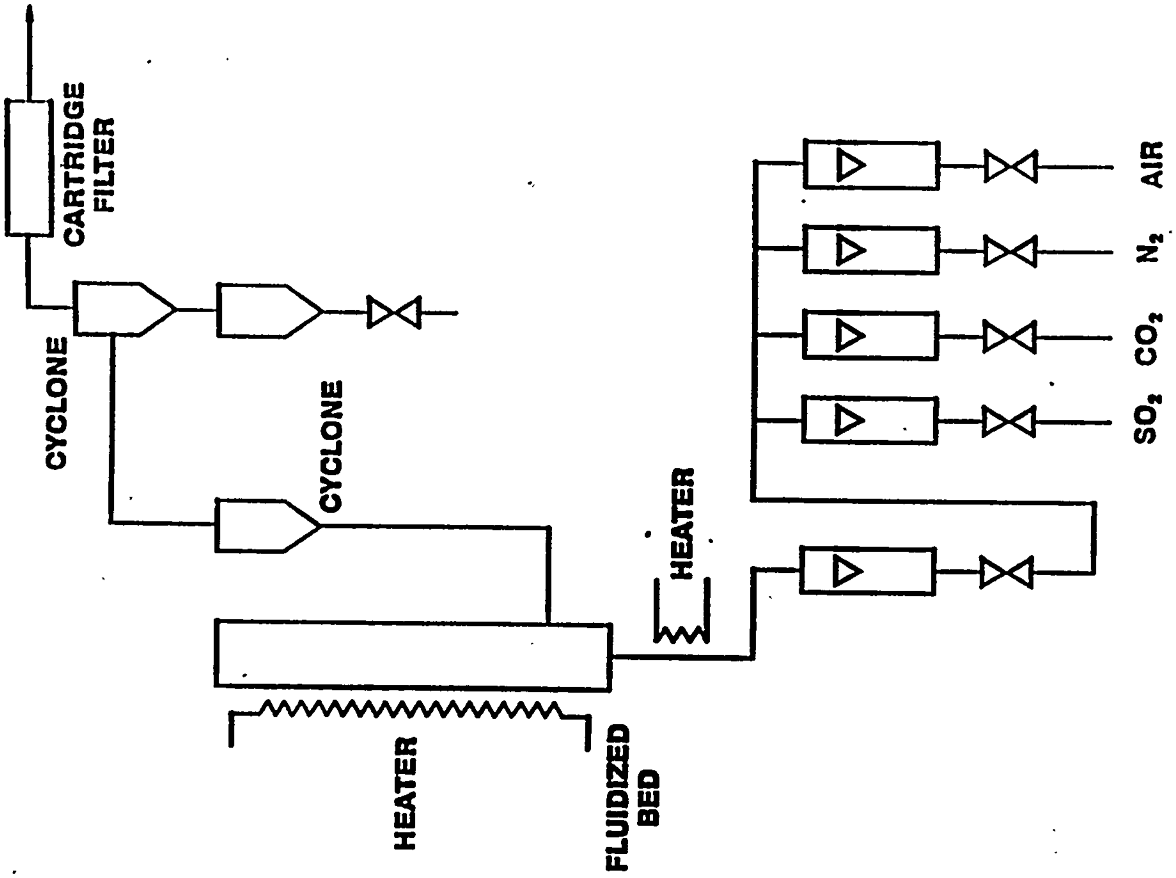


Figure 66 Laboratory CaS Conversion and Attrition Test Rig

4.10 COMPUTER MODELING OF PYROLYZER

Rationale and Objectives

The pyrolysis process involves both two-phase hydrodynamics and chemical reactions. Our approach in designing and testing the HIPPS pyrolyzer is based on our experience with the second-generation testing at Foster Wheeler and on computer modeling. The PFB process yields are determined with a proprietary fluidized-bed gasifier simulation computer program that incorporates data from FWDC second-generation PFB pilot plant tests. The computer program has received certain validation for the PFB pyrolyzer and is relevant for the HIPPS pyrolyzer as well.

The design of the pyrolyzer depends upon the particle and gas dynamics. A computer program based on analytical approaches proposed by Zenz and Briens and factors obtained from commercial circulating fluid bed operating plants has been developed by Foster Wheeler. This program is proposed for the design of the HIPPS pyrolyzer.

Morgantown Energy Technology Center (METC) of DOE has developed a general-purpose hydrodynamic computer model (MFIX) that describes chemical reactions and heat transfer in dense or dilute fluid-solids flows which occur in chemical reactors. MFIX predicts detailed information on pressure, temperature, composition, void fraction, and velocity distribution in a reactor. We believe utilization of the MFIX computer model in sizing and yield prediction for the pyrolyzer will enhance our confidence in designing and characterizing the HIPPS pyrolyzer. Another objective is to develop and validate MFIX as a pyrolyzer design tool that can be reliably used for commercial plants.

Data Requirements

As discussed above and described in Section 2.3.5, the pyrolyzer process design is proposed to be based on FWDC's proprietary fluidized bed gasifier simulation computer program. This computer model solves char-gasification kinetics and sulfur-capture kinetics simultaneously with mass and energy balances. The hydrodynamics to size the pyrolyzer will be addressed by an FWEC program based on analytical correlations and commercial CFB plant data. Although, Foster Wheeler is comfortable with this approach, we believe utilization of a comprehensive independent computer prediction model such as MFIX will significantly enhance our confidence in pyrolyzer design and scale-up. This additional analytical tool will make our predictions and design more reliable ranging from initial component testing to the commercial plant.

To that end, we propose to use the MFIX program throughout the Phase 2 program beginning with the pyrolyzer component testing to the commercial-unit design. The computer predictions will be validated and the program upgraded throughout the Phase 2 scale-up program.

Approach

Our approach is to use the MFIX computer model to supplement our basic design and prediction tools at each stage of testing and scale-up. The MFIX program effort will be performed in parallel with the Phase 2 design and scale-up work.

We are currently in the process of acquiring the MFIX computer code from METC. Foster Wheeler personnel will be trained and will initially use the code to validate our second-generation PFB pilot plant data.

To support the HIPPS Phase 2 program, the MFIX code will be used to design the component-level pyrolyzer tests proposed at FWDC. The results will be compared with our other prediction and design tools and engineering judgement used to finalize the component (pyrolyzer) design and test plan. At the conclusion of the tests, the MFIX model predictions will be compared with the test data and appropriate submodels in the MFIX code will be modified, as necessary. The modified code, along with other FWDC tools, will then be used to design and set test plan for the subsystem pyrolyzer tests planned at UTSI. Based on the test results, the MFIX code will again be upgraded.

The MFIX code will then be used to assist in pyrolyzer design and test planning for the prototype plant. It will also be used in task 6 for HIPPS commercial plant design update under Phase 2.

Finally in Phase 3, the code will be finalized based on results of the prototype testing and used in update of the commercial plant design.

In summary, we propose to use and upgrade the MFIX computer code as the pyrolyzer testing at component, subsystem and prototype level continues. This should lead to availability of a reliable pyrolyzer design tool for commercial HIPPS plants.

Resource Requirement and Availability

As mentioned earlier, we plan to acquire the MFIX code shortly and train our engineers on its use. We will also perform initial validation based on our second-generation PFB pilot plant data. This will result in availability of the code for use on the HIPPS Phase 2 program with trained engineers. Engineering personnel from METC will also be available for consultation.

Schedule

A major objective of this element of the RD&T plan focuses on development of a reliable tool for pyrolyzer design for commercial plants. To that end, we will to carry this activity throughout Phases 2 and 3, in concert with the component, subsystem and prototype testing. The code will also be used to upgrade pyrolyzer designs for the commercial plants in Phases 2 and 3.

4.11 CERAMIC AIR HEATER DEVELOPMENT (ALTERNATIVE DESIGN)

This section describes the work for Phase 2 of the HIPPS project involve with the design, development, and fabrication of a high–temperature, high–pressure ceramic air heater. The organization of the development effort is shown in Figure 67.

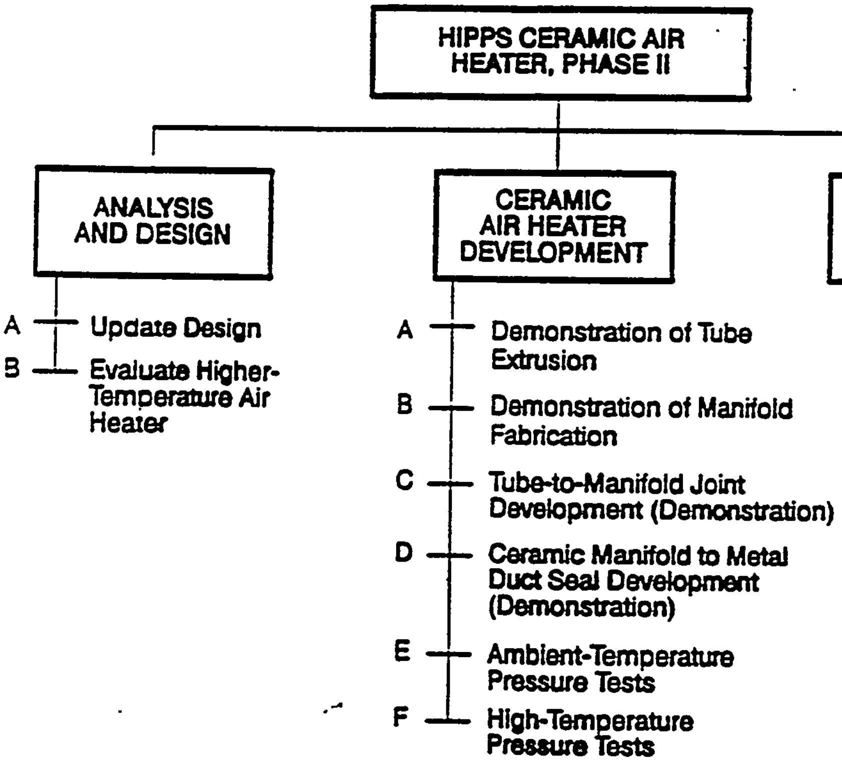


Figure 67 Ceramic Air Heater Development Organization

4.11.1 Design and Analysis

This effort is aimed at providing analysis support to accommodate changes in conditions which alter the overall ceramic air heater design and evaluate operation at higher temperatures. For example, if the number of units changed, this could significantly effect furnace layout and air heater cost.

For new, higher–temperature operation, the maximum tube wall temperature and stresses will be determined. Depending on the stress level, the analysis might include a probabilistic stress evaluation. For various operating conditions, the maximum reasonable operating conditions will be determined.

4.11.2 Ceramic Air Heater Development

The objective of this effort is to perform appropriate R&D on component fabrication and joining technique development and testing to validate the ceramic heat exchanger design features. The planned work is described below.

Ceramic Component Fabrication Development

Tube Extrusion Fabrication

One of the goals of the design process for this tubular ceramic heat exchanger is to minimize the number of tubes and hence, tube–to–manifold joints. To accommodate this goal, internally finned tubes with a cruciform pattern will be fabricated from silicon carbide. Tubes with an outer diameter of 2 in. are envisioned, with lengths up to 13 ft. Fabrication of these tubes will be subcontracted to a commercial high–performance ceramic supplier such as Carborundum Company. Based on past experience, the most promising material for this application is Hexoloy SA sintered alpha–silicon carbide manufactured by the Carborundum Company. Previously manufactured cruciform tubes of Hexoloy SA were 1.5 in. OD and 5 ft long. The diameter and length envisioned for this heat exchanger design are larger and longer than previously manufactured. This fabrication task is required to develop the manufacturing skills necessary to produce the tubes to the desired size. Several tubes of the desired diameter and length will be fabricated for this task, as well as several short lengths for use in bonding studies.

Manifold Fabrication. The manifolds will be fabricated from the same ceramic material as the tubes in order to eliminate the problem of thermal expansion mismatch between dissimilar materials. It is imperative that stresses due to thermal expansion mismatch be minimized to produce effective tube–to–manifold bonds, which can contain high pressure with a high degree of integrity. Slip casting is the anticipated form of fabrication for the manifolds due to their intricate shape requirement. The fabrication effort for the manifolds will be performed under a subcontract to a commercial high–performance ceramic supplier such as Carborundum Company. Several short sections of manifold (approximately 1–ft length) will be fabricated to support bonding and pressure containment studies. A full–length manifold will be slip cast to prove fabrication capability, but it will not be sintered due to lack of a furnace with sufficient size.

Tube–to–Manifold Bonding

Joint Design. Design details for the attachment of the cruciform tubes to the manifold will be developed in this task. Detailed drawings of the design will be produced and used by the ceramic component supplier to design and fabricate the tube and manifold components.

Joining Technique Development. In this effort, joining methods will be developed to bond cruciform tubes to manifolds. Several potential methods such as ceramic joining, brazing and microwave sintering will be evaluated.

Development of ceramic bonds between tubes and manifolds will be performed during this effort. The main joining approach will involve the co–sintering of the silicon carbide components. This approach produces joints which exhibit the minimum possible deviation in properties from those of the parent materials. For example, bonds can be formed between SiC samples using SiC tape containing graphite and fired at elevated temperatures. Successful ceramic bonding of sintered silicon carbide has been performed between SiC samples. Other potential techniques, such as microwave sintering, will be evaluated. Microwave sintering uses microwave energy to directly and rapidly heat the joint interface. Another joining technique, high–temperature metallic brazing, can join sintered silicon carbide parts. Braze materials in the Au–Pd and Au–Pt families have been identified as candidates for the application temperatures and atmospheres.

This effort will focus on comparative evaluation of the joining methods, selection of a suitable method, and development of the selected method into a practical and cost–effective means to perform the joining process on parts in actual size. The initial part of this effort will involve completing the preliminary evaluation of the joining technique selected for study in Phase I and evaluating alternative methods. To support the evaluation of the joining methods, fabricated joint samples will be examined for their microstructural characteristics. Joint strengths and other joint properties will be determined to establish the effect of processing parameters on the mechanical integrity and properties of the joint. The joining methods will be compared to select the most suitable technique for further development. The selected technique will be optimized by several parametric design experiments. Joints of actual sizes and configurations will be demonstrated. Various designs and options will be examined to develop the technique into a practical means for joining SiC parts in actual sizes.

Ceramic Manifold–to–Metallic Duct Sealing

Seal Design. Design of the seal at the transition from the ceramic manifold to the insulated metallic duct will be performed under this subtask. The design will draw on past concepts of similar transition joints developed for other high–pressure, high–temperature heat exchangers.

Seal Fabrication. A ceramic manifold–to–metallic duct assembly will be assembled for use in pressure containment tests. The seal assembly will be fabricated using full–size diameter components, though the lengths of the ceramic manifold and the metallic duct components will be shortened to facilitate handling and pressure testing.

Ambient–Temperature Pressure Testing

Ambient–temperature pressure containment tests will be performed on individual components and bonded and sealed assemblies. The components will be subjected to internal pressures in excess of the design pressures. These tests will be performed under the following work elements.

Cruciform Tube. Silicon carbide cruciform tubes will be pressurized internally to at least 200 psi and held at pressure to detect for leakage. Should a tube fail during testing the broken pieces will be collected, the tube reconstructed, and the cause of failure (flaw type and location) will be determined. A test fixture will be fabricated to pressurize the tubes, measure for possible leakage, and provide protection in the case of a failure.

Manifold Section. Pressure testing of a header section will be performed to at least 200 psi to evaluate its containment capability. The holes to which the cruciform tubes would be bonded will be capped so that the strength of the manifold wall will be tested. If the manifold section fails during the test, an evaluation of the broken pieces will be conducted to determine the cause of failure. Fabrication of a test fixture will be required for the pressurization and safety containment of the manifold section.

Tube–to–Manifold Bond. Bonded cruciform tube–to–manifold assemblies will be pressure tested to at least 200 psi to evaluate the integrity of the bond joint. Assemblies which pass the test will be subjected to several thermal cycles to the design operating temperature, and then retested to determine the effects, if any, on the pressure containment ability of the bond joint. It is anticipated that the test fixture fabricated to support manifold section activities, with some modifications, will be used for this test.

Ceramic Manifold–to–Metallic Duct Seal. The ceramic manifold–to–metallic duct assembly will be pressure–tested to at least 200 psi to determine the integrity of the seal. If leakage is observed at the seal, the assembly will be removed from the test stand, the seal modified, and the assembly retested in an attempt to achieve an acceptable seal. A test fixture will be fabricated to pressurize the ceramic manifold–to–metallic duct assembly. The fixture will have the capability to monitor pressure and leakage while providing safety containment of the assembly in the event of a failure.

High–Temperature Pressure Testing

High–temperature pressure containment tests will be performed on bonded and sealed assemblies. These tests will be required prior to developing a prototype heat exchanger. Bonded samples will be first tested at high temperatures and ambient pressure to examine the integrity of the joint. After ambient pressure testing, bonded samples will be pressure tested at high temperatures (1800° to 2300°F). A test fixture will be set up and a test plan will be prepared to support this effort. The plan will encompass the following: (1) statement of objectives, (2) test description including test setup, test conditions, and test procedures, and (3) description of methods for assessing results. One important aspect of high–temperature pressure testing is to address the issue of catastrophic failure of tubes and manifolds. Tests will be carried out under simulated conditions to establish whether catastrophic failure is a problem. If catastrophic failure is likely to occur, several design modifications will be considered. A few options are listed below:

- Rely on compartmentalization of the air heater to limit the extent of damage.
- Separate the header/tube modules in the gas flow direction enough so that flying debris from one tube will not hit other modules.
- Put a screen between header/tube modules.

Tube and header materials can be modified to improve their resistance to catastrophic failure. For example, thicker and tougher (reinforced or composite) materials can be evaluated for this case. Modeling and analysis will be carried out if necessary to support the evaluation of the various options mentioned above.

References:

1. S. Ubhayaker, "The Healy Clean Coal Project: Design Verification Tests," Proceedings of the Second Annual Clean Coal Technology Conference, Atlanta, GA 1993.

2. R.H. and R.E. Mitchell, "Unified-High Temperature Char Combustion Kinetics for a Suite of Coals of Various Rank," 24th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA (1992).

3. R. H. Hurt, R.E. Mitchell, L.L. Baxter, and D.R. Hardesty, "Char Combustion Kinetics of U.S. Coals: A Comprehensive Data Base for Industry," Proceedings of the Ninth Annual Pittsburgh Coal Conference, Pittsburgh, PA, (1992).

4. Okkes, A.G., "Get Acid Dew Point of Flue Gas", Hydrocarbon Processing, July 1987, pp 53-55.

5. W.F. Domeracki, T.E. Dowdy and D.M. Bachovchin, "Topping Combustor Development for Second-Generation Pressurized Fluidized Bed Combined Cycles" ASME 94-GT-176, (1994).

6. T. Knowlton, et al., "Solids Pressure Reduction without Lockhoppers: The Restrictive Pipe Discharge System," Institute of Gas Technology, Chicago, IL, 1986.

7. T. Brogan, "Method For Reducing No_x Emisssions from Combustion Processes", U.W. Patent 4,335,084, June 15, 1982.

8. N.S. Jacobson, J.Am. Ceram. Soc., 76 (1993) 3.

9. R.G. Munro and S. J. Dapkunas, J. Res. Natl. Inst. Stand. Technol, 98 (1993) 607.

10. K. Breder and V.J. Tennery, Materials Support for HITAF, Quarterly Technical Progress Report for July 1, 1993 to September 30, 1993, Oak Ridge National Laboratory.

11. D.P. Butt, R.E. Tressler, and K.E. Spear, J.Am. Ceram. Soc., 75 (1992) 3257 and 3268.

12. J.R. Price and M. Van Roode, in "Ceramic Thin and Thick Films," B.V. Hiremath, Ed., American Ceramic Society, Westerville, OH, 1990, p. 169.

13. M. Van Roode, J.R. Price, and C. Stala, Paper 91-GT-38, International Gas Turbine and Aeroengine Congress and Exposition, Orlando, FL, June 3-6, 1991, American Society of Mechanical Engineers, New York, 1991.

14. T.N. Tiegs and P.F. Becher, Bull. Am. Ceram. Soc., 66 (1987) 339.

15. W.A. Kern, R.E. Tressler, and M.J. McNallan, Center for Advanced Materials Newsletter, Pennsylvania State University, 6(1) (1992) 1.

16. V. Parthasarathy, B. Harkins, W. Beyermann, J. Keiser, W. Elliot, Jr., and M. Ferber in Proceedings of the 16th Annual Conference on Composites and Advanced Ceramic Materials, Cocoa Beach, Fl, January 7-10, 1992, American Ceramic Society, Westerville, OH, 1992, p. 503.

17. M. Wiesel, in Eur-Ceramics II, Vol. 1 Basic Science and Processing of Ceramics, G. Ziegler and H. Housner, eds., 1991, p. 689.

18. T. Yano, H. Suematsu, and T. Iseki, J. Mater. Sc., 23 (1988) 3362.

19. C.H. Bates, M.R. Foley, G.A. Rossi, G.J. Sunberg, and F.J. Wu, Bull. AM. Ceram. Soc., 69 (1990) 350.

20. I. Ahmad, W.M. Black and R. Silberglitt, in Proceedings of the 16th Annual Conference on Composites and Advanced Ceramic Materials, Cocoa Beach, FL, January 7-10, 1992, American Ceramic Society, Westerville, OH, 1992, p. 520.

21. B.H. Rabin, J. Am. Ceram. Soc., 73 (1990) 2757.

22. B.H. Rabin and G.A. Moore, Mat. Res. Soc. Proc., 314 (1993) 197.

23. N.J. Orozco, presented at the Joint Contractors Review Meeting FE/EE Advanced Turbine Systems Conference, FE Fuel Cells and Coal-Fired Head Engines Conference, Morgantown Energy Technology Center, Morgantown, WV, August 3-5, 1993.

24. Glicksman, L., "Scale Models of Circulating Fluidized Bed Combutores: Simplification of Convection Heat Transfer", DOE Contract DE-FC21-88MC25049.

5.0 PHASE 2 AND 3 STATEMENT OF WORK

ENGINEERING DEVELOPMENT OF COAL-FIRED HIGH PERFORMANCE POWER SYSTEMS

PHASES II & III

STATEMENT OF WORK

1.0 BACKGROUND

Early in the twenty-first century, new electricity generating plants will be needed to meet continuing increases in demand for electric power. In addition, a large number of existing generating units will reach the end of their useful service lives and new units will be required to replace this existing capacity. Coal, as the Nation's most abundant and lowest cost fossil energy source, represents an important option for powering forthcoming electric generating plants. However, this option is threatened by public concerns regarding the environmental impacts of coal use, including emissions of "greenhouse" gases.

To address the entire spectrum of environmental concerns associated with coal use, the Pittsburgh Energy Technology Center (PETC) began a three-phase program for the development of Coal-Fired High Performance Power Systems (HIPPS). A major objective of the HIPPS Program is to achieve significant increases in the thermodynamic efficiency of coal use for electric power generation. Through increased efficiency, all airborne emissions can be decreased, including emissions of carbon dioxide. Moreover, higher efficiency yields environmental benefits throughout the entire fuel cycle, including coal mining and transportation, reduced solid wastes, reduced water requirements and reduced thermal loadings to rivers and water bodies.

The HIPPS Program was formally initiated in September 1990 with the release of a Program Research and Development Announcement (PRDA DE-RA22-90PC90159). This Announcement described the overall Program and solicited proposals for Phase I: Concept Definition and Preliminary R&D. The scope of the PRDA was limited to indirectly-fired high efficiency coal-fueled power generation systems involving one or more advanced technologies that were not being pursued within the Department of Energy's Coal R&D Program. Contracts were awarded to teams led by United Technologies Research Center and Foster Wheeler Development Corporation. Work on Phase I began in March 1992.

The major participants on the United Technologies' team are the UTC Turbo Power and Marine Division, Bechtel Corporation, Oak Ridge National Laboratory, and Power Technology International. The United Technologies' system incorporates a coal-fired high temperature advanced furnace that would heat the compressed air sent to the gas turbine. The major participants of the Foster Wheeler team -- Allied-Signal's AiResearch Division, Bechtel Corporation, General Electric, Research-Cottrell, and TRW -- are also evaluating a combined-cycle with gas and steam turbines. The Foster Wheeler team's approach features a coal pyrolyzer that produces both a gaseous fuel and a char. Both products would be used in a high-temperature advanced furnace to heat the compressed air sent to the gas turbine.

In addition to the above two teams, the Department's Coal R&D Program supported development work begun by Hague International prior to the release of the HIPPS PRDA. The work by Hague International centers on the development of an externally-fired, combined-cycle system in which the heating of the compressed air fed to the gas turbine would occur in a high-temperature ceramic heat exchanger, which would be coupled to a coal-fired combustor.

As a consequence of the two HIPPS projects and the externally-fired combined cycle project, three contractor organizations have performed work that is relevant to the subject solicitation. However, participation in Phase I or in any other federally-supported activity is not a prerequisite to participation in Phases II and III.

Industry cost sharing is part of the HIPPS Program. Required levels of cost sharing increase as the Program proceeds from phase to phase and the technology moves nearer to commercialization. The minimum required levels of contractor cost sharing are 25 percent in Phase II and 40 percent in Phase III.

2.0 PURPOSE AND OBJECTIVES

The purpose of this Statement of Work is to complete the engineering development of a coal-fired HIPPS that will be capable of dramatically improving the environmental performance and efficiency of coal use for electric power generation. This Statement of Work covers Phases II and III of an ongoing program being funded through the Coal R&D Program within the U.S. Department of Energy. This solicitation is limited to development of high-efficiency systems containing a gas turbine that is indirectly fired by coal. Specifically, "indirect firing" means that products from the combustion of coal are not allowed to contact the working components of the gas turbine. Heat from the combustion of coal is transferred to a Brayton cycle working fluid such as air. Heat recovered from the combustion flue gases and from the turbine exhaust may be used to drive a steam cycle. It is not the intent of this solicitation to accelerate R&D on power generation systems based on fluidized bed coal combustion, fuel cells, gas turbine systems involving either coal gasification or the direct firing of coal into a gas turbine, or magnetohydrodynamics.

Within this solicitation, a HIPPS is defined to include the complete plant for receiving and burning coal, producing electricity, controlling all airborne emissions and processing all waste streams. If the proposed HIPPS concept includes the use of deeply cleaned coals that are currently not readily available, the system boundary is defined to include advanced coal preparation facilities, whether at the power plant site or at the mine mouth, and all subsystems required for the transport, storage, and handling of the deeply cleaned coal product.

The program objectives are as follows:

1. Environmental Performance

Efficiency: A total station efficiency (coal pile to busbar) of at least 47%, calculated using the higher heating values of the input fuels. Compared to a conventional coal-fired plant with 35% efficiency, carbon dioxide emissions would decrease by one-fourth, at a minimum, as would thermal loadings to system cooling water.

Airborne Emissions: The airborne emission objectives are based upon fuel input. Considering the objective for efficiency improvement, the following objectives provide over a twelve-fold decrease in emissions of nitrogen and sulfur oxides and particulates per unit of electric power produced, compared to today's requirements for new coal-fired plants.

- NO_x: No more than 0.06 lbs (measured as NO_2) per million Btu of fuel input.
- SO_x: No more than 0.06 lbs (measured as SO_2) per million Btu of fuel input.
- Particulates: No more than 0.0003 lbs per million Btu of fuel input. This low level of particulate emissions should effect a substantial reduction in the release of potentially toxic trace elements (e.g., Sb, As, Ba, Cr, Mn, Mo, Ni, Zn) that can be emitted from coal-fired power plants. The HiPPS shall comply with all regulations concerning trace element emissions, including Hg, that would be effective at the time of commercial deployment.

Solid Wastes: All solid wastes, including coal ash and non-hazardous wastes produced by flue gas treatment systems, must be benign with regard to disposal. Preference will be given to approaches in which solid waste generation is minimized through the production of usable by-products.

2. Fuel Requirements

Acceptable Fuels: The ultimate goal is the development of advanced power generation systems in which coal is the predominant fuel (>95 percent of heat input). Early commercial systems capable of firing coal as the primary fuel (>65 percent of heat input) are acceptable, so long as such initial systems are capable of evolving to configurations in which coal would be the predominant fuel. Preference will be given to initial systems in which coal provides greater than the minimum acceptable level of heat input, provided that the proposer can demonstrate that this approach would involve no substantial increase in technical risk. Natural gas is an example of an acceptable secondary fuel for initial system configurations.

Suitable Coals: Systems capable of firing all major minable reserves of bituminous coals, subbituminous coals, and lignites are of interest. It is recognized that a single power system may not be applicable to such a broad range of coals. Accordingly, the engineering development activities proposed as a result of this solicitation may address (be limited to) a specific, but major, subset (rank and/or type) of U.S. coal reserves.

3. End-use Requirements

Load: Baseload power generation with a nominal annual capacity factor of 65 percent.

Size: Efficient and economic power generation for generating units (a plant may contain several generating units) with a rated net electrical output of approximately 300 MWe.

Performance Attributes: Safety, reliability, and maintainability to match or exceed conventional coal-fired power plants. Preference will be given to systems that allow load-following with minimal degradation of efficiency, and that are amenable to construction using factory assembled modular components based upon standard designs.

4. Economic Performance:

Costs of Power: Ten percent lower cost of electricity relative to a modern coal-fired power plant conforming to current New Source Performance Standards.

3.0 PROGRAM APPROACH

In recognition of the national importance of assuring the continued use of coal as an environmentally sound option for electric power generation, the Department of Energy is implementing a multi-year R&D program for the development of a coal-fired HIPPS. The program consists of three phases, with the second and third phases being addressed in this Request for Proposals. The following summarizes the work areas now being addressed in Phase I and the approach underlying the accompanying Statement of Work for Phases II and III.

1. PHASE I - Concept Definition and Preliminary R&D

The major participants in Phase I are identified in the Background section of this Statement of Work. The objectives of Phase I are to develop in detail (1) a complete definition of a HIPPS concept, (2) an analysis of the advanced concept's technical and economic feasibility, and (3) an R&D plan covering all engineering development and testing work to be conducted in Phase II. The scope of Phase I activities includes the following:

a. Concept Definition and Analysis, including analyses of advanced cycles and technical assessments of subsystems and components regarding performance requirements, developmental status and prognosis, design options, durability, complexity and reliability, operating requirements, and capital and operating costs.

b. Preliminary R&D, as required to develop technical information essential to conducting a credible evaluation of the advanced concept's technical and economic feasibility. Appropriate R&D activities for Phase I include engineering analyses, experimental research, and modeling.

c. HIPPS Commercial Plant Design, specifically, a preliminary engineering design of a non-site specific, greenfields HIPPS plant with a baseload duty cycle and performance matching or exceeding the Program Objectives.

d. Engineering Research, Development and Test (RD&T) Plan for Phase II, including a design deficiency analysis and the development of a detailed plan for RD&T required to meet Phase II objectives.

2. PHASE II - Engineering Development and Testing

Both Phases II and III of this solicitation are being procured through this Request for Proposals. Participation in Phase I is not a prerequisite to participation in Phases II and III. The objective of Phase II is to develop a complete design base for the construction and operation of a HIPPS prototype plant. Phase II work covers a duration of approximately 54 months, beginning with contract award. Refer to the included schedule.

The Statement of Work for the Phase II effort provides for a comprehensive program of engineering research and development (Task 2). Significant portions of Phase II work are directed at subsystem testing (Tasks 3, 4, and 5), including the construction of new facilities or modifications (including instrumentation) to existing test facilities. The use of existing facilities is strongly encouraged, should this result in the most cost-effective approach.

The objectives of the subsystem tests are to verify component and subsystem performance models and approaches, to verify scaling-laws, and to develop the technology base for the detailed design of the HIPPS prototype plant. The scale of subsystem testing should be appropriate to attaining these objectives in a cost-effective manner. The number of subsystems to be tested will depend upon the development status of each subsystem. For example, the selected flue gas desulfurization subsystem may have already undergone testing, and further testing of this subsystem in Phase II would not be warranted. HIPPS concepts require a high temperature furnace firing coal or coal-derived products (e.g., pyrolysis char). Design and scale-up of an advanced furnace is anticipated to require the construction and operation of a test facility with a firing rate in the range of 50 million Btu per hour.

Phase II also includes confirmation of the site identified in the contractor's proposal, or the selection of a new site, for the HIPPS Prototype Plant. The gathering of all data required by the Department to evaluate the potential impacts of the project, as required by the National Environmental Policy Act, will be completed in Phase II prior to proceeding to Phase III. Phase II ends with an update to the HIPPS Commercial Plant Design (Task 6), the development of a site-specific engineering design and test plan for the HIPPS prototype plant (Task 7), and preparation of the Phase II Technical Report (Task 8).

3. PHASE III - Prototype High Performance Power Plant

Competition for Phase III will be limited to participants that successfully complete Phase II. At the completion of Phase II, each contractor will provide three documents upon which the evaluation and Phase III selection process will be based: (1) the Phase II Technical Report prepared under Task 8; (2) a Business and Management Proposal (updated and detailed) for Phase III; and (3) a Cost Proposal (updated and detailed) for Phase III. The Phase II Technical Report will be considered as the technical proposal for selection of Phase III work.

Phase III consists of the detailed design, construction, operation, testing and evaluation of a HIPPS prototype plant (Tasks 9, 10, 11). It is currently envisaged that this plant will utilize either a frame-type power turbine or an aeroderivative turbine and that the plant total generating capacity will depend on the type of machine chosen. Furthermore, the HIPPS Prototype Plant must include all major subsystems required to demonstrate program objectives, including efficiency, emissions, and waste disposal, and readiness for commercial deployment. Phase III also includes an update to the HIPPS commercial plant design, based upon the results of testing and evaluation of the HIPPS Prototype Plant (Task 12). A Phase III Final Report will be prepared (Task 13). It is anticipated that Phase III will cover a period of 54 months.

4.0 DETAILED REQUIREMENTS

PHASE II: ENGINEERING DEVELOPMENT AND TESTING

Task 1 - Project Planning & Management

Task 1.1 - Project Planning

A *Management Plan* and a *Research, Development and Test (RD&T) Plan* accompanied the contractor's proposal. For these two plans, the contractor shall prepare and submit to the DOE Contracting Officer's Representative (COR), within thirty (30) calendar days following contract initiation, revisions conforming in detail to negotiations conducted prior to contract award. As part of the effort to develop the *Management Plan*, the contractor shall establish an advisory panel to serve to critique the development effort throughout the duration of the project. All of the contractor's work under the contract shall be based on the approved Management Plan and RD&T Plan.

The contractor shall submit revisions to the approved Management Plan and/or the approved RD&T plan when directed by the DOE COR pursuant to the "Technical Direction" clause of the contract or whenever Statement of Work requirements are changed by contract modification. The contractor may submit recommended revisions to the Management Plan and/or the RD&T Plan whenever the contractor deems such revisions to be desirable for optimal achievement of contractual goals. All contractor-recommended Management Plan and/or RD&T Plan changes must be approved by the DOE COR before they can be implemented by the contractor.

Task 1.2 - Environmental Report

The Department of Energy will assess the environmental impact of this project as part of its compliance with the National Environmental Policy Act. Information contained within the Environmental Volume submitted with the contractor's proposal will be used to address Phase II requirements and make a preliminary assessment of Phase III (e.g., concerning the acceptability of the Prototype Plant test site). To begin the process to assure the timely receipt of information required to plan and conduct the environmental study that will be used by the Department in its decision on whether to proceed with Phase III, the contractor shall prepare and submit to the DOE COR, within thirty (30) days following contract initiation, a detailed *Environmental Report* conforming to the requirements set forth in Part III, Section J, Attachment B. This report shall consist of the Environmental Volume submitted with the contractor's proposal, revised as required to conform in detail to negotiations conducted prior to contract award.

The contractor shall update the Environmental Report as engineering research and development (Task 2), subsystem testing (Task 5), and engineering design activities (Tasks 3, 6, and 7) provide improved data and greater definition of the prototype and commercial HIPPS plants, and whenever any significant impact on the environment is possible due to changes in the RD&T plan or in test facility or plant design. Any impacts on project cost, whether positive or negative, are to be clearly indicated in the appropriate cost reporting documentation. All revisions to the Environmental Report shall be provided to the DOE COR as part of the contractor's monthly progress reports. The latest version of the Environmental Report shall be included in the Phase II Technical Report (see Task 8).

Task 1.3 - HIPPS Commercial Plant Design

Included in the Contractor's proposal is a preliminary engineering design of a HIPPS commercial plant. This design is for a non-site-specific, greenfields plant with a baseload duty cycle, a net output of approximately 300 MWe, and performance matching or exceeding the Program Objectives. The contractor shall update and revise this HIPPS Commercial Plant Design to ensure that:

(1) The design fully reflects technical information known to the contractor at the time this task is conducted; and

(2) The design documentation conforms with instructions provided in this Request for Proposals Part IV, Section L.024, "Preparation of Technical Proposal, Preliminary Plant Design."

The design documentation shall include:

- Complete plant description, including the plant layout and estimated land area requirements, flowsheets and mass and energy balances for the overall plant and all major subsystems, a complete definition of the generating unit design boundary, and a quantitative description of all required off-sites.

- Clear statements of all assumptions used to complete the design, including the rationale of the design.

- Complete engineering calculations for important subsystems and major components.

- A list of all major equipment (i.e., having a cost equal to or exceeding 0.5% of total plant cost, and/or critical to plant operation or performance), including equipment specifications, and identification of equipment requiring custom design.

- A list of all components of uncertain design, performance, or cost, or which have not been demonstrated at appropriate scale or conditions of interest.

- A Class II cost estimate (± 25%) of the HIPPS Commercial Plant, itemized at the level of major subsystems for conventional sections of the plant (e.g., major subsystems would be a conventional coal receiving system, a coal storage system, or a conventional steam turbine/generator set) and at the level of major components for advanced sections such as the High Temperature Advanced Furnace (HITAF) and the advanced flue gas desulfurization unit. Using the latter as an example, major components could include the spray tower, reagent storage tanks, pumps, flue gas booster fans, etc. For each cost item, the estimate shall specify direct and indirect construction costs, sales taxes, engineering and construction management costs and fees, process and project contingencies, and initial catalyst and chemical charges.

- An itemized estimate of operating and maintenance costs to include operating labor, maintenance labor and materials, coal and all other consumables, and credits from revenue derived from salable by-products. The itemization shall distinguish between fixed and variable costs.

- An itemized estimate of the levelized cost of electricity.

- A discussion of and, where appropriate, a quantitative technical assessment of the impact of significant design and operational uncertainties on the performance and costs of the generating plant.

The cost analysis of the preliminary engineering design is to follow the economic methodology described in *Technical Assessment Guide*, EPRI TR-102276-V1R7, Volume 1: Revision 7, June 1993. Any significant deviations from this methodology must be approved by the DOE COR.

Task 2 - Engineering Research and Development

The contractor shall implement the program of Engineering Research and Development defined in the RD&T Plan. The primary objectives of Task 2 are to conduct engineering analyses, modeling, and experimental R&D and testing required to support the design and testing of major subsystems (Tasks 3 and 5), the design and operation of the prototype HIPPS plant (Tasks 7, 9, and 11), and preliminary engineering designs of full-scale commercial generating units (Tasks 6 and 12). Specifically, Task 2 shall include the following R&D activities:

- Engineering Analyses, including the gathering and evaluation of information needed to enhance empirical correlations, improve numerical modeling, or scale-up the design of components and subsystems.

- Experimental Research, including R&D and testing, and evaluation of materials, required for the development and design of components and subsystems.

- Modeling, including the application of numerical models (fluid flow, chemical kinetics, etc.) required for analyzing experimental data and designing the HITAF, advanced flue gas emission control systems, a low-NO_x supplemental fuel combustor, if needed, and other subsystems and components. Modeling activities can include the use and improvement of empirical and semi-empirical correlations and analytical approaches for meeting subsystem and component design, scale-up, and performance requirements.

Task 3 - Subsystem Test Unit Design and Test Plan

To develop the HIPPS Prototype Plant design base and to ensure its successful operation, it is anticipated that testing of one or more subsystems, e.g., the high temperature air furnace (HITAF) may be required. The choice of scale should be such that the results obtained can be applied to the design of the HIPPS Prototype Plant. A scale of 50 million Btu per hour may be appropriate for the furnace subsystem; however, the choice of this or other scales must be justified based on overall project cost-effectiveness and/or technical risk of scale-up for design of the HIPPS Prototype Plant. The subsystem testing may require either significant modifications to existing test facilities available to the contractor, or the construction of new test facilities. The use of existing facilities is encouraged, should this result in the most cost-effective approach. Task 3 covers the design and detailed planning required for the construction/modification and operation of the necessary subsystem test unit(s). Upon completion of Subtasks 3.1 and 3.2, a Subsystem Test Unit Review shall be held at a date and location designated by the DOE COR. The review shall include a presentation by the contractor regarding the subsystem test unit(s) design and test plans. For each subsystem test unit, work performed under this Task shall be documented in the RD&T Plan and submitted to the DOE COR for approval prior to implementation in Tasks 4 and 5.

Task 3.1 - Test Unit Design

The contractor shall design test units required for subsystem testing. The design of each subsystem test unit will be based on the results of engineering R&D conducted in Task 2 and on the requirements of the HIPPS commercial plant design. Each subsystem test unit design shall include all instrumentation; materials of construction; and facilities for the delivery, storage, handling, and disposal or removal of all materials and reagents required for and resulting from the operation of the test unit. The subsystem test units shall be designed to:

- Provide for sufficient instrumentation to achieve the subsystem test objectives, as stated in the RD&T Plan.
- Provide for reliable testing at conditions appropriate to commercial operation for periods sufficient to obtain the required database.
- Provide for the cost-effective evaluation of materials of construction suitable for use in the HIPPS Prototype Plant at conditions representative of commercial operations.
- Be in compliance with all applicable codes and standards, and provide for personnel and operational safety and control standards meeting or exceeding all applicable federal, state, and local regulations.
- Provide for cost-effective operations by using to the extent possible existing contractor facilities, components, and equipment, and when essential, to provide for cost-effective construction or modification of facilities.

Task 3.2 - Subsystem Test Planning

Concurrent with developing the design of each subsystem test unit, the contractor shall develop a detailed plan, including budget and schedule, for the construction/modification and operation of the subsystem test unit(s). This plan will become an integral part of the RD&T Plan, updating the subsystem test plans included in the contractor's original RD&T Plan. This section of the plan shall include securing of all applicable construction and operating permits; completing all necessary agreements with host facilities, and management procedures for monitoring and controlling all procurement and construction activities; providing detailed Quality Assurance/Quality Control (QA/QC) procedures consistent with DOE Order 5700.6C; ensuring adequacy of data acquisition, data analysis, engineering analysis and test evaluation; establishing procedures for startup and shutdown of the test unit, disposal of process wastes, and closure/dismantling of the test unit.

Task 4 - Subsystem Test Unit Construction

Upon approval by the DOE COR of the updated RD&T Plan that contains the subsystem test plans, the contractor shall implement the plan, and be fully responsible for all aspects of permitting, procurement, construction, modification, and fabrication required for each subsystem test unit. In implementing Task 4, the contractor shall:

- Ensure that the construction and installation of all equipment is in compliance with all applicable codes and standards and supply, at the request of the DOE COR, all documentation necessary to verify such compliance.
- Upon request by DOE, provide the COR with access to all phases of the contractor's procurement, fabrication, and assembly activities, including visits to the facilities of contractors, subcontractors, and major vendors: and provide for copies of all documentation necessary to verify contractor activities, including QA/QC compliance.
- Conduct acceptance testing of individual components and subsystems, or witness acceptance testing at a supplier's facility and certify to the DOE COR that all purchased or fabricated equipment and subassemblies of the test units are fully functional and meet all design specifications before DOE, through the contractor, takes title to them.

Task 5 - Subsystem Test Operation and Evaluation

Task 5.1 - Subsystem Test Operations

The contractor shall conduct subsystem tests in accordance with the approved RD&T Plan, and shall be responsible for the following:

- Furnishing all required fuels, reagents, labor, and other materials and supplies needed to conduct meaningful tests.
- The safe, efficient operation of the subsystem test unit(s). The contractor shall be responsible for all administrative, management, personnel training, technical, supervisory, and operating functions associated with all subsystem test unit operations.
- The safe and proper disposition of all fuels, chemicals, chemical by-products, effluents, gases, wastes, etc., required for or produced by the operation of the subsystem test unit(s). The contractor shall provide for the efficient, safe disposal of these materials in accordance with all applicable Federal, State and local regulations. The contractor will ensure that the availability of the subsystem test unit(s) is not impaired by failure to provide for proper disposal of these process wastes.

- Following the conclusion of the subsystem test program, the closure and dismantling of the test unit(s), as directed by the COR, the return or disposal of government-owned property as directed by the DOE Property Administrator, and site restoration.

All activities conducted as part of this Statement of Work, with regard to operations management, health, safety, housekeeping, etc., shall, at a minimum, comply with all applicable Federal, state, and local regulations, and conform to the standards of the host facility (if any) and those generally accepted within the chemical and power generation industries.

Interim technical analysis of the subsystem operations will be an ongoing activity and will be reported by the contractor in its regular monthly progress reports.

Task 5.2 - Subsystem Test Evaluation

As scheduled and provided for in the RD&T Plan, the contractor shall critically evaluate the results of all tests performed in Task 5.1. For each test subsystem test unit, the contractor shall provide the DOE COR with a *Subsystem Test Report* that shall include the following:

- For each test or test sequence performed using the subsystem test unit, a summary and analysis of all results.
- A summary of all the primary experimental data, engineering analyses, and computations.
- A comparison of the results with the objectives of the RD&T Plan to determine the extent to which research needs were successfully addressed, and a residual needs analysis which highlights remaining or incompletely resolved research needs.
- A critical re-evaluation of the subsystem to assess whether further development is needed.
- Revision of the RD&T Plan, including schedule and resources required for continued subsystem development, if further development is necessary. The revised RD&T Plan shall highlight the residual research needs and provide the detailed plans for their resolution via engineering R&D and/or subsystem testing.

Task 6 - HIPPS Commercial Plant Design Update

Based upon the results obtained under Tasks 2 and 5, the contractor shall revise the HIPPS Commercial Plant Design of Task 1.3. The design shall be augmented by relevant information published in the literature, other DOE information, and the engineering judgment and experience of the contractor. The design shall meet the requirements set forth in the Statement of Work for Task 1.3.

The design shall also be appropriate to the following testing schedule: within eighteen (18) months after initial start-up and shakedown, at least 4000 hours of steady-state operations, including operations at partial load down to at least 50 percent of design capacity.

Where data or information on subsystems are insufficient to support engineering design, the contractor shall make appropriate assumptions based on Task 2 results, best engineering judgment, and professional practice. The preliminary engineering design shall include as a minimum the following:

- Complete HIPPS Prototype Plant description, including flowsheets and mass and energy balances for the Plant and all major subsystems, a complete definition of the Plant design boundary, and a quantitative description of all required off-sites and interfaces with the host facility, if any.

- Complete documentation of rationale for all assumptions used to complete the HIPPS Prototype Plant Design.

- Complete engineering calculations for important subsystems and major cycle components.

- The HIPPS Prototype Plant layout and estimated land area requirements.

- A list of all major equipment, including equipment specifications and identification of equipment requiring custom design.

- A list of the function and location of instrumentation (sensors) used for data acquisition.

- A list of all components whose design or performance is uncertain or not demonstrated, and a list of all operational uncertainties.

- A preliminary scaling analysis, confirming the similitude between the HIPPS Prototype Plant Design and the Contractor's HIPPS Commercial Plant Design and including the scale-up ratios of major system components.

- A Class III cost estimate (± 15%) of HIPPS Prototype Plant design and construction costs, itemized at the level of major subsystems for conventional sections and at the level of major components for advanced sections. For each cost item, the estimate shall specify direct and indirect construction costs, sales taxes, engineering costs and fees, process and project contingencies, and initial catalyst and chemical charges. Detailed construction drawings are not required.

- An itemized estimate of operating and maintenance costs to include operating and on-site technical labor, maintenance labor and materials, all consumables, credits for steam transfer to the host facility and, if appropriate, credits for revenue derived from salable by-products.
- A discussion of and, where appropriate, a quantitative analysis of the impact of design and performance uncertainties on the performance and costs of the HIPPS Prototype Plant.

The contractor shall update the RD&T Plan to assure that the design, performance, and operational uncertainties of the HIPPS Prototype Plant are appropriately addressed during Phase II.

The update of the RD&T Plan shall include a detailed *prototype plant test plan* for the operation, demonstration, and evaluation of the HIPPS Prototype Plant. The prototype plant test plan shall be formulated to demonstrate:

- Continuous, steady-state operation of the plant at 100 percent of rated capacity.
- Acceptable turndown and load following.
- Plant compliance with the program objectives for environmental performance.
- Safe, reliable operation consistent with commercial power generation practice.
- Major subsystem performance consistent with the program objective for energy efficiency.
- Adequacy of plant control systems and instrumentation, materials of construction, and operational integrity.

The updated RD&T Plan shall also be specifically designed to provide for the:

- Development and collection of all data necessary to compute heat and material balances, to scale up the HIPPS Prototype Plant to the size range appropriate to initial commercial plants, and for the evaluation of plant economics.
- Characterization of all salable or reusable by-products, and evaluation of the stability and toxicity of all waste solids, effluents, and gases.

At a minimum, the HIPPS Prototype Plant test plan shall include:

- A summary of all data to be acquired to evaluate plant and major system performance and verify compliance with project objectives and regulatory requirements. The plan shall also include a detailed description of all data acquisition procedures and protocols.

- Volume IV shall fully document the HIPPS Prototype Plant Engineering Design and Test Plan, as developed in Task 7.2. The latest version of the Environmental Report shall be included in the Phase II Technical Report as an Appendix to Volume IV. Volume IV also shall outline the contractor's planned approach to provide or acquire all of the services normally associated with the detailed design and construction of a major plant. These services can include the preparation of detailed designs, specifications and vendor bid packages; construction management; construction, installation and acceptance testing of components, equipment and subsystems.

PHASE III
PROTOTYPE HIGH PERFORMANCE POWER PLANT

Task 9 - HIPPS Prototype Plant Detailed Design

Upon receipt of written authorization to proceed to Phase III, the contractor shall prepare detailed construction and fabrication drawings, together with a Class IV (± 5%) cost estimate for the HIPPS Prototype Plant design, construction, operation and maintenance. This cost estimate shall be provided to the DOE COR. The contractor shall commit no more than 25% of the contractually funded amount for Phase III until written approval is received from the Contracting Officer.

The detailed design shall be based on the engineering design of Phase II (Task 7.2), and will include the following:

- A detailed plant description, and a summary of the operations, maintenance, and safety manuals.

- Complete construction-ready drawings for the HIPPS Prototype Plant and its major components, including all major equipment, piping, instrumentation, storage facilities, control room, switchgear, switchboards, power station service equipment, and waste disposal facilities.

- Complete and detailed drawings showing the location of all tie-ins on the HIPPS Prototype Plant, and detailed specifications for the tie-ins at the host facility, if any.

- Detailed specifications, descriptions, and assembly instructions for all systems shipped as subassemblies.

- Design, fabrication, and installation specifications, plans and drawings for all architectural, structural, mechanical, and electrical requirements.

- Detailed specifications for all offsites, including: utilities; by-product and waste storage, handling and disposal; shipping and receiving stations; and raw material and coal storage and handling.
- Detailed specifications for all materials of construction.
- Complete vendor bid packages and bid evaluation criteria.
- A detailed construction plan and schedule for required permits; procurement, shipment, construction, erection, and assembly; testing and verifying the complete functioning of the Prototype Plant and its subsystems; estimated time to install and tie in the Prototype Plant to the host facility, if applicable; utilities and other offsites; shakedown and start-up; and demonstration of specification performance at nameplate capacity.
- A detailed, itemized budget covering all costs associated with implementing the construction plan and schedule, to include labor and materials required for start-up and verification.

Task 10 - HIPPS Prototype Plant Construction

During the period of construction, the contractor shall:

- Be responsible for all aspects of permitting, procurement, construction, modification, fabrication and testing required to prepare the HIPPS Prototype Plant for operations.
- Monitor, control, and, in its monthly report to DOE, report on progress, expenditures, and expenditures versus planned budget.
- Guarantee that the construction and installation of all equipment is in compliance with all applicable codes and standards; and supply, at the request of the DOE COR, any and all documentation necessary to verify such compliance.
- Provide, at all reasonable times, the DOE COR with access to any and all phases of the contractor's procurement, fabrication and construction activities. This includes visits and QA/QC compliance of the contractor's facilities, as well as the facilities of subcontractors and major vendors. Copies of all contractor and subcontractor requisitions, purchase orders, test orders, test reports, test procedures, qualification procedures, and certifications, or other documentation necessary to verify the quality and timeliness of the procurement, fabrication or construction shall be furnished to the DOE COR upon request.

Task 11 - HIPPS Prototype Plant Operation, Testing and Evaluation

The contractor shall implement HIPPS Prototype Plant testing and evaluation in accordance with the previously approved HIPPS Prototype Plant test plan, a part of the RD&T plan. A HIPPS Prototype Plant Pre-Startup Review shall be held at a date and location designated by the DOE COR. The Review shall include a presentation by the contractor concerning HIPPS Prototype Plant start-up and shakedown procedures, operating plans and schedules, testing protocols and data to be collected, and other appropriate topics as specified by the COR.

Task 12 - Commercial Plant Design Update

Based upon the testing and evaluation conducted under Task 11, the contractor shall revise the HIPPS Commercial Plant Design previously documented by the contractor in the Phase II Technical Report.

Task 13 - Phase III Final Report

The contractor shall prepare a Draft Final Report covering all work conducted in Phase III. The Draft Final Report shall be submitted to the DOE COR within sixty (60) calendar days prior to the completion of Task 13. The DOE COR shall then have thirty (30) calendar days to review the Draft Final Report and provide comments to the contractor. Within thirty (30) calendar days after the receipt of the comments of the DOE COR, the contractor shall submit the revised Final Report. As a separate volume of the Phase III Final report, the contractor shall document the HIPPS Commercial Plant Design Update performed under Task 12.