DOE/NASA/0051-2
NASA CR-165235

Conceptual Design Study of Potential Early Commercial MHD Powerplant

Final Report of Task 2 Results

Finn A. Hals
Avco Everett Research Laboratory, Inc.

March 1981

Prepared for
National Aeronautics and Space Administration
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U.S. DEPARTMENT OF ENERGY
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NOTICE

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Washington, D.C. 20585
Under Interagency Agreement DE-AI01-77ET10769

TABLE OF CONTENTS

Section		Page
	List of Illustrations	vii
	List of Tables	xi
1.0	INTRODUCTION	1-1
	1.1 Scope	1-1
	1.2 Objective	1-1
2.0	REFERENCE PLANT OVERALL POWER SYSTEM DESIGN AND PERFORMANCE	2-1
	2.1 Overall Power Plant Configuration and Design Parameters	2-1
	2.2 Nominal Load Performance Analysis	2-6
	2.3 Part-Load Performance Analysis	2-13
	2.4 Plant Startup Procedures	2-20
	2.4.1 Cold Startup Procedure	2-21
	2.4.2 Hot Startup Condition	2-25
3.0	SUBSYSTEMS/COMPONENTS DESIGN	3-1
	3.1 MHD Channel	3-1
	3.1.1 MHD Channel Calculations and Performance	3-1
	3.1.2 MHD Channel Mechanical Design	3-33
	3.1.3 Loading and Consolidation Circuitry	3-41
	3.2 Superconducting Magnet	3-43
	3.3 Coal Combustor	3-51
	3.3.1 General	3-51
	3.3.2 Mechanical Design	3-51
	3.3.3 Combustor Cooling	3-54
	3.3.4 Electrical Isolation	3-55

Section		Page
3.4	MHD Generator Inlet Nozzle	3-57
3.4.1	General Considerations	3-57
3.4.2	Nozzle Design and Construction	3-57
3.4.3	Nozzle Cooling	3-59
3.5	Diffuser and Transition Section	3-60
3.6	Heat Recovery, Seed Recovery System (HRSR)	3-63
3.6.1	Steam Generator Including Intermediate Temperature Oxidizer Preheater, Low-Temperature, Secondary Air and Nitorgen Heaters and Economizer	3-63
3.6.2	Stack Gas Cleaning	3-83
3.7	Steam Turbine Generator	3-90
3.8	Cycle Compressor and Drive	3-90
3.9	Coal Drying, Pulverizing and Feeding	3-91
3.10	Seed Management and Processing	3-94
3.10.1	Seed Management	3-94
3.10.2	Seed Reprocessing	3-99
3.10.3	Seed Feed System	3-117
3.11	Inverter System	3-119
3.11.1	Introduction	3-119
3.11.2	Inverter Bridges	3-119
3.11.3	Converter Transformers	3-123
3.11.4	Use of Water-Cooled Thyristor Bridges	3-127
3.11.5	Harmonic Filters	3-127
3.11.6	Reactive Compensation	3-128
3.12	Balance of Plant Equipment	3-130
3.12.1	Heat Rejection and Cooling Water Systems	3-130
3.12.2	Waste Removal Systems	3-131
3.12.3	Coal Receiving, Storage and Reclaim	3-134

Section		Page
	3.12.4 Feedwater, Condensate and Steam Systems	3-134
	3.12.5 Miscellaneous Mechanical Systems and Equipment	3-135
	3.12.6 Electrical Equipment	3-135
	3.13 O_2 Plants	3-143
4.0	PLANT LAYOUTS	4-1
5.0	BUILDINGS AND STRUCTURES	5-1
	5.1 General	5-1
	5.2 Foundations	5-1
	5.3 Structures	5-2
	5.3.1 Administration and Office Building	5-2
	5.3.2 Maintenance Building	5-2
	5.3.3 MHD Building	5-2
	5.3.4 Coal Feed Structure	5-3
	5.3.5 Cryogenic Systems Building	5-3
	5.3.6 Steam Turbine-Generator Building	5-3
	5.3.7 Steam Generator Building	5-4
	5.3.8 Water Treatment Building	5-4
	5.4 Cranes and Hoists	5-4
	5.4.1 MHD Building Crane	5-4
	5.4.2 Maintenance Building Crane	5-4
	5.4.3 Turbine Building Crane	5-4
	5.4.4 Miscellaneous Hoists and Trolleys	5-5
	5.5 Chimney	5-5
6.0	ESTIMATED PLANT COSTS AND COST OF ELECTRICITY	6-1
	6.1 Capital Costs	6-1
	6.2 Cost of Electricity	6-7

Section		Page
7.0	RELIABILITY/AVAILABILITY ANALYSIS	7-1
	7.1 Introduction	7-1
	7.2 Component Availability	7-4
	7.2.1 Channel Availability	7-4
	7.2.2 Availability with Two Parallel Power Trains	7-12
	7.2.3 Air Compressor and Driver	7-12
	7.2.4 Nozzle	7-13
	7.2.5 Diffuser	7-13
8.0	NATURAL RESOURCE REQUIREMENTS AND ENVIRONMENTAL INTRUSION	8-1
9.0	SUMMARY AND CONCLUSIONS	9-1
10.0	REFERENCES	10-1
APPENDICES		
A	COAL AND ASH ANALYSES OF SELECTED COALS	A-1
B	SUMMARY OF AUXILIARY POWER REQUIREMENTS (KW)	B-1
C	MAJOR EQUIPMENT LIST	C-1
D	CALCULATIONS ON AVAILABILITY ANALYSIS	D-1
E	NEW STATIONARY SOURCES PERFORMANCE STANDARDS FOR ELECTRIC STEAM GENERATING UNITS	E-1

LIST OF ILLUSTRATIONS

Figure		Page
2-1	Heat Balance 100% Heat Load	2-3
2-2	Energy Flow Diagram of Task II - Plant for Nominal Load	2-9
2-3	Flow Diagram of Task II Plant for 75% Load	2-15
3-1	Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air	3-5
3-2	Mollier Chart, Combustion Prodcuts of Montana Subbituminous Coal and Oxygen Enriched Air	3-6
3-3	Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air	3-7
3-4	Flow Chart of MHD4 Channel Model	3-8
3-5	Typical Velocity Profile at Channel Exit	3-10
3-6	Channel Operating Characteristics at Full Load with Analytical Magnet Design	3-20
3-7	Channel Operating Characteristics at Full Load with Final Magnet Design	3-22
3-8	Channel Operating Characteristics at 75% Load with Analytical Magnet Design	3-24
3-9	Channel Operating Characteristics at 50% Load with Analytical Magnet Design	3-25
3-10	Axial Static Pressure Distribution	3-27
3-11	Axial Static Temperature Distribution	3-28
3-12	Channel Mach Number Distribution	3-29
3-13	Plasma Electrical Conductivity Distribution	3-30
3-14	Equi-Potential Surface Angle Distribution	3-31
3-14A	Electrode Voltage Drop Distribution	3-32

Figure		Page
3-15	Electrode Structure (Schematic)	3-36
3-16	Electrode Assembly (Schematic)	3-37
3-17	MHD Generator Channel	3-39
3-18	Five Terminal Diagonal Load Connection	3-42
3-19	Magnetic Field Profile	3-46
3-20	Magnet Plan View	3-47
3-21	Magnet Cross Section	3-48
3-22	Coal Combustor	3-52
3-23	MHD Generator Inlet Nozzle	3-58
3-24	Diffuser and Transition Section	3-61
3-25	HRSR System Key Plan	3-67
3-26	Arrangement of Heat Recovery Steam Generator System	3-69
3-27	N_2 Heater and Air Heater Arrangement	3-77
3-28	Furnace Draft Control	3-80
3-29	Steam Temperature Control	3-82
3-30	Combustion Controls	3-84
3-31	Feedwater Controls	3-85
3-32	Precipitator for MHD-ETF Case III 900 MW	3-87
3-33	Inlet and Outlet Nozzle for MHD-ETF Case III 900 MV	3-88
3-34	Arrangement of Coal Processing Equipment	3-92
3-35	Solubility in Water of Potassium Sulfate (K_2SO_4), Potassium Carbonate (K_2CO_3) and Potassium Formate (KCO_2H)	3-103

Figure		Page
3-36a	Process Flow Diagram for Seed Regeneration System for 70% Sulfur Removal	3-105
3-36b	Mass Flows and State Data for Figure 3-36a	3-106
3-37	Preliminary Equipment Arrangement Plan for Seed Reprocessing Plant	3-107
3-38a	Process Flow Diagram for Seed Regeneration System for 100% Sulfur Removal	3-115
3-38b	Mass Flow and State Data for Figure 3-38a	3-116
3-39	Schematic Diagram of Seed Feed System	3-118
3-40	Diagram of Combustor Slag Collection System	3-132
4-1	Plot Plan for Conceptual Early Commercial MHD Power Plant	4-3
4-2	Plant Island Arrangement - Conceptual Early Commercial MHD Power Plant	4-5
4-3	Section Through Plant Island	4-7
6-1	Capital Costs vs Plant Size	6-8
6-2	Levelized COE vs Plant Size	6-13
7-1	Permissible Expenditure vs Worth Factor	7-5
7-2	Channel Availability vs Channel Mean Times Between Failure as a Function of Channel Mean Time to Repair	7-6
7-3	Unit Availability vs Channel Mean Time Between Failure as a Function of Channel Mean Time to Repair	7-9
9-1	Net Plant Efficiency vs Channel Isentropic Efficiency	9-6

LIST OF TABLES

Table		Page
1-1	Contract Team	1-2
2-1	Plant Design Parameters for Task II - Conceptual Design	2-5
2-2	Overall Heat Balance for Different Preheat Temperatures	2-11
2-3	Comparative Overall Energy Balance for Different Preheat Temperatures	2-12
2-4	Overall Heat Balance	2-17
2-5	Overall Energy Balance for Nominal and Part Load	2-18
2-6	Channel Performance Data at Full and Part Load Operation	2-19
3-1	MHD Channel Operating Characteristics at Various Loads	3-2
3-2	Comparison of Channel Nominal Load Operating Characteristics with Initial Analytical and Final Magnet Designs	3-3
3-3	Mass Flow Rates and Coal Thermal Input to MHD Combustor for 34% by Volume and 35% O_2 by Volume	3-12
3-4	Oxidizer with 34% O_2 by Volume	3-13
3-5	Oxidizer with 35% O_2 by Volume	3-14
3-6	Summary of Velocity Distribution Variations	3-16
3-7	MHD Channel Performance Data Comparison for CO_2^- Negative Ion	3-17
3-8	Calculated MHD Channel Performance Characteristics at Full Load	3-19
3-9	Channel Performance Data at Full and Part Load Operation	3-23

Table		Page
3-10	Channel Weight Summary	3-40
3-11	Superconducting Magnet Design Data	3-45
3-12	Comparison of MHD Magnets	3-53
3-13	Combustor Weight Summary	3-54
3-14	Diffuser and Transition Section Weights	3-62
3-15	HRSR System Design Summary	3-71
3-16	HRSR System Assembly Details	3-72
3-17	Electrostatic Precipitator Design Details	3-89
3-18	Seed Data for 70% (NSPS) and 100% Sulfur Removal	3-96
3-19	Seed and Ash Mass Balances for HRSR System	3-97
3-20	Seed Losses and Make-Up Costs	3-98
3-21	Sulfur Flows and Seed Reprocessing Requirements	3-100
3-22	Overall Energy Requirements	3-111
3-23	Solubilities for the System K_2CO_3-K_2SO_4-H_2O	3-113
3-24	Five-Terminal Parallel Connection	3-121
3-25	Five-Terminal Parallel Connection	3-122
3-26	Five-Terminal Parallel Connection	3-125
6-1	Project Cost Estimate (Dollars x 10^{-3})	6-2
6-2	Economic Parameters	6-9
6-3	Escalation and Interest Cost Factors	6-10
6-4	Levelized COE for Various Parameters	6-14
7-1	Component Availability Data	7-2
7-2	MHD Component Costs	7-3
7-3	Channel LIFE (MTBF) Versus Repair Time (MTTR)	7-8
7-4	Channel Life 5,000 HR	7-11

Table		Page
8-1	Environmental Intrusion	8-2
8-2	Natural Resource Requirements	8-3
8-3	Estimated Usage of Critical Elements	8-4
9-1	Power Plant Comparison Summary	9-2
9-2	Comparative MHD Channel Performance Data	9-4
9-3	Cost Distribution for Early Commercial MHD/Steam Base Load Power Plant	9-8

1.0 INTRODUCTION

1.1 SCOPE

This report is the final document reporting information developed in a second task, Task II, of a Program Study of Potential Early Commercial MHD Power Plants under NASA Contract DEN 3-51.

Task I of the program consisted of parametric analysis of three different reference power plants with parametric variations of the various design parameters for each of these plants. The results of Task I are contained In Reference 1. The first phase of the study served to provide information and basis for a comparative evaluation among different plant designs and of the effects of variations in specific plant assumptions and parameters.

Task II, reported on in this document, consisted of the conceptual design of one of the reference plants analyzed in Task I. The Task II plant was identified as attractive and selected on the basis of Task I results. It employs oxygen enrichment of the combustion air and has a nominal plant capacity of 950 MW_e. Task II permitted more detailed design analysis than that possible in the initial parametric analysis. Therefore, Task II provides more information and forms a better basis for evaluation of the reference power plant selected for conceptual design. The conceptual design effort in Task II included part load performance analysis and reliability analysis as additional design activities.

Task II was conducted by the same contract team that conducted Task I. The contract team consisted of AERL as the prime contractor and program manager, and Combustion Engineering, Inc. and Chas. T. Main, Inc., as contract team members and subcontractors. The main responsibilities of each team member in performing the work reported on in Task II is outlined in Table 1-1.

1.2 OBJECTIVE

The overall objective of this program is to develop information on potential early commercial coal burning MHD/steam power plants in order to identify attractive reference designs applicable to early or first commercial MHD power plants. These attractive power plants shall have acceptable performance and costs but shall require less development than more advanced and mature MHD power plant designs defined by previous studies such as ECAS.

TABLE 1-1

CONTRACT TEAM

AERL Program Manager	Combustion Engineering, Inc. Subcontractor	Chas. T. Main, Inc. Subcontractor
Responsible for:	Responsible for:	Responsible for:
1. Plant Definition and Main Design Parameters	1. HRSR	1. Plant Arrangement and Layout
2. Plant Integration and Performance	2. Coal Processing	2. Plant Costs and COE
3. MHD Equipment	3. Gas Cleaning	3. Inversion
• MHD Combustor and Nozzle		4. Seed Processing
• MHD Generator Including Electrode Consolidation Circuitry and Diffuser		5. BOP Equipment
• Superconducting Magnet		
4. O_2 Plant		

The purpose of the second conceptual design phase was to perform more detailed design analysis of the Task I reference power plant which employed oxygen enrichment of the combustion air. This conceptual plant design information serves to form a better basis than the initial parametric analysis in Task I for assessing the commercial attractiveness, technical feasibility and development requirements of the power plant selected from Task 1 results.

2.0 REFERENCE PLANT OVERALL POWER SYSTEM DESIGN AND PERFORMANCE

2.1 OVERALL POWER PLANT CONFIGURATION AND DESIGN PARAMETERS

The reference power plant configuration and basic design parameters selected for conceptual plant design in Task II were based on the results developed in the Task I parametric analysis.

The plant configuration is shown in the schematic flow diagram in Figure 2-1, and the selected plant design parameters are listed in Table 2-1. The main feature of this reference power plant is the use of oxygen enrichment of the combustion air. This permits the use of an intermediate oxidizer preheat temperature attainable with a metallic, recuperative type, tubular heat exchanger which is part of the bottoming plant heat recovery system. The conceptual design was based on an oxidizer preheat temperature of 1200°F and with 1100°F and 1300°F as parametric variations to show the effect of preheat temperature on overall performance. The selected oxygen content in the oxidizer was 34-35% oxygen by volume. This appeared to be an optimum oxygen concentration from the Task 1 results. The Task II plant design parameters listed in Table 2-1 correspond to the design parameters used for the base case of the same reference plant (Reference Plant 3) in Task I. However, a change was made in the method of coal drying. Initially in Task I, coal was considered dried directly with hot flue gas of 600°F. In Task II, nitrogen supplied from the oxygen plant was heated by flue gas and considered used for coal drying instead. Nitrogen is inert, clean and essentially free of water. Thus it possesses very good characteristics for coal drying. It also avoids problems related to flue gas seed contamination. The use of nitrogen for coal drying was selected because of the above attractive features although it increases the stack gas loss slightly. Another option which can be considered is to remove seed impurities from the flue gas by electrostatic precipitation (ESP) of hot flue gas ($\sim$ 600°F) before coal drying. However, this increases the size and cost of the ESP. Detailed optimization of coal drying and other plant equipment were beyond the scope of this study effort.

For completeness a brief description of the overall plant design characteristics are included here. Dried subbituminous coal (5% moisture content) is burned directly with preheated oxygen enriched combustion air (1200°F) in the high-temperature MHD coal combustor under pressure. The dried coal is burned

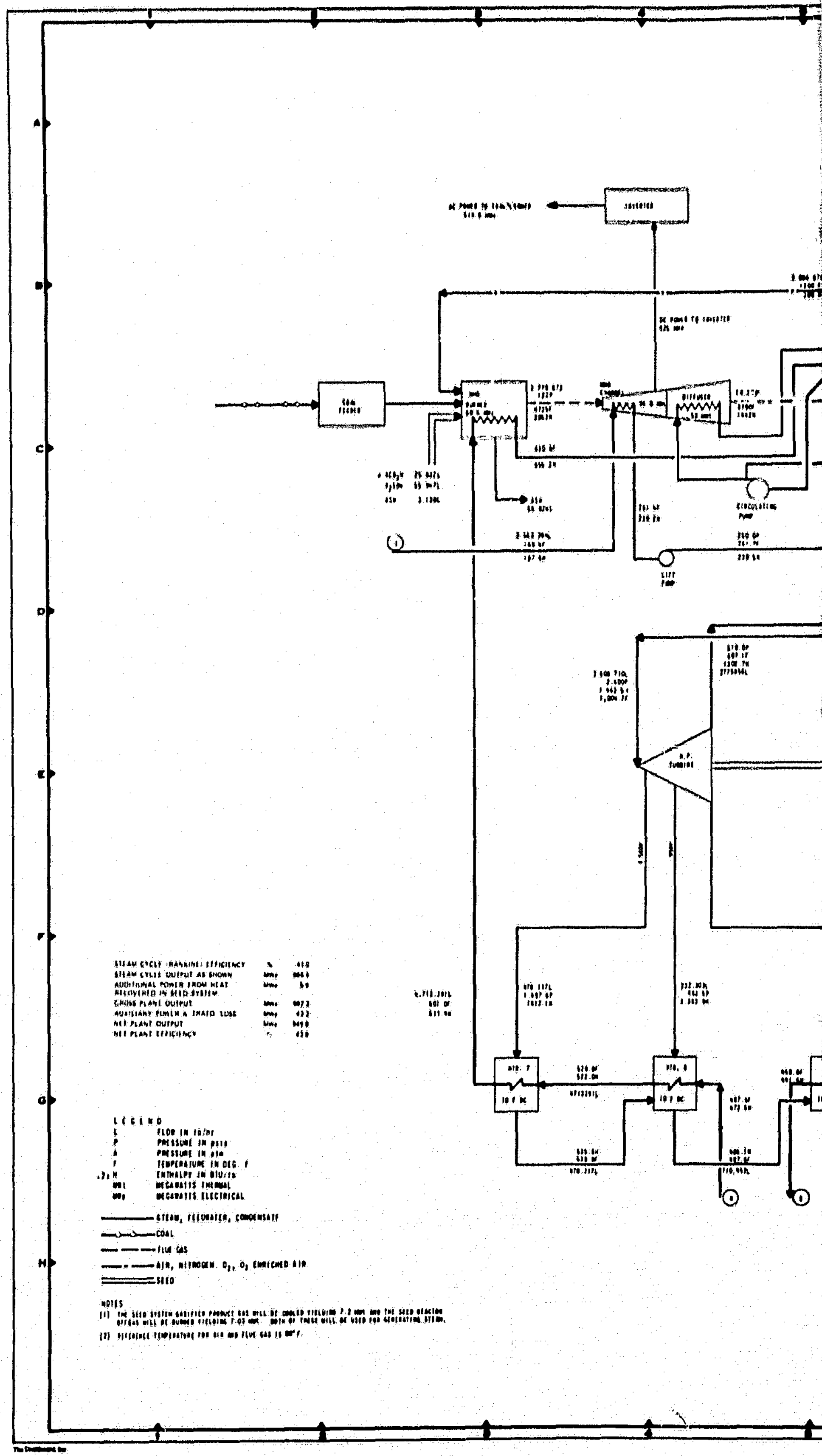


Figure 2

FOLDOUT FRAME

1

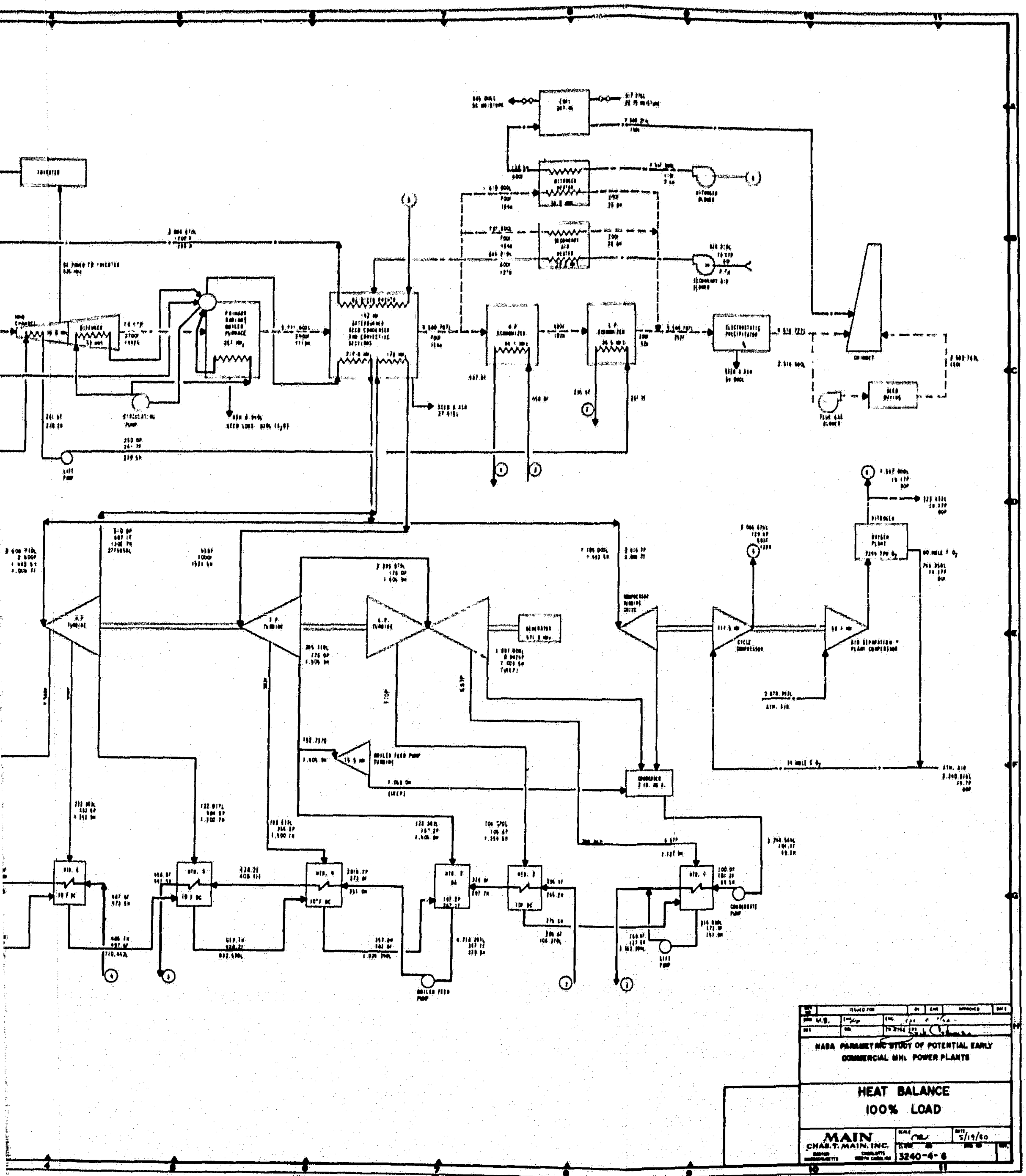


Figure 2-1 Heat Balance 100% Heat Load

TABLE 2-1

PLANT DESIGN PARAMETERS FOR TASK II - CONCEPTUAL DESIGN

1. Plant Size - MW (Nominal)	900
2. Fuel Type	Mont. Subbit.
3. MHD Combustion:	
Oxidizer O_2 content - % Vol.	~34
Fuel Moist. as fired - %	5
Combustor Type	Single Stage
Ash Removal - %	80
Oxidizer/Fuel Equiv. Ratio	0.90
Combustor Coolant	HPBF Water
4. MHD Generator:	
Channel Type	Diagonal
Peak Magnetic Field - Tesla	~6
Gas Seed Conc. - %K	1.0-1.5
Channel Gas Velocity	Subsonic
Diffuser Rec. Factor	0.6
Diffuser Exit Press. - atm	1.0
Channel Coolant	LPBF Water
5. Bottoming Plant:	
Main Steam	2400 psia/1000°F
Reheat Steam	1000°F
Final MHD Comb. Gas. Ox/Fuel Eq. Ratio	1.05
Oxidizer Preheat Temp. - °F	Base 1200°F. Alt. 1100°F and 1300°F
Condenser Press - HgA	2 in.
6. Seed Regeneration Process	Formate

under fuel rich conditions in the MHD combustor for NO_x- emission control. An oxidizer/fuel equivalence ratio of 0.9 of stoichiometric conditions is employed. Potassium seed is added and the seeded combustion products expand through the MHD generator where dc power is extracted. Heat recovered from the hot MHD generator exhaust gas is used for steam generation, oxidizer preheating, feedwater heating in a split high pressure (HP) and low pressure (LP) economizer, coal drying, and preheating of secondary combustion air. The secondary combustion air is introduced into the bottoming plant steam generator for after burning.

Final oxidation of the fuel-rich MHD combustion gases is then accomplished considering both complete oxidation of all unburned species in the gas and possible reformation of nitrogen oxides. Steam conditions for the bottoming steam plant are 2400 psig/1000°F/1000°F. Flue gas at stack gas temperature is also utilized for spray drying in the seed regeneration system for effective utilization of waste heat.

The oxygen plant is integrated with the power plant. The required compressor power for oxygen manufacturing is provided by steam turbines which are part of the bottoming plant steam cycle.

Seed is recovered in the bottoming plant and from the stack gas by electrostatic precipitation. Since the potassium seed has a high chemical affinity to sulfur, it is used for removal of the sulfur produced in the gas from the coal burned. Final sulfur removal is obtained by regeneration and recycling of recovered seed. The process selected for regeneration of seed is the formate process.

The plant was designed to comply with EPA New Source Performance Standards for Electric Utility Generating Units, NSPS 1979.

2.2 NOMINAL LOAD PERFORMANCE ANALYSIS

The plant performance analysis concentrated on establishing plant performance at nominal full load. The performance analysis followed in principle the approach used in Task I and is broadly outlined in Section 2.0 of Reference 1. A general discussion of the performance analysis is also included here before the results of the performance calculations are presented.

The net power output from the plant, P_p can be expressed as

$$P_p = P_m + P_{st} - [P_c + P_o + P_a]$$

where

P_m = Gross MHD Power (MW)

P_{st} = Gross Steam Power (MW)

P_c = Cycle Compressor Power (MW)

P_o = O_2-Plant Compressor Power (MW)

P_a = $[P_{aux} + P_i + P_t]$

P_i = dc/ac Inverter Power Loss (MW)

P_t = Transformer Power Loss (MW)

P_{aux} = Auxiliary Power

The steam power, P_{st}, again can be expressed as

$$P_{st} = \eta_s [P_f + P_s + P_c - P_m - P_1]$$

where

P_f = Total coal heat input (MW and based on HHV)

P_s = Heat input with seed (MW)

P_1 = Stack and other heat losses (MW)

η_s = Steam cycle (Rankine) efficiency (%)

The overall net plant efficiency, $\eta_o = P_p/P_f$, can now be expressed by

$$\eta_o = \eta_m + \eta_s [1 - \eta_m + \bar{P}_s - \bar{P}_1 - \bar{P}_o] - \bar{P}_a$$

or

$$\eta_o = \eta_m (1 - \eta_s) + \eta_s(1 + \bar{P}_s - \bar{P}_1 - \bar{P}_o) - \bar{P}_a$$

where

$$\eta_m = \frac{P_m - P_c - P_o}{P_f} \qquad \bar{P}_1 = \frac{P_1}{P_f}$$

$$\overline{P}_s = \frac{P_s}{P_f} \qquad \overline{P}_o = \frac{P_o}{P_f} \qquad \overline{P}_a = \frac{P_a}{P_f}$$

The cycle compressor power P_c appears as heat input to the oxidizer since intercooling of this compressor is not assumed. No heat recovery from the oxygen plant compressor is considered here.

The plant efficiency η_o was optimized by optimization of net MHD power generation, $P_m - P_c - P_o$, and effective utilization of waste heat, as in Task I. Similarly, the critical channel design parameters such as power density, electrical fields, current density and Hall parameter were limited to the same reasonable design values as in Task I. For a detailed description of the MHD channel performance calculations, reference is made to paragraph 3.1.1 of the MHD channel design description. The channel performance calculations resulted in a final selection of 34% oxygen by volume of the oxidizer along with a seed concentration of 1% potassium by weight of the MHD combustion gases. (In case of the use of Ill. #6 bituminous coal of a relatively high sulfur content, a minimum potassium concentration of about 1-1/4% is required to obtain the required sulfur removal from the gas as reported in Reference 1).

A flow diagram with heat and mass balances and state point conditions for nominal load is shown in Figure 2-1. Figure 2-2 is a simplified energy flow diagram for the same nominal (100%) load design conditions.

The net plant output from the plant is 949 MW_e, corresponding to a net plant efficiency η_o of 43.9% (coal to busbar). The Rankine efficiency η_s of the bottoming steam and feedwater cycle is 41.8% (Steam Power/Heat Absorbed by Steam Cycle). Altogether, seven feedwater heaters including the deaerator are employed. It is noted that low-pressure and low-temperature feedwater of about 170°F-260°F is used for channel cooling. High-pressure and high-temperature feedwater is used for cooling of the high-temperature MHD combustor. Cooling of the diffuser is incorporated as part of the evaporative circuit of the steam cycle. A small amount of heat is recovered from the seed regeneration process. This includes combustion of small amounts of CO and H_2 contained in the off-gas from the seed regeneration process reactor. The additional power from recovery of heat from the seed regeneration process to the steam cycle is calculated to be 5.9 MW_e.

The oxygen plant is integrated with the power plant and produces oxygen at 80% purity (80 mole % O_2). The amount of oxygen delivered from the oxygen plant at full load (nominal)

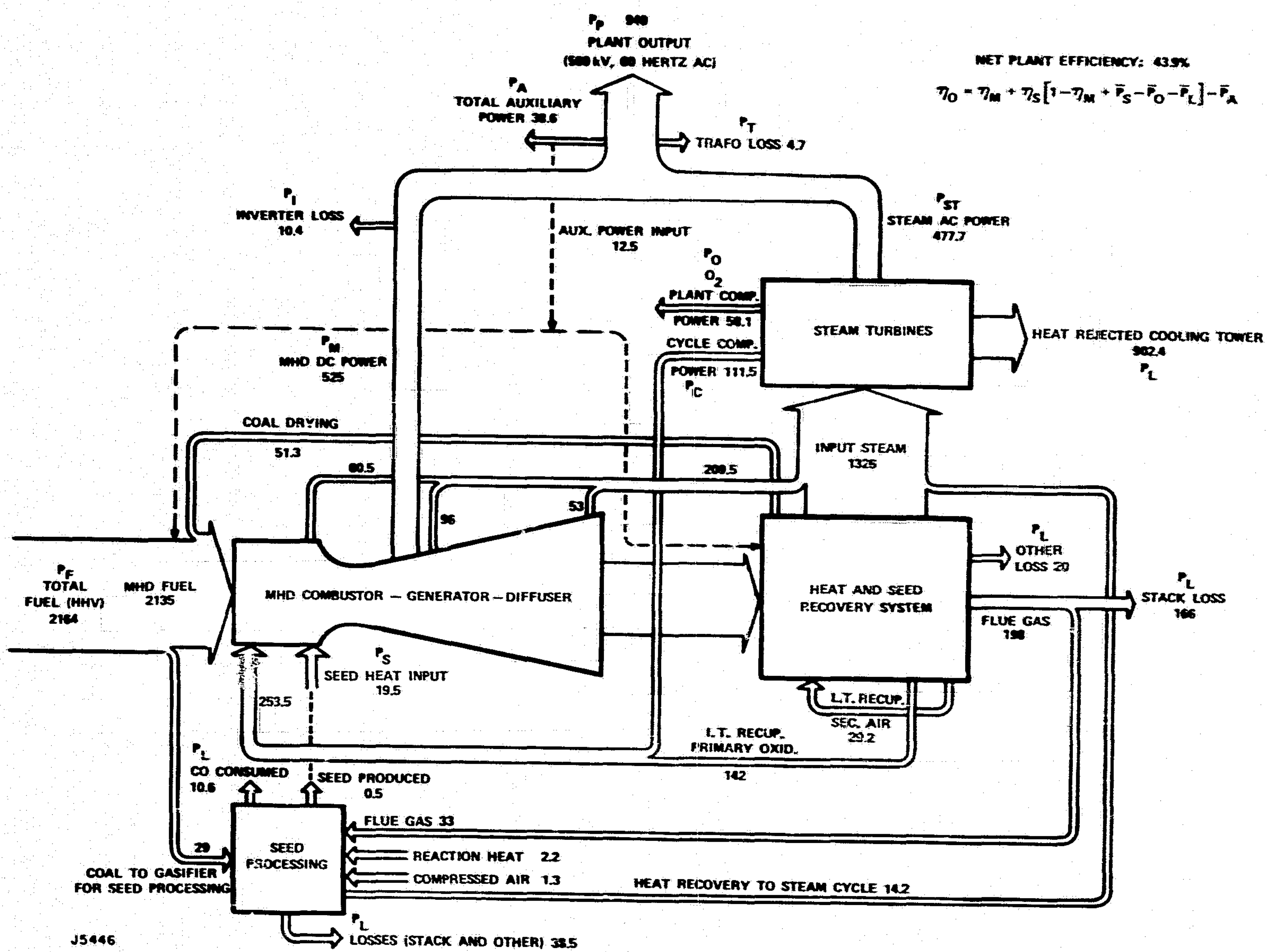


Figure 2-2 Energy Flow Diagram of Task II - Plant for Nominal Load

operation is 7344 tons/day (TPD) of contained oxygen. The specific compressor power required for manufacturing of oxygen is 190 kWhr/ton of contained oxygen or 58.1 MW at nominal load conditions. (All data for the oxygen plant are based upon information provided by NASA). The oxygen plant compressor and cycle compressor have steam turbine drives. The output from the main steam turbine ac generator is 471.8 MW_e and the MHD power output after inversion is 514.6 MW_e. Auxiliary power and transformer losses are 43.3 MW_e.

The results from nominal load performance analysis presented above were based on the base preheat temperature of 1200°F and 34% oxygen by volume content of the oxygen enriched combustion air.

Performance analyses were also conducted for parametric oxidizer preheat temperatures of 1300°F and 1100°F. Each of these two parametric variations of preheat temperature were accompanied by a corresponding variation of the oxidizer oxygen content so as to keep the MHD combustion temperature constant. Accordingly, the parametric increase of the oxidizer preheat temperature to 1300°F was accompanied by a decrease in the oxygen content to 33.4% by volume, and the decrease to 1100°F preheat temperature by a corresponding increase in the oxygen content to 34.7%. In this way, the MHD generator performance and operating characteristics would be the same as for the base design with 1200°F preheat temperature, except for a slight variation in total gas flow rate resulting from small variations in the oxidizer flow rate. (Coal thermal input is considered constant, and the effects from the variations in gas composition resulting from the smaller variations in the oxygen content of the oxidizer with preheat temperature are small and hence disregarded.) Comparative overall heat balances and gas mass flow rates for the two parametric oxidizer preheat temperatures of 1300°F and 1100°F and for the base design preheat temperatures of 1200°F are listed in Table 2-2. The power output from the MHD generator is considered proportional to the gas mass flow rate for these small parametric variations in flow rates.

The amounts of heat absorbed from the gas in the bottoming plant heat recovery system will also vary with variation of the preheat temperature. The variations in the amounts of heat absorbed in the steam generator and economizer are relatively small so that the steam cycle efficiency is considered to remain the same. However, the power output from the steam plant will vary in proportion to the total amount of heat absorbed from the gas for steam generation and feedwater heating including MHD flow train heat losses.

The resulting overall energy balances for the two parametric preheat temperatures are listed in Table 2-3. Corresponding data for the base design preheat temperature are also included in this table for comparison.

TABLE 2-2

OVERALL HEAT BALANCE FOR DIFFERENT PREHEAT TEMPERATURES

	Base	Param. Variation	Param. Variation
Preheat Temperature - °F	1200	1300	1100
O_2-Content of Oxidizer - vol. %	34.0	33.4	34.7
Total MHD Gas Mas Flow Rate - kg/s	474.0	480.6	465.1
<u>Heat Inputs (MW)</u>			
Coal (HHV)	2135.0	→	→
Coal Drying	51.3	→	→
Primary Oxidizer	253.5	282.3	224.5
Secondary Air	31.1	→	→
Seed Chemistry	19.5	→	→
Heat Input from Aux.	10.6	→	→
Total	2501.0	2529.8	2472.0
<u>Heat Outputs (MW)</u>			
MHD Power	524.9	532.3	515.0
MHD Heat Losses	209.5	→	→
Steam Generator + Economizer	1326.0	1320.4	1333.5
I.T. Oxidizer Heater	142.0	169.0	115.4
L.T. Secondary Air Heater	29.2	→	→
Coal Drying	51.3	→	→
Stack Loss	198.0	→	→
Heat Losses	20.1	→	→
Total	2501.0	2529.8	2472.0

TABLE 2-3

COMPARATIVE OVERALL ENERGY BALANCE FOR DIFFERENT PREHEAT TEMPERATURES

	Base Case T_{ph} = 1200°F 34.0% O_2	Param. Variation T_{ph} = 1300°F 33.4% O_2	Param. Variation T_{ph} = 1100°F 34.7% O_2
Fuel Input - MW			
MHD Combustor	2135	2135	2135
Gasifier for Seed Regen.	29	29	29
Total	2164	2164	2164
Gross Power Outputs - MW			
MHD Power	525.0	532.3	515.0
Steam Power*	647.3	644.9	650.4
	1172.3	1177.2	1165.4
Auxiliary and Losses - MW			
Cycle Compressor	111.5	113.3	109.1
O_2 Plant Compressor	58.1	56.5	59.7
Auxiliaries	38.6	38.6	38.6
Inverter and Transformer	15.1	15.4	14.8
	223.3	223.8	222.2
Net Plant Output - MW	949.0	953.4	943.2
Net Plant Efficiency - %	43.9	44.1	43.6

*Includes Power from Recovery of Available Heat in Seed Regeneration System.

An increase or decrease of the preheat temperature of 100°F to 1300°F and 1100°F, respectively, resulted in a relatively small increase or decrease of the overall plant efficiency of about ± 1/4 percentage point. This shows that the plant performance is relatively insensitive to such variations in preheat temperature. Resulting variations in plant costs because of assumed variations in the size of the oxygen plant and the need for more costly high-temperature alloys for the higher temperature section of the metallic recuperative preheater are presented later in Section 6.0.

2.3 PART-LOAD PERFORMANCE ANALYSIS

Part-load performance analyses were carried out after major component and plant equipment design and performance had been established for the nominal load condition.

In order to maintain a relatively high plant efficiency at part load, one endeavors to optimize the net energy output of the prime MHD cycle (MHD generator power output minus cycle compressor and oxygen plant compressor power or $P_m - P_c - P_o$) and to utilize the waste heat effectively in the bottoming steam cycle as in full load operation. Part load of the MHD generator was accomplished by reducing the gas mass flow rate and hence the thermal input to the channel and coal input to the plant. Gas stoichiometry, and seed fraction were maintained constant at all loads.

As load is reduced from the nominal design value by reduction of mass flow and coal input to the plant, the mass flow and thermal input to the bottoming heat recovery plant is also reduced. Although the MHD generator exhaust gas temperature is almost independent of load and may rise slightly at part load operating conditions, the maintenance of full load steam superheat and reheat temperatures and oxidizer preheat temperature becomes an increasing problem as load decreases. Therefore, an important part of part-load performance analysis was to determine the practical operating conditions of the bottoming heat recovery system at part load.

Iterative performance analyses between the steam generator and the overall steam and feedwater cycle were necessary to define the final main and reheat steam temperatures. These iterative analyses defined the final main steam temperature as 1005°F and the reheat steam temperature as 955°F at 75% of nominal coal thermal input to the plant. Flue gas recirculation was incorporated to reach these steam conditions. The Rankine steam cycle efficiency for these part load steam conditions of 2400 psig/1005°F/955°F were calculated to be 40.84%. This is 1 percentage point lower than at full load.

The part-load analyses conducted also revealed that the oxidizer preheat temperature could not be maintained as mass flow and load decreased. Therefore, a small increase in the oxygen content of the oxidizer was considered at part load in order to avoid the decrease in flame temperature and MHD generator performance which would otherwise result. The slight increase in oxygen enrichment of the combustion air at part load is well within the capacity of the oxygen plant established for full load. At 75% of coal thermal input the oxidizer preheat temperature was reduced to 1070°F. The oxygen content of the combustion air was increased to 35% by volume (from 34% by volume at nominal load) to compensate for this reduction in preheat temperature. By further reduction of load to 50% of nominal coal thermal input, the oxidizer preheat temperature is expected to be reduced further to about 925°F. For this lower oxidizer preheat temperature at this load condition, the oxygen content of the oxidizer is considered increased to 36% oxygen by volume to maintain the MHD combustion temperature.

Performance calculations with total heat and energy balances were established for the part-load condition at 75% of nominal coal input to the plant. Figure 2-3 is a flow schematic for this part-load condition with state point conditions. Overall energy and heat balances for the same part-load condition are listed in Tables 2-4 and 2-5. Corresponding comparative data are also listed in these tables for nominal load condition.

The overall plant efficiency is 41.8% for this part-load condition with 75% of nominal coal input or 2.1 percentage points lower than at nominal load. Thus, a relatively high efficiency is maintained at part-load operation. It should be recognized that a complete optimization of the bottoming plant HRSR system with more detailed and iterative design analyses including controls were beyond the scope of the conceptual design analysis conducted. Such more detailed design analyses are required to optimize plant performance and operation at part load. The total net plant output is 677.7 MW_e or 71.4% of nominal. The gross (P_m) and net ($P_m - P_c - P_{O2}$) power outputs from the MHD generator are reduced to 358 MW_e and 241.3 MW_e, respectively, compared to 525 MW_e and 355.4 MW_e at nominal load.

The channel operating conditions at part load at 75% of nominal coal thermal input are listed in the middle column in Table 2-6. The first column in this table list corresponding data for nominal load reported in the previous paragraph. The last column presents additional channel part-load performance data calculated for 50% of nominal coal thermal input to the plant.

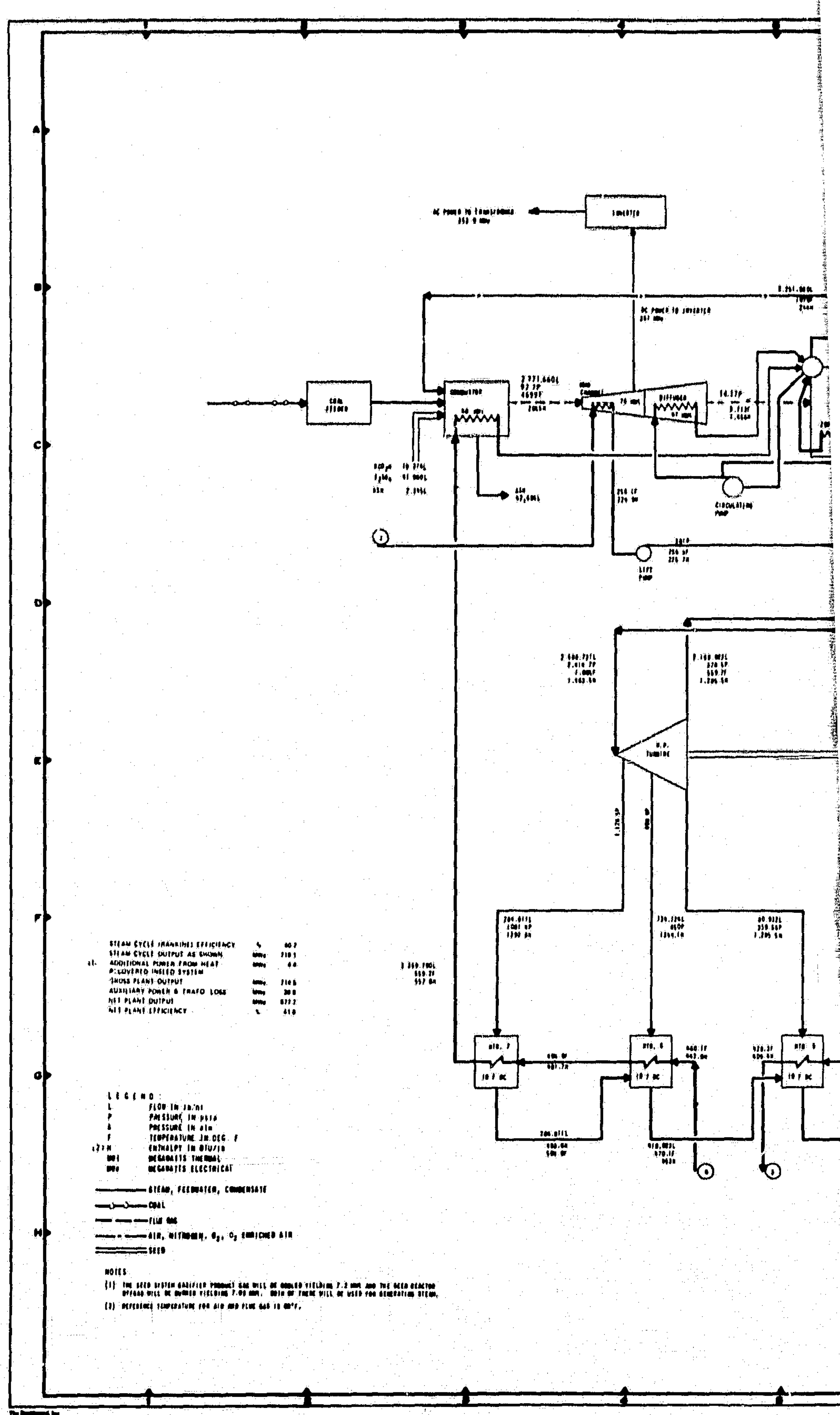
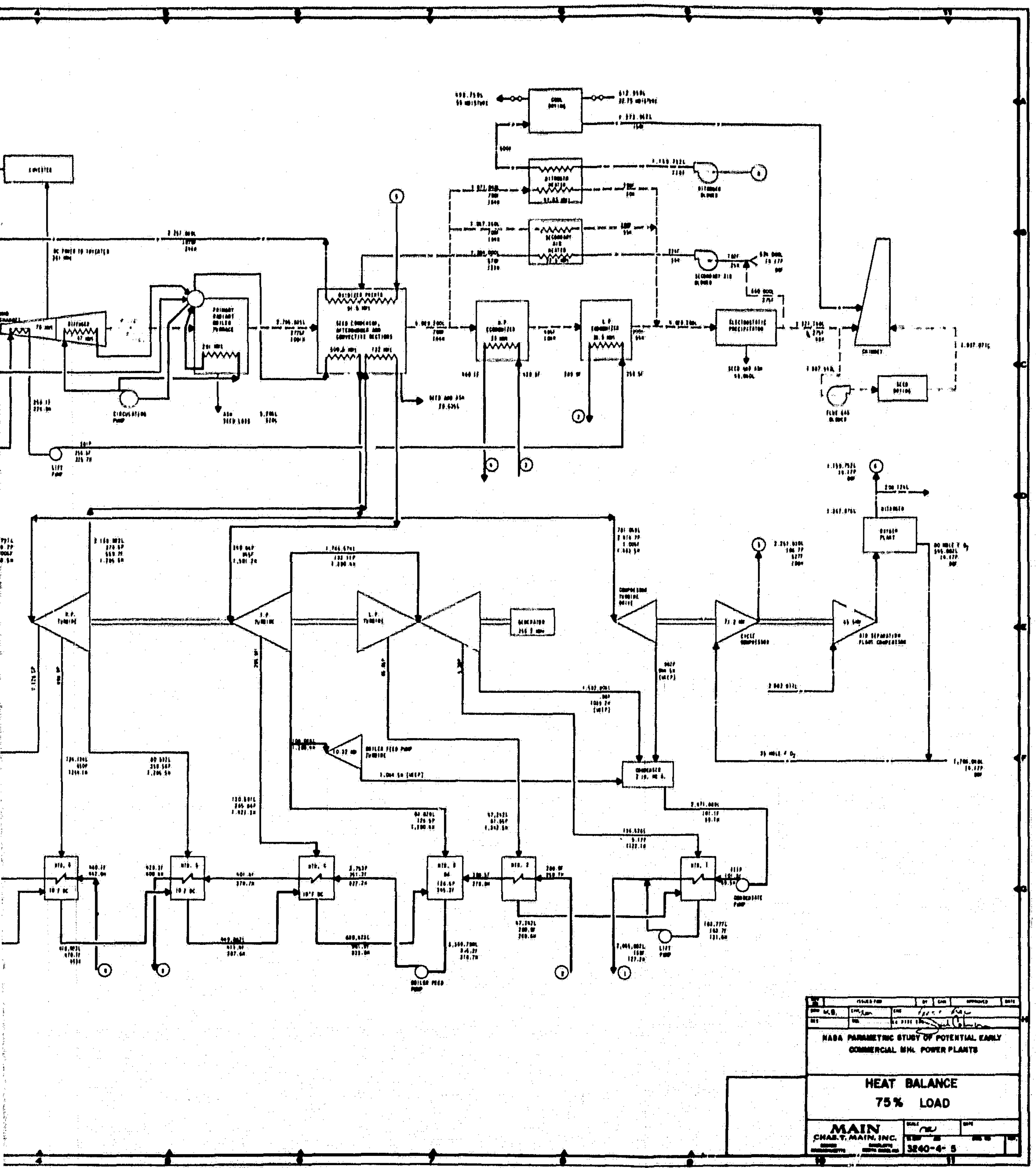


Figure 2-3 Flow Diagram



2-3 Flow Diagram of Task II Plant for 75% Load

TABLE 2-4

OVERALL HEAT BALANCE

	Nominal	Part Load
Heat Inputs (MW)		
Coal (HHV)	2135.0	1601.3
Coal Drying	51.3	38.5
Primary Oxidizer	253.5	162.5
Secondary Air	31.1	21.5
Seed Chemistry	19.5	14.6
Heat Input from Aux.	10.6	8.0
Total	2501.0	1846.4
Heat Outputs (MW)		
MHD Power	524.9	361.1
MHD Heat Losses		
Burner	60.5	48.0
Channel	96.0	76.0
Diffuser	53.0	47.0
I.T. Oxidizer Heater	142.0	91.3
L.T. Secondary Air Heater	29.2	20.0
Coal Drying	51.3	38.5
Stack Loss	198.0	150.6
Heat Losses	20.1	21.9
Steam Generator	1246.4	932.5
Economizer	79.6	59.5
Total	2501.0	1846.4

TABLE 2-5

OVERALL ENERGY BALANCE FOR NOMINAL AND PART LOAD

	Nominal Load	Part Load
Fuel Input - MW		
MHD Combustor	2135	1601
Gasifier for Seed Regeneration	29	22
Total	2164	1623
Gross Power Outputs - MW		
MHD Power	525.0	361.0
Steam Power*	647.3	477.3
	1172.3	838.3
Auxiliary and Losses - MW		
Cycle Compressor	111.5	71.2
O_2 Plant Compressor	58.1	45.5
Auxiliaries	38.6	33.4
Inverter and Transformer	15.1	10.5
	223.3	160.6
Net Plant Output - MW	949.0	677.7
Net Plant Efficiency - %	43.9	41.8

*Includes Power from Recovery of Available Heat in Seed Regeneration System.

TABLE 2-6

CHANNEL PERFORMANCE DATA AT FULL AND PART LOAD OPERATION

Plant Thermal Input Oxidizer Preheat Oxidizer O_2-Content	100% (Nominal) T_{ph} 1200°F 34% O_2	75% T_{ph} 1070°F 35% O_2	50% T_{ph} 925°F 36% O_2
P_o (atm)	8.3	6.54	5.08
T_o (K)	2881	2866	2840
Inlet Mach No. (-)	0.885	0.721	0.539
Exit Mach No. (-)	0.722	0.499	0.325
Electrical Load Parameter (-)	0.7862	0.79776	0.7894
Length (m)	21.5	21.5	21.5
$\mathbb{P}_{MHD}$ (MW_e)	525	358	204
η_{is} (%)	74.0	76.4	76.9
η_{en} (%)	24.5	22.7	19.9

It is noted that for subsonic channel operation as here selected for commercial operation, the reduction in combustor pressure from nominal load is less than the corresponding reduction in gas mass flow rate. The electrical load parameter has been increased slightly at part-load operation so as to take full advantage of the channel length and magnetic field profile established for full-load design. This results in a slightly higher isentropic efficiency at part load than at full load which is indicative of efficient channel operation. Reasonable values for all of the important channel electrical operating parameters (E_x, E_y, J_y, $\omega\tau$) are obtained at part-load operation.

2.4 PLANT STARTUP PROCEDURES

This section briefly discusses the startup procedures from both a cold condition and a hot standby condition. The plant controls provide for semi-automatic startup procedures. Initially, operators put systems and equipment in standby status to assure that they are ready to start at the proper place in the startup sequence. As the operator begins the startup procedures, equipment conditions (pressure, temperature, speed, etc.) are stored and displayed for the operator's use by the plant data acquisition system. This will provide the operator with such information as actual warmup rates of the boiler and turbine. In the case of the boiler this information dictates, among other things, when the startup oil guns can be discontinued. Turbine metal temperatures dictate to the operator when steam can be put to the turbine and at what rate it can be loaded.

Once startup of the major components has been initiated, automatic controls will take over certain functions. After lighting off the boiler warmup oil burners, separate combustion controls will maintain the correct fuel/air ratio. The data acquisition system will allow the operator to follow the temperature rise of critical boiler components. The boiler temperature is one input for the operator to use in deciding when the next item in the startup procedure is to be initiated. The operator also initiates the beginning of the turbine heat soak and startup of the turbine auxiliaries. At the proper metal temperatures the operator will admit steam to and roll the turbine, allowing it to accelerate at a predetermined rate which is maintained by turbine controls.

When the unit has stabilized at a minimum generation rate the plant would be put in the fully automatic mode of operation. Plant operation is then automatically controlled by the coordinated plant control system.

The hot and cold startup procedures are discussed in the following sections. As discussed above, the startup sequences are normally initiated according to the readiness of various pieces of equipment. Therefore, the steps outlined below overlap in varying amounts, also depending on the readiness of the equipment.

2.4.1 Cold Startup Procedure

A cold startup is defined as a startup for which the major equipment is at or near ambient temperature, the magnet is deenergized but at cyrogenic temperature and the bottoming plant is at cold conditions. The following is a description of the cold startup sequence for the major equipment. It assumes that the plant has previously been operational.

Unit Support Auxiliaries Startup

Prior to anticipated plant startup, the following unit support auxiliaries must be started up or verified as operating.

a. Physically inspect plant and equipment for startup readines.

b. Instrument air system operating.

c. Service air system functional.

d. Fire protection system functional.

e. Service water system operating.

f. Water treatment system operating.

g. Wastewater treatment system operating.

h. Energize electrical power supply system required for plant operation.

i. Energize and checkout electronic control systems and safety interlock systems.

j. Start fuel oil forwarding system.

k. Start oxygen enrichment plant auxiliaries.

At this point, the plant is ready for the startup procedure.

Startup Procedure

Condensate System

a. Establish safe operating level in condenser hotwell.

b. Start a condensate pump.

Boiler Feed Pump (Startup motor driven)

a. Start boiler feed pump and allow to recirculate on low flow supplying feedwater to boiler as required.

Condenser

a. Verify condenser ready for service.

b. Start circulating water system.

Steam Generator (Boiler)

a. Establish proper drum water level.

b. Start boiler circulation.

c. Set vent and drain valves in startup positions.

d. Prepare boiler for service.

e. Start secondary air blower to supply combustion air and start induced draft fan and maintain furnace pressure.

Auxiliary Steam Turbines

a. Verify lube oil coolers in service.

b. Start lube oil system.

c. Place turbine on turning gear.

Main Steam Turbine

a. Verify lube oil coolers in service.

b. Start lube oil system.

c. Place turbine on turning gear.

AC Generator

a. Start seal oil system if not in service.

b. Fill generator with hydrogen to operating pressure as required.

c. Verify hydrogen coolers ready for service.

MHD Channel and Magnet

a. Insure that cooling water systems are in operation.

b. Verify magnet cryogenic systems are at correct operating conditions.

c. Start energizing magnet. Four hours are required to completely energize magnet.

Integrated Unit Warmup

a. Light off boiler warmup oil burners. Combustion controls maintain fuel-air ratio.

b. Increase refractory temperature at a rate not to exceed 100°F per hour.

c. Limit primary radiant boiler furnace outlet temperature to 1000°F until steam flow is established through the superheaters and oxidant flow through its heater.

d. Prepare coal processing system for startup. Charge the petro-carb injectors, keeping the system pressurized with inert flue gas or heated nitrogen.

e. Continue heating up refractory and increasing oil firing at the required rate allowing steam to bypass the main steam turbine into the condenser.

f. Put steam seals in service on turbines and start condenser vacuum pumps.

g. When steam pressure and temperatures are suitable, warm up and roll main steam turbine. Place turbine driven boiler feed pump and turbocompressors into operation.

h. Place oxygen plant in service.

i. Accelerate main steam turbine to operating speed and synchronize ac generator. Bring to minimum load of about 5 MW.

j. Start combustor slag removal system.

k. Turn on the electrostatic precipitators.

l. Start oxidizer flow through the combustor at twenty-five (25) percent for initial coal firing conditions and light off combustor. Allow the boiler combustion control system to maintain the air flow and firing as required for the bottoming plant. Allow boiler warmup guns to cut back to prevent excessive temperatures in the bottoming plant.

m. Continue to increase coal firing and decrease warmup oil gun firing until the oil guns can be removed from service. Deactivated oil guns are protected by cooling with inert flue gas.

n. Start seed injection. Synchronize MHD generation as conditions allow.

o. Slowly reduce main combustor oxidizer-fuel ratio to the required substoichiometric levels. Simultaneously increase secondary air flow to the boiler afterburner section completing combustion in an excess air condition.

p. Allow the unit to stabilize at minimum generation rate and verify that required control systems are in the automatic mode.

Completion of Cold Startup

a. The cold startup is complete at this stage.

b. Start seed regeneration system.

c. Start bottoming plant ash removal system.

Plant Loading

a. Increase plant generation loading as required by dispatch keeping within the temperature ramp rates of the main steam turbine and ac generator, which is ~ 3% load per minute.

2.4.2 Hot Startup Condition

A unit hot startup is the result of a shutdown for a relatively short period of time. The criteria for determining a hot startup condition are that the magnet is fully energized, the boiler refractory temperatures are greater than ambient, the steam turbines and ac generator are in a hot standby condition, and the oxygen plant is in cold standby condition. Prior to hot startup, the auxiliary systems shall have the following status:

Condensate system operating

Feedwater system operating

Condenser and circulating water system operating

Coal injection system on standby

Seed injection system on standby

Main boiler in hot standby condition with recirculating pumps running

Steam seals on turbine

Following is a sequence of operations required for a hot unit startup.

a. Start secondary air blower to supply combustion air for boiler warmup oil burners and start induced draft fan.

b. Allow for boiler purge. Then start windbox oil burners and continue to raise boiler temperature.

c. Bypass generated steam around the turbine to the condenser until the steam temperature conditions match the turbine and bring up to operating speed. Synchronize and load up to 10%.

d. Continue unit warmup increasing boiler oil firing. Increase main steam turbine load as steam conditions allow.

e. When steam conditions permit run up cycle and oxygen plant compressor steam turbines and bring compressors to minimum unloaded condition.

f. Turn on electrostatic precipitators.

g. Start combustor slag removal system.

h. Start oxidizer flow through the combustor at 25% for initial coal firing and light off combustor. Allow boiler combustion control system to maintain the air flow and firing as required for the bottoming plant. Allow the boiler warmup oil guns to cut back to prevent excessive temperatures in the bottoming plant.

i. Continue increasing coal firing and decreasing warmup oil gun firing until the oil guns can be removed from service. Deactivated oil guns are to be protected by cooling with inert flue gas.

j. Start seed injection. Synchronize MHD generator and load as conditions allow.

k. Slowly reduce the main combustor oxidizer-fuel ratio to the required substoichiometric levels. Simultaneously increase secondary air flow to the boiler afterburner section to complete combustion at excess air condition.

l. Allow the unit to stabilize at minimum generation rate and verify that required control systems are in the automatic mode.

Completion of Hot Startup

a. The hot startup at this stage is complete. The estimated time for the hot startup is dependent on the initial conditions. Time to stabilize at minimum generation should be from two to twenty-four hours.

b. Start seed regeneration system.

c. Start ash removal system.

Plant Loading

a. It is estimated that the plant generation can be increased at ~ 10% load per minute depending on the boiler and turbine manufacturers requirements.

3.0 SUBSYSTEMS/COMPONENTS DESIGN

3.1 MHD CHANNEL

3.1.1 MHD Channel Calculations and Performance

3.1.1.1 Introduction and Summary

MHD channel calculations and performance analyses were conducted for both nominal and part load operation. The basic plant design parameters for the channel calculations have already been presented in the previous section. Both the PDG series programs and the MHD4 program were used to perform the channel calculations. The calculation procedure used in the MHD4 program is described in subsection 3.1.1.3, and the PDG series of programs has been described before.[2]

Channel calculations were first performed for nominal load to establish the optimum oxygen content, seed rate, pressure ratio, channel loft and magnetic field profile. Part load performance calculations were subsequently conducted with the channel geometry and magnetic field profile established for nominal load. At part load conditions, the oxygen content of the oxidizer was increased to compensate for the reduction in preheat temperature as discussed in the previous section. Results from the channel calculations at nominal load and part load are summarized in Table 3-1.

The plant overall heat and energy balances were based on analytical channel performance calculations which needed to be conducted first for performing and finalizing the conceptual design of plant equipment. The magnetic field distribution specified by these channel calculations was used as the base for the conceptual design of the superconducting magnet. The conceptual design of the magnet again defined the final magnetic field distribution from practical magnet design considerations. Channel performance calculations with this final magnetic field distribution were conducted at the end of the program as a check on the channel performance. Comparative channel performance data with the initial analytical field distribution and final field distribution established from magnet conceptual design are listed in Table 3-2. The variations in channel performance data are very small and have an insignificant effect on channel and plant design and performance.

TABLE 3-1

MHD CHANNEL OPERATING CHARACTERISTICS AT VARIOUS LOADS

Load Condition (Coal Input)	%	100 (nominal)	75	50
Oxidizer Oxygen Content	%	34	35	36
Preheat Temp.	°F	1200	1075	925
Channel Mass Flow Rate	kg/s	472	346	227
Channel Inlet Stagnation Pressure	ata	8.3	6.5	5.1
Channel Inlet Stagnation Temp.	°K	2881	2866	2840
Channel Inlet Mach No.		0.885	0.721	0.539
Loading Parameter		0.7862	0.79776	0.7894
Channel Flow		Subsonic Decelerating	Subsonic Decelerating	Subsonic Decelerating
Gross Power Output	MW	525	357	204
Enthalpy Extraction	%	24.5	22.7	19.9
Isentropic Efficiency	%	74.0	76.4	76.9
MHD Efficiency*	%	16.6	15.1	12.6
Channel Exit Stagnation Pressure	ata	1.11	1.05	1.02
Channel Exit Mach No.		0.722	0.500	0.325
Diffuser Efficiency		0.6	0.6	0.6
Channel Length	m	21.5	21.5	21.5
Channel Inlet	m x m	0.92 x 0.92	0.92 x 0.92	0.92 x 0.92
Channel Outlet	m x m	2.50 x 2.50	2.50 x 2.50	2.50 x 2.50
Maximum Transverse Current Density (Jy)	amp/cm^2	0.82	0.74	0.61
Maximum Hall Field (Ex)	kV/m	1.8	1.2	0.88
Maximum Transverse Field (Ey)	kV/m	4.0	3.4	2.5
Maximum Hall Parameter ($\omega\tau$)		3.9	3.9	4.0
Average Power Density	MW/m^3	8.4	5.7	3.2

* $$\eta_m = \frac{P_m - P_c - P_o}{P_f}$$

TABLE 3-2

COMPARISON OF CHANNEL NOMINAL LOAD OPERATING CHARACTERISTICS WITH INITIAL ANALYTICAL AND FINAL MAGNET DESIGNS

		Initial Magnet Design	Final Magnet Design
Channel Mass Flow Rate	kg/sec	472	472
Channel Inlet Stagnation Pres.	ata	8.3	8.3
Channel Inlet Stagnation Temp.	°K	2881	2881
Channel Inlet Mach No.		0.885	0.807
Loading Parameter		0.7862	0.77957
Channel Flow		Subsonic Decelerating	Subsonic Decelerating
Gross Power Output	MW	525	527
Enthalpy Extraction	%	24.5	24.6
Isentropic Efficiency	%	74.0	74.2
MHD Efficiency*	%	16.6	16.7
Channel Exit Stagnation Pres.	ata	1.11	1.09
Channel Exit Mach No.		0.722	0.637
Diffuser Efficiency		0.60	0.60
Channel Length	m	21.5	21.5
Channel Inlet	m x m	0.92 x 0.92	0.93 x 0.93
Channel Outlet	m x m	2.50 x 2.50	2.60 x 2.60
Maximum Transverse Current Density (Jy)	amp/cm^2	0.82	0.88
Maximum Hall Field (Ex)	kV/m	1.8	1.5
Maximum Transverse Field (Ey)	kV/m	4.0	4.0
Maximum Hall Parameter ($\omega\tau$)		3.9	3.9
Average Power Density	MW/m^3	8.4	7.9

*
$$\eta_m = \frac{P_m - P_c - P_o}{P_f}$$

3.1.1.2 Channel Working Fluid

Thermochemical, thermodynamic and electrical properties of the combustion gases used as the working fluid for the MHD generator were calculated. Respective Mollier diagrams for combustion gases produced by combustion of the selected sub-bituminous Montana Rosebed coal dried to five percent moisture content are shown in Figures 3-1 through 3-3. Figure 3-1 is for the conditions of 34% by volume oxygen of the oxidizer, one percent by mass potassium of the combustion gases, and an oxidizer/fuel equivalence ratio of 0.90. Figures 3-2 and 3-3 are for identical reactant conditions except the oxygen content is 35% and 36% by volume, respectively. The pressures on the Mollier charts are in NEMA atm (1 NEMA atm equals 0.96392 std atm).

3.1.1.3 Channel Calculation Procedure

Two series of MHD channel computer programs, the PDG series and the MHD4 series, were used for the channel analysis. The PDG programs concentrate on the channel core flow and have a relatively unsophisticated treatment of the channel boundary layer, and, as a consequence, take less computer time and are much less costly to use than the MHD4 series of programs. For more sophisticated treatment of boundary layer phenomena, the MHD4 program was used to perform the channel analysis.

In the "design" mode both of these programs calculate the channel loft and all operating parameters for specified channel design. In the "off-design" mode the programs can be used to calculate the channel operating parameters for a specified channel loft.

The basic channel calculation procedure for the MHD4 program is schematically outlined in Figure 3-4. The main features of the calculations are briefly described below. Major input data required for a "design" mode calculation are the reactants composition which is used to generate the thermochemical, thermodynamic and electrical properties of the gas, the total mass flow rate, the combustor stagnation pressure and enthalpy, and specified design conditions of magnetic field, electrical load parameter and Mach number along the channel. In order to match the specified diffuser exit pressure without excessive channel length and for a specified diffuser performance, several design iterations were required. Such design iterations were also needed to select the optimum Mach number, loading parameter, magnetic field profile, and pressure ratio. Additional design iterations were necessary for the part load performance calculations, but now with the difference that the channel geometry and magnetic field profile already were defined.

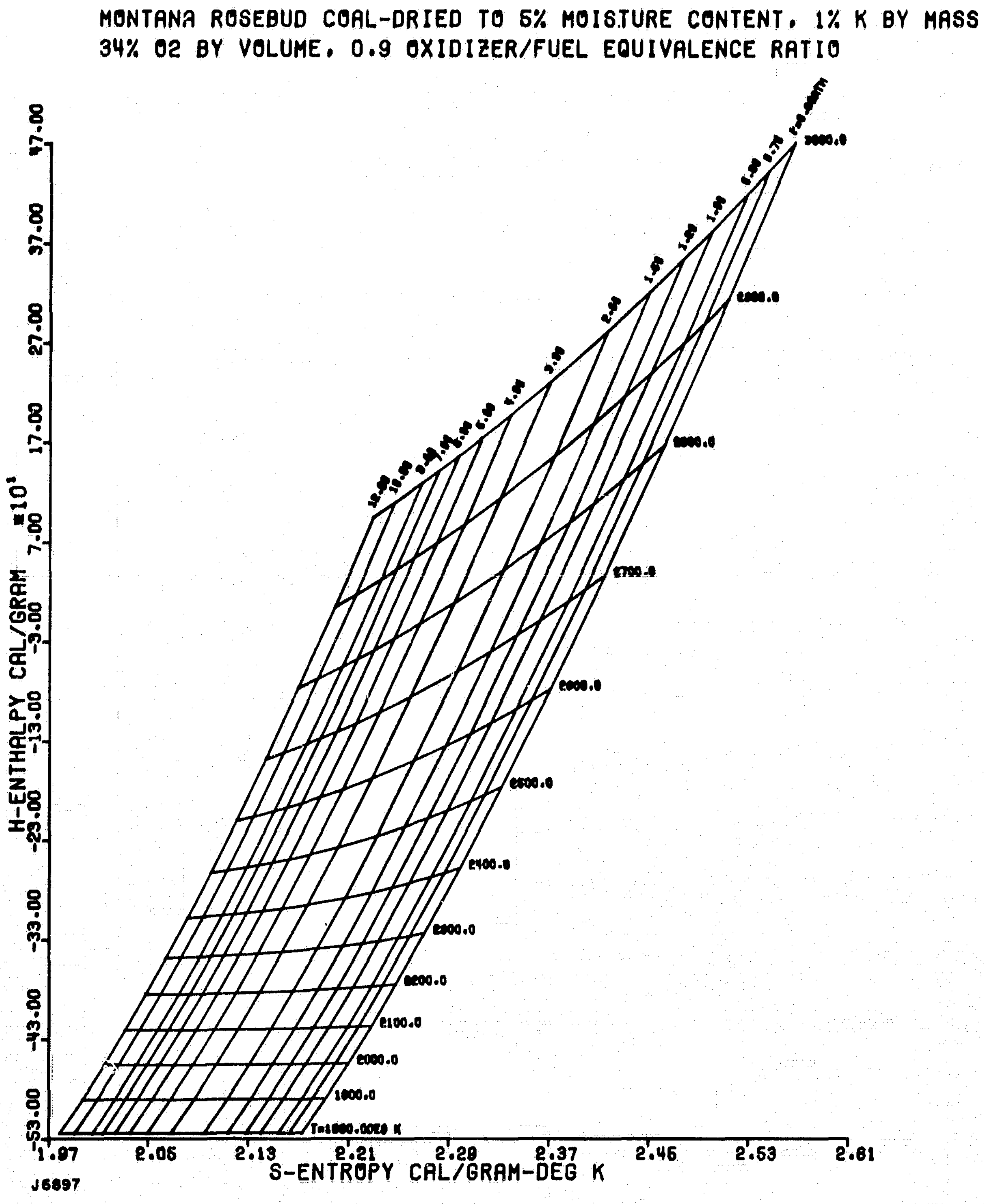


Figure 3-1 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

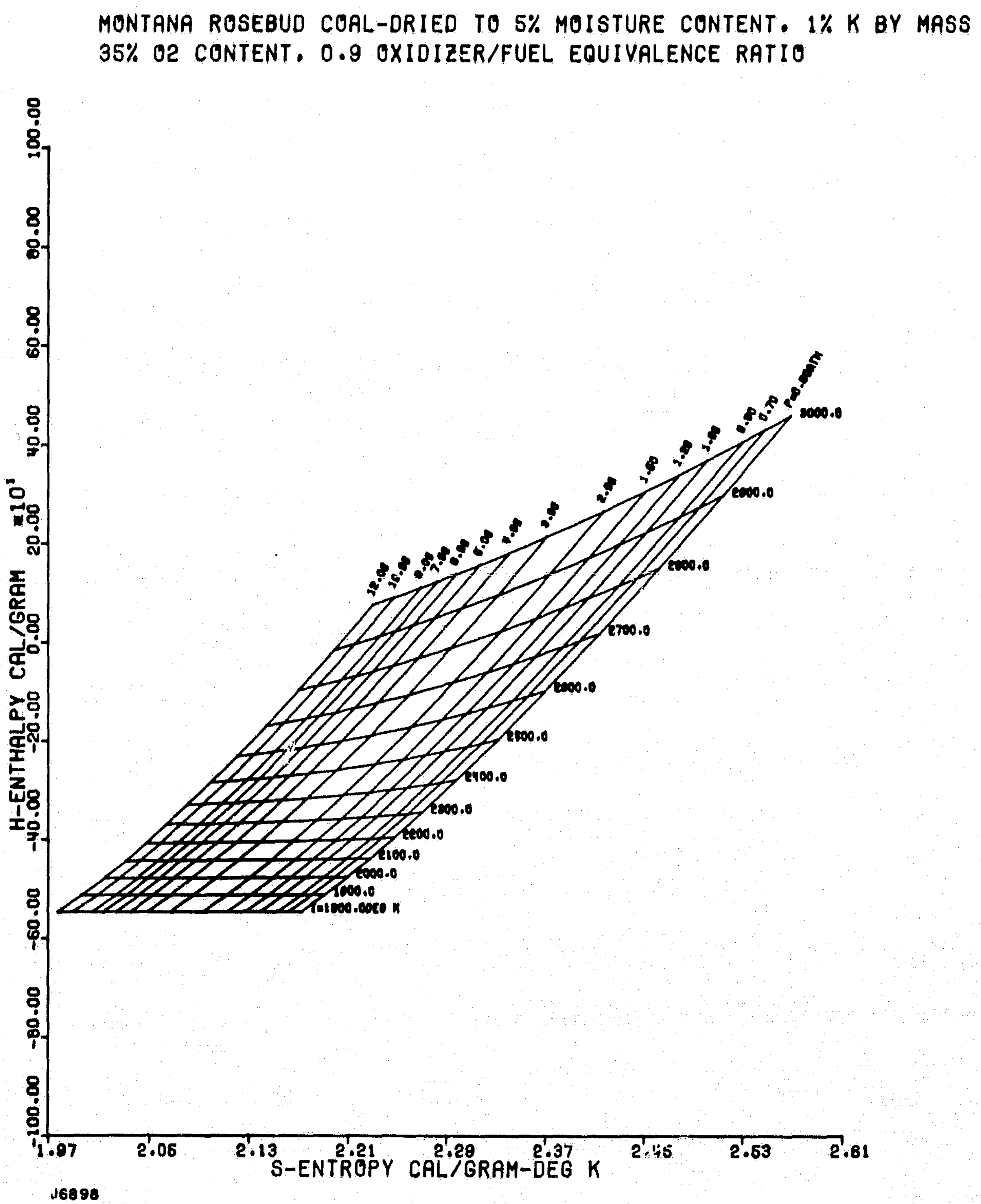


Figure 3-2 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

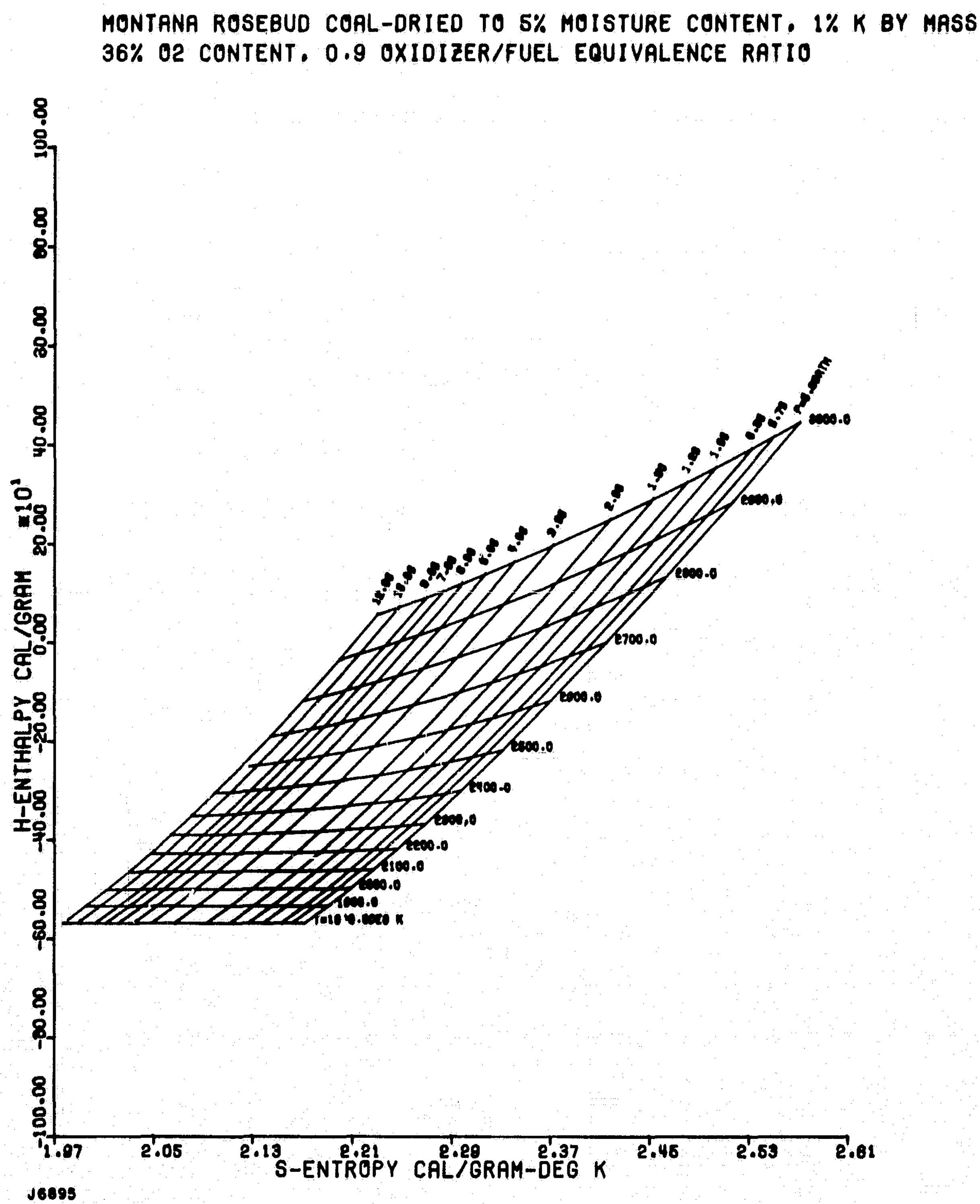


Figure 3-3 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

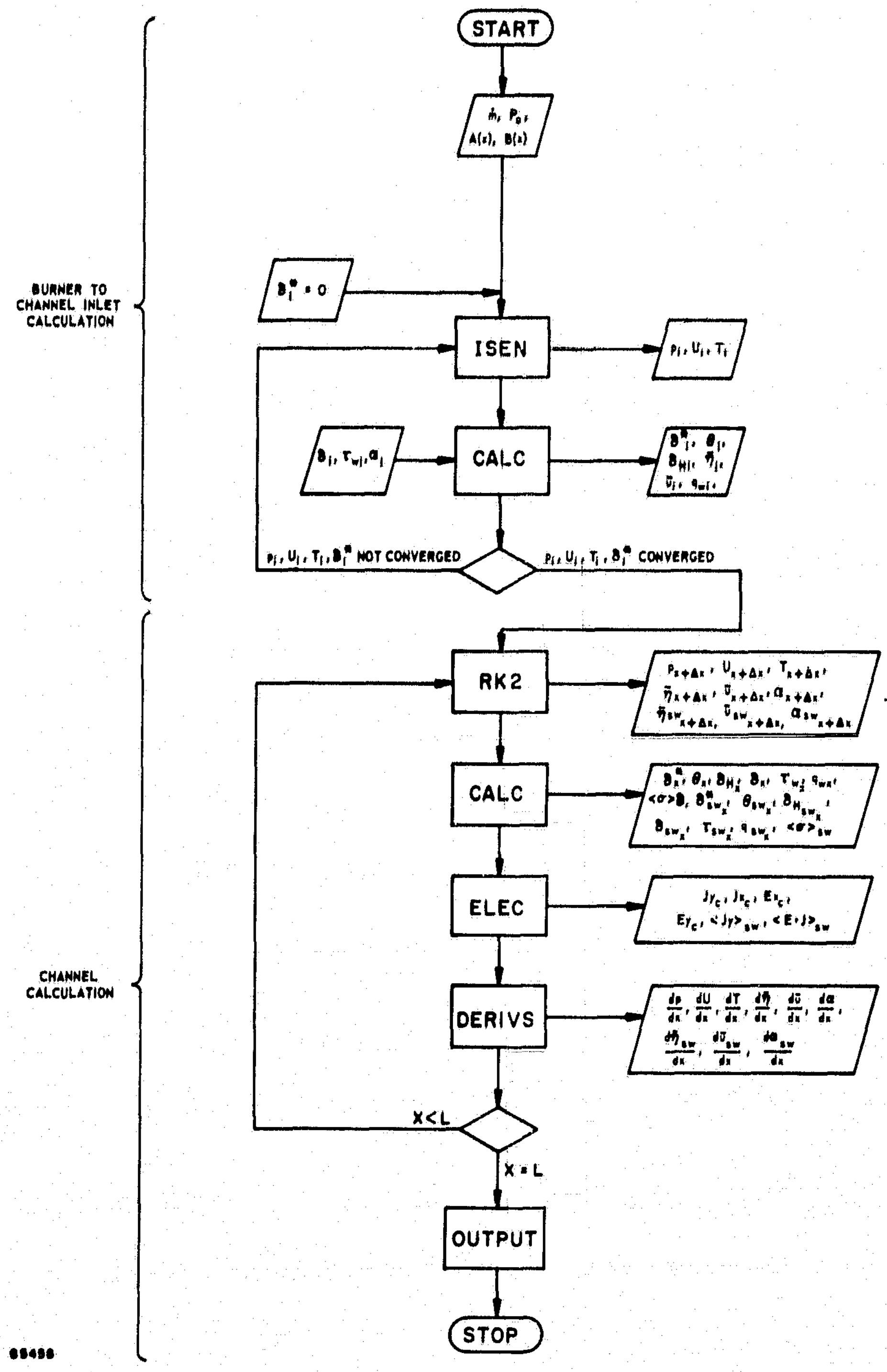


Figure 3-4 Flow Chart of MHD4 Channel Model

The flow model for the channel assumes the flow to be developing rather than fully developed. Therefore, the flow is divided into an inviscid core region occupying most of the channel volume and boundary layer and slag flow regions confined to the immediate vicinity of the channel walls. The behavior of the boundary layers determine the magnitude of the electrode voltage drops, the heat loss to the walls, the frictional stagnation drop, the probability of axial shorting, the potential for flow separation, etc.

Because of the influence of the boundary layers, detailed analyses of the electrode wall and sidewall boundary layers are part of the MHD4 program. MHD effects substantially modify the boundary layer profiles, especially the electrode wall enthalpy profile and the insulating wall velocity profile. The enthalpy distribution affects the electrical conductivity distribution, and, hence, the boundary layer impedance. This distribution in turn responds to the excessive Joule dissipation near the electrode wall. For the sidewall bounday layers, where the favorable axial pressure gradients are not balanced by the Lorentz force near the wall, the velocity distribution may exhibit overshoot, which may result in negative momentum and displacement thicknesses. A typical MHD4 prediction of the velocity profiles at the channel exit is shown in Figure 3-5. The mathematical details of the boundary layer modeling techniques of MHD4 have been described previously.[3]

Because of the effects of MHD interactions and $P_r \neq 1$, a more general expression between the boundary layer enthalpy and velocity profiles than that given by Crocco's relationship is used. Consequently, the thermal boundary layer and the velocity boundary layer are allowed to develop separately; hence, the thermal boundary and velocity boundary layer are not forced to be of the same thickness. The effect of arc drops, leakage currents, rough walls and shocks are included in MHD4.

The slag layer model used in MHD4 allows for electrical leakage in the slag layer. The thickness of the slag layer is considered in the determination of the geometric area of the channel.

3.1.1.4 Basis for Channel Design

The relationship to and importance of the channel performance on the overall net plant efficiency were discussed in Section 2.1. It was mentioned that the net plant efficiency was optimized by optimization of the net power output from the MHD generator (P_m - P_c - P_o). Also, that the channel design and critical operating parameters were limited to be representative of reasonable projections from present experience and state of the art in MHD technology.

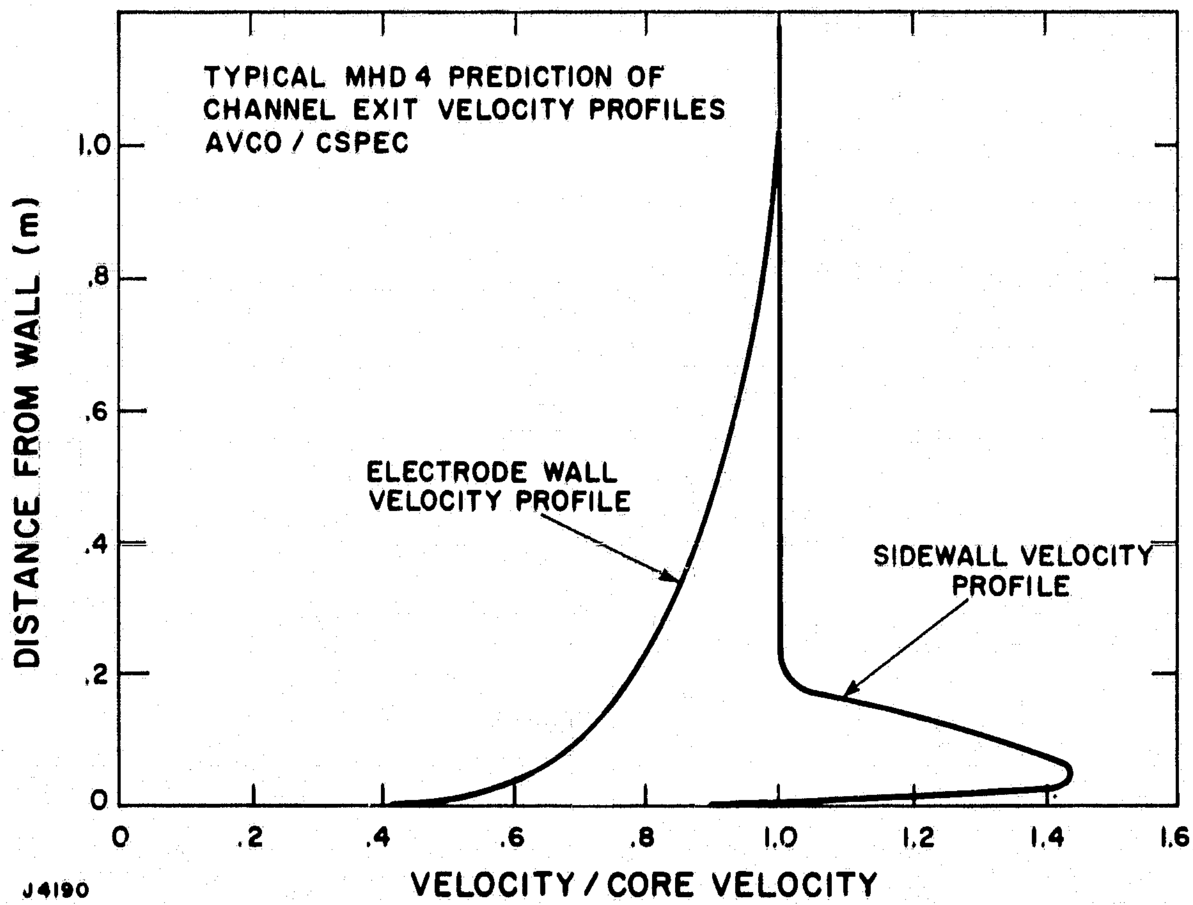


Figure 3-5 Typical Velocity Profile at Channel Exit

In summary, the channel design and optimization must be based on a compromise between performance (high enthalpy extraction and isentropic efficiency), cost (particularly the magnet), reliability and lifetime (relatively low electrical stresses), mechanical design and construction.

3.1.1.5 Performance Calculations

Performance analysis of the nominal load operating condition were conducted for various combinations of electrical load parameters and pressure ratios, and magnetic field profiles. The axial magnetic field and velocity profiles were adjusted as necessary to maintain the values of the critical channel design parameters within their prescribed limits.

Initial performance calculations were performed with the more simple channel computer programs and for the purpose of comparison between different assumed design conditions. Also, the electrical conductivity of the gas used in these initial channel calculations was based on older data for the electrical properties of the gas (CO_2^-, etc.) than the more refined channel performance calculations conducted later with the more sophisticated boundary layer treatment.

MHD channel performance calculations were first conducted for two different degrees of oxygen enrichment of the combustion air of 34% by volume and 35% oxygen by volume, respectively, and for potassium seed concentrations in the gas of 1% and 1.5% by weight. All of these channel calculations were performed for the same nominal flow rate of MHD combustion gases and the same preheat temperature of 1200°F.

The mass flow rates of coal and of air and oxygen for combustion of the coal for the two cases with 34% by volume and 35% oxygen by volume are listed in Table 3-3. These correspond in both cases to an oxygen/fuel equivalence ratio of 0.9 of stoichiometric condition.

The first channel calculations were performed with constant gas velocity and for various pressure ratios and electrical load parameters. Tables 3-4 and 3-5 summarize results from these channel calculations. P_{MHD} is the gross power output from the MHD generator. $P_{MHD} - P_{COMPR}$ represents the net power output from the MHD prime cycle after deduction of required compressor power both for compression of the oxidizer (air + oxygen) to the cycle pressure and for production of oxygen for oxygen enrichment of the combustion air. (The oxygen plant was here assumed to produce oxygen at 95% purity with a power consumption of 205 kWhr per ton of oxygen produced.)

TABLE 3-3

MASS FLOW RATES AND COAL THERMAL INPUT TO MHD COMBUSTOR FOR 34% BY VOLUME AND 35% O_2 BY VOLUME

		34% O_2	35% O_2
Coal:			
Raw (27.7% Moisture)	pph	817,276	836,388
Dried (5% Moisture)	pph	665,005	680,556
Thermal Input (HHV)	MW	2,135	2,185
Oxidizer:			
Air	pph	2,480,239	2,426,651
*From O_2-Plant (95% O_2 by volume)	pph	606,542	646,193
Preheat Temperature	°F	1,200	1,200
Oxygen Plant Capacity	TPD	6,957	7,413

*Initially oxygen production at 95% purity was assumed. This was later changed to 80% purity which was finally selected.

TABLE 3-4

OXIDIZER WITH 34% O_2 BY VOLUME

Seed	wt%K	1.0	1.0	1.5	1.5	1.5	1.5
Pressure Ratio		8.3	8.3	8.3	8.3	8.6	8.6
El. Load Parameter		0.80	0.82	0.80	0.82	0.80	0.82
P_m	MW	511.4	520.4	505.7	514.9	512.5	521.6
P_m-P_c*	MW	341.0	350.1	335.4	344.5	339.8	348.8
η_m*	%	16.0	16.4	15.7	16.1	15.9	16.3
Channel Length	m	24.3	28.6	22.6	26.4	24.4	28.7

*
$$\eta_m = \frac{P_m - P_c}{P_f}$$

P_c = Cycle Comp. + O_2-Plant Comp.

TABLE 3-5

OXIDIZER WITH 35% O_2 BY VOLUME

Seed	wt%K	1.0	1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5	1.5
Pressure Ratio		8.3	8.3	8.6	8.6	8.3	8.3	8.6	8.6	8.9	8.9
El. Load Parameter		0.80	0.82	0.80	0.82	0.80	0.82	0.80	0.82	0.80	0.82
P_m	MW	517.0	526.4	524.0	533.3	512.2	521.6	519.1	528.5	525.7	535.0
$P_m - P_c$*	MW	343.5	352.8	348.1	357.4	338.6	348.0	343.2	352.6	347.5	356.8
η_m*	%	15.7	16.2	15.9	16.4	15.5	15.9	15.7	16.1	15.9	16.3
Channel Length	m	22.1	26.0	23.9	28.1	20.2	23.7	21.8	25.6	23.5	27.7

---

* $\eta_m = \frac{P_m - P_c}{P_f}$

P_c = Cycle Comp. + O_2-Plant Comp.

η_{MHD} is the power output from the MHD prime cycle (P_m - P_c) in percent of the thermal input of coal to the MHD combustor. A high performance value of η_{MHD} is indicative of a high overall plant efficiency. It is clear that η_{MHD} can be increased by an increase of the electrical load parameter and/or pressure ratio. However, this increases the channel length and hence the cost of the MHD generator, in particular the magnet. An increase in oxygen enrichment increases the size and hence cost of the oxygen plant.

On the basis of the initial performance calculations along with cost considerations, an oxygen enrichment of 34% by volume, 1%K by seed weight, and a channel pressure ratio of 8.3 were selected as basic design conditions for further channel and plant design.

Deceleration of the gas flow in the channel was subsequently investigated for optimization of the channel performance. In addition, channel performance calculations were conducted with omission of the electronegative effect of the negative ion CO_2^- in the gas, because more recent investigations indicated that this effect is expected to be insignificant.

Table 3-6 summarizes the effect of the velocity distribution on channel performance. It shows that a slight gain in the MHD power can be obtained for the case with slightly decelerating flow. The velocity distribution specified by design case 3 in Table 3-6 was selected for further design investigations, because it yielded practically the same maximum power output as in Design Case 1 for a shorter channel length. Also, the power output was increased to 515.4 MW from 511.4 MW compared to constant flow velocity with essentially the same channel length ($\sim$ 24 m). Table 3-7 compares the channel performance with the original electronegative effect of CO_2^- and without this effect. Essentially the channel length was reduced from 24.6 m to 21.5 m for the same pressure ratio and power output.

The electronegative effect of the CO_2^- ion in our initial channel performance calculation was based on an electron affinity of + 0.5 eV according to JANNAF.[4] However more recent data indicate a value of $\sim$ - 0.5 eV.[5,6] This negative value of electron affinity reduces the CO_2^- concentration substantially and diminishes its effect on the gas conductivity to the point of insignificance. Therefore the negative ion CO_2^- was excluded in our subsequent more detailed and final performance calculations conducted with the MHD4 program. As mentioned in subsection 3.1.1.3, the MHD4 program used is based on a quasi-one-dimensional model which separates the flow into a frictionless adiabatic core and boundary layer regions near the walls. This model takes into account the different behavior of the boundary layer along the electrode and sidewalls of the channel. It also includes the effects of slag on the walls of the channel and

TABLE 3-6

SUMMARY OF VELOCITY DISTRIBUTION VARIATIONS

Case No.	1	2	3	4
Mach No. Distribution	0.9 \ 0.85	0.9 \ 0.85	0.885 \ 0.874 \ 0.823	0.885 \ 0.877
P_o (NEMA atm)	8.3	8.3	8.3	8.3
T_o (K)	2874	2874	2874	2874
Inlet (mho/m)	8.05	8.05	8.10	8.10
Electrical Load Parameter (-)	0.80	0.80	0.80	0.80
Length (m)	26.2	25.8	24.6	23.9
P_m (MW_e)	516.5	511.8	515.4	511.4
P_c	112.3	112.3	112.3	112.3
P_o	58.1	58.1	58.1	58.1
$P_m - P_c - P_o$	346.1	341.4	345.0	341.0

TABLE 3-7

MHD CHANNEL PERFORMANCE DATA COMPARISON FOR CO_2^- NEGATIVE ION

Case	1	2
Mode	w/CO_2^-	w/o CO_2^-
P_o (NEMA atm)	8.3	8.3
T_o (I)	2874	2874
Inlet Mach No.	0.886	0.886
El. Load Parameter	0.80	0.86
P_m (MW_e)	515.4	515.3
η_{is}(%)	72.6	72.6
η_{en}(%)	24.1	24.1
Length (m)	24.6	21.5

allows for electrical leakage in the slag layer. Based on a review of the information available for slagging channels and electrical properties of ash, a liquid slag layer of ~ 2 mm and an average conductivity of 5 mho/m were used for the detailed channel design.[7,8]

In connection with the use of the more sophisticated MHD4 program for detailed channel calculations, the momentum transfer cross sections of the working fluid were reviewed and the most recent published values of the cross sections for KOH and H_2O were incorporated. For KOH, the cross-section values published by Norcross were incorporated.[9] For H_2O the cross-section values published by Spencer in 1976[10] were first used and the final calculations incorporated the most recent values published by Itikawa in 1978.[11]

In the final detailed full load MHD channel performance calculations with the MHD4 program, the gas velocity distribution and electrical loading were varied to establish optimum design conditions.

The results of these last full load channel calculations are summarized in Table 3-8. In the first column, Case 1, the most recent momentum transfer cross sections values for H_2O published by Itikawa were used for establishing the electrical properties of the working fluid. In the second column, Case 2, the cross section values published by Spencer were used. These design calculations were with identical pressure ratios and channel lengths and variable electrical load parameters.

The use of the most recent cross section values published by Itikawa results in a slightly higher power output from the MHD generator than the use of the H_2O cross section values published by Spencer, 525 MW versus 512 MW, respectively, because a somewhat higher electron mobility of the working fluid is obtained with the use of Itikawa's cross section values. The values of the important channel operating parameters (Ey, Ex, $\omega\tau$, Jx) are reasonable and essentially the same for both cases.

The refined calculation procedures served the purpose of establishing the MHD generator performance with a higher degree of certainty and accuracy. The calculated channel performance with the use of Itikawa's H_2O cross section data (Case 1 in Table 3-8) was used as the basis for determining plant performance and equipment design. Figure 3-6 shows operating characteristics of this channel at full load with a nominal power output of 525 MW_e.

The magnetic field distribution is the analytical profile specified by the channel design calculation. This field distribution was used as the base for the conceptual design of the

TABLE 3-8

CALCULATED MHD CHANNEL PERFORMANCE CHARACTERISTICS
AT FULL LOAD

Case No.	1	2
H_2O Cross Section	Itikawa	Spencer
P_o (NEMA atm)	8.3	8.3
T_o (K)	2881	2881
Inlet Mach No. (-)	0.885	0.885
Exit Mach No. (-)	0.722	0.747
Electrical Load Parameter (-)	0.786	0.771
Length (m)	21.5	21.5
P_m (MW_e)	524.9	512.5
η_{is} (%)	74.0	72.2
η_{en} (%)	24.5	24.0
$Ey_{c_{max}}$ (kV/m)	4.0	3.9
$Ex_{c_{max}}$ (kV/m)	1.8	1.8
$Jy_{c_{max}}$ (kV/m)	0.82	0.76
$\omega\tau_{max}$ (kV/m)	3.9	3.9

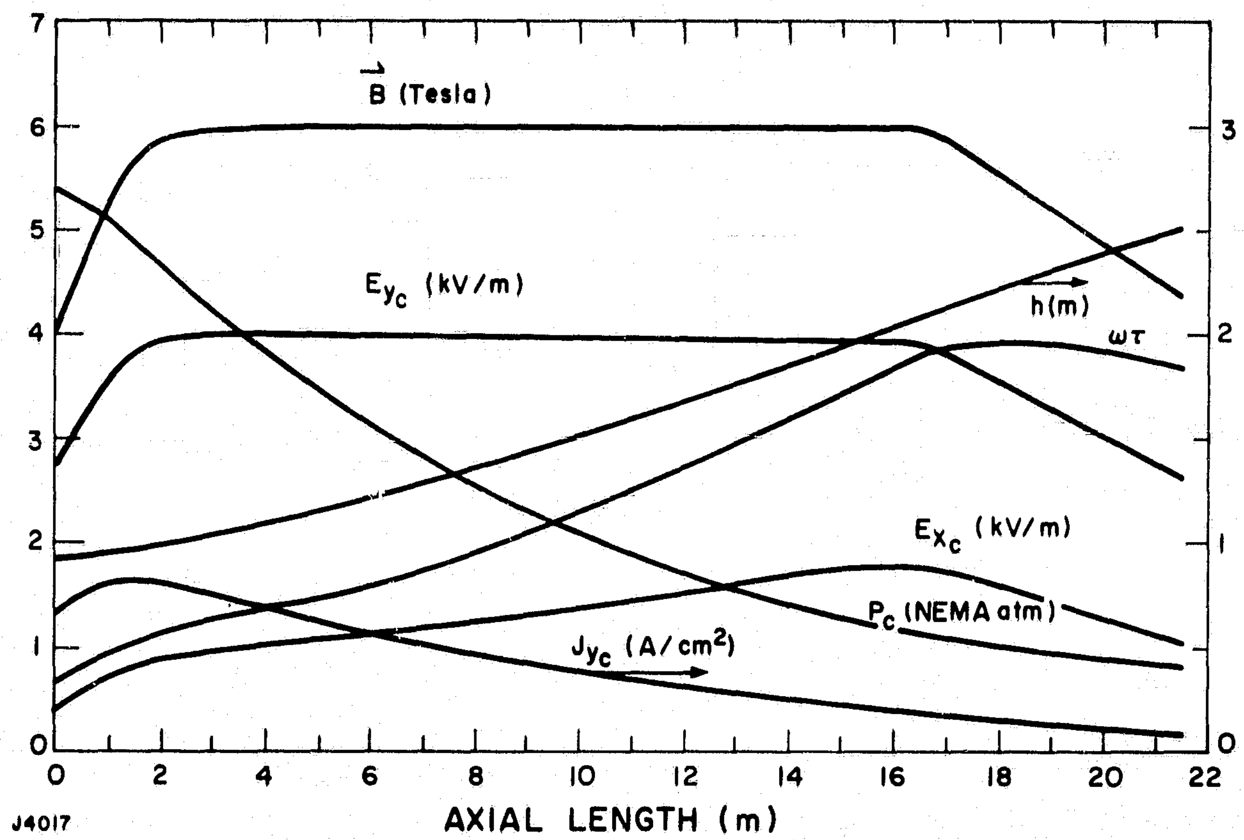


Figure 3-6 Channel Operating Characteristics at Full Load with Analytical Magnet Design

superconducting magnet. The conceptual design of the magnet again defined the final magnetic field distribution from practical magnet design considerations. Channel performance calculations with this final magnetic field distribution were conducted at the end of the program as a check on the channel performance. Comparative channel performance data with the initial analytical field distribution and final field distribution established from the magnet conceptual design were previously listed in Table 3-2. Figure 3-7 shows the channel full load operating characteristics with the final conceptual design field distribution. To conclude, the variations in channel performance and operational characteristics are very small and have insignificant effects on channel and plant design and performance.

Detailed part load performance calculations were conducted after the channel geometry and magnetic field profile had been established from the full load performance calculations. The magnetic field profile used in the part load calculations was identical to the analytical field profile shown in previous Figure 3-6 for full load operation.

In order to maintain a relatively high plant efficiency at part load, the net energy output of the MHD generator (P_m - P_c - P_{O2}) was again optimized. Part load of the MHD generator was accomplished by reducing the gas mass flow rate and hence the thermal input to the channel and coal input to the plant. Gas stoichiometry, the degree of oxygen enrichment of the combustion air and seed fraction were maintained constant.

Calculated performance and operating data for the MHD generator for 75% and 50% of full load mass flow rates are listed in Table 3-9. Corresponding data already reported for full load operation are included for comparison. It is noted that for subsonic channel operation as here selected for commercial operation, the reduction in combustor pressure from nominal load is less than the corresponding reduction in gas mass flow rate. The electrical load parameter has been increased slightly at part load operation so as to take full advantage of the channel length and magnetic field profile established for full load design. This results in a slightly higher isentropic efficiency at part load than at full load which is indicative of efficient channel operation. Reasonable values for all of the important channel electrical operating parameters (Ex, Ey, Jy, $\omega\tau$) are obtained at part load operation. Variations of the important channel operating characteristics at 75% and 50% of coal thermal input are shown on Figures 3-8 and 3-9.

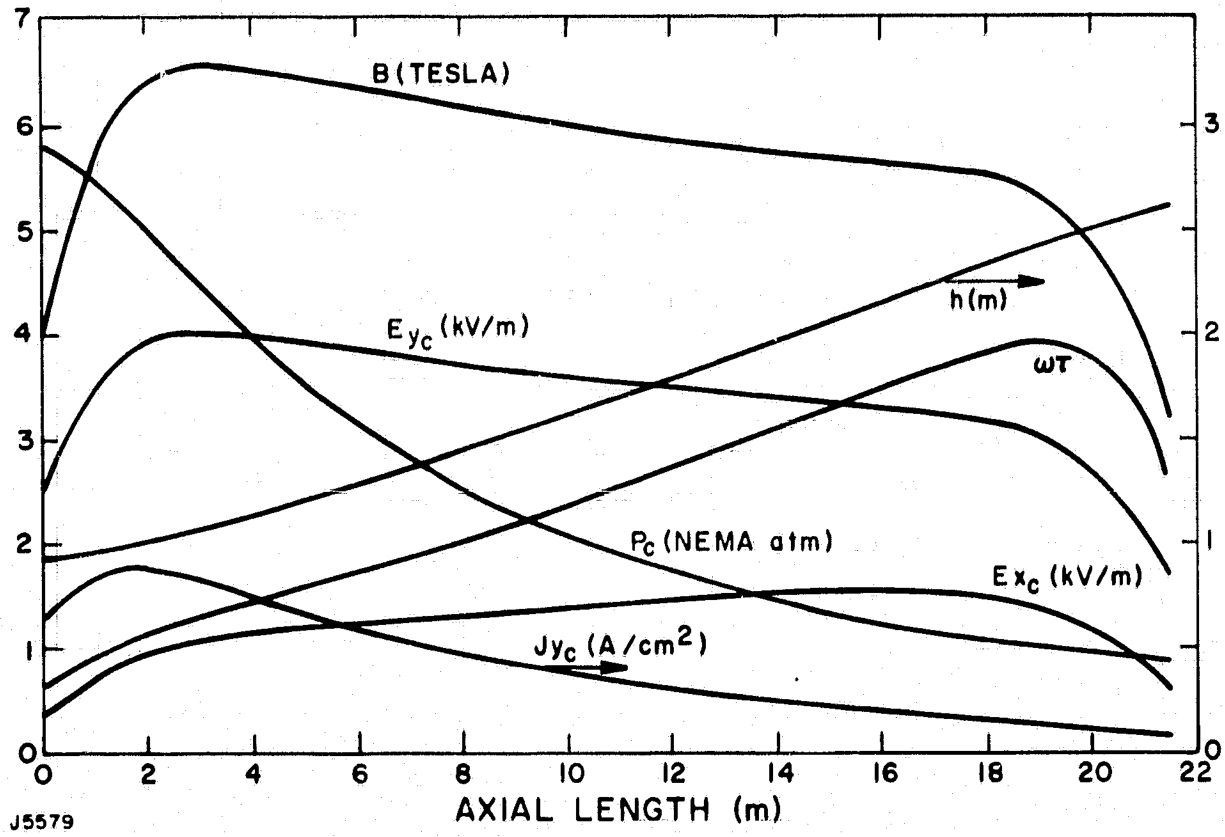


Figure 3-7 Channel Operating Characteristics at Full Load with Final Magnet Design

TABLE 3-9

CHANNEL PERFORMANCE DATA AT FULL AND PART LOAD OPERATION

Case No.	BLD75	BLD105	BLD144
Coal Thermal Input %	100	75	50
Oxidizer O_2-Cotent %	34	35	36
Oxidizer Preheat °F	1200	1070	925
Mass Flow (kg/sec)	472.0	345.9	226.5
P_o (NEMA atm)	8.3	6.54	5.08
T_o (K)	2881	2866	2840
Inlet Mach No. (-)	0.885	0.721	0.539
Exit Mach No. (-)	0.722	0.499	0.325
Electrical Load Parameter (-)	0.7862	0.79776	0.7894
P_m (MW_e)	524.9	357.3	203.7
η_{is} (%)	74.0	76.4	76.9
η_{en} (%)	24.5	22.7	19.9
$Ey_{c_{max}}$ (kV/m)	4.0	3.4	2.5
$Ex_{c_{max}}$ (kV/m)	1.8	1.2	0.87
$Jy_{c_{max}}$ (kV/m)	0.82	0.74	0.61
$\omega\tau_{max}$ (-)	3.9	3.9	4.0

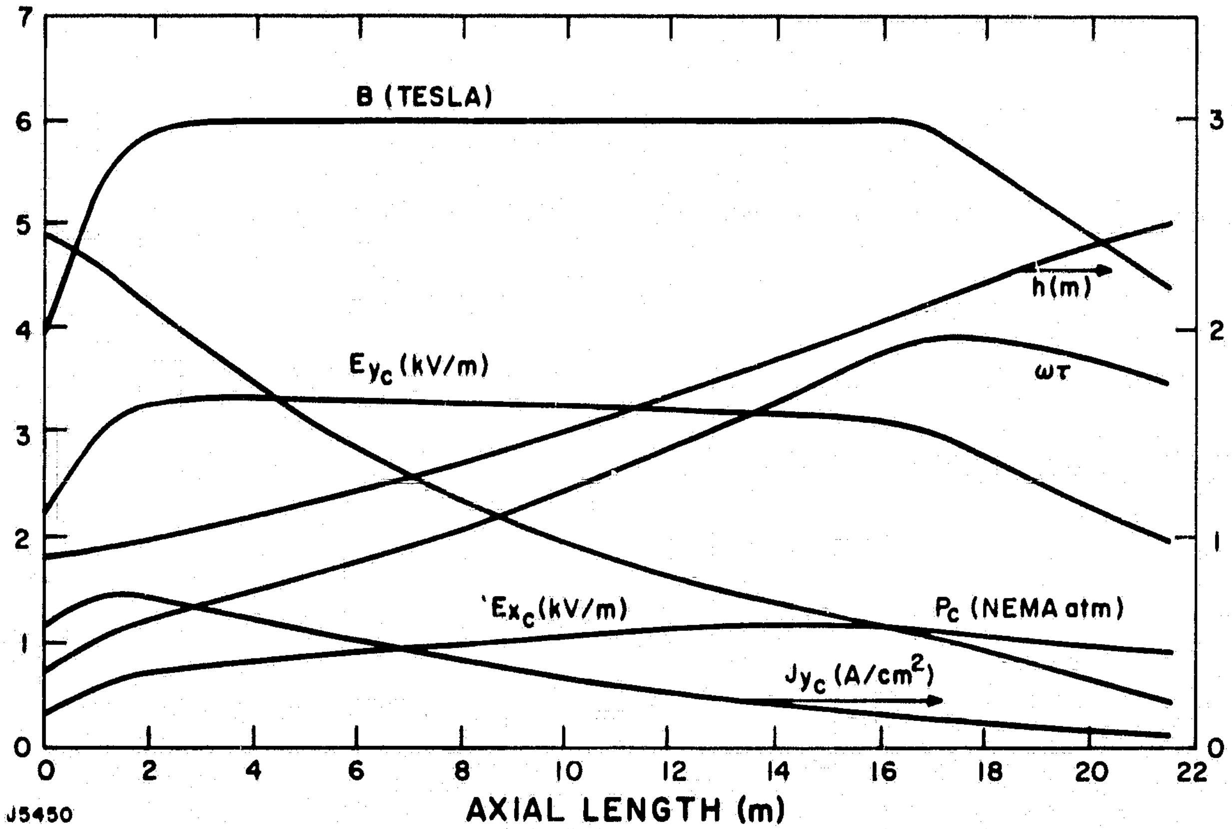


Figure 3-8 Channel Operating Characteristics at 75% Load with Analytical Magnet Design

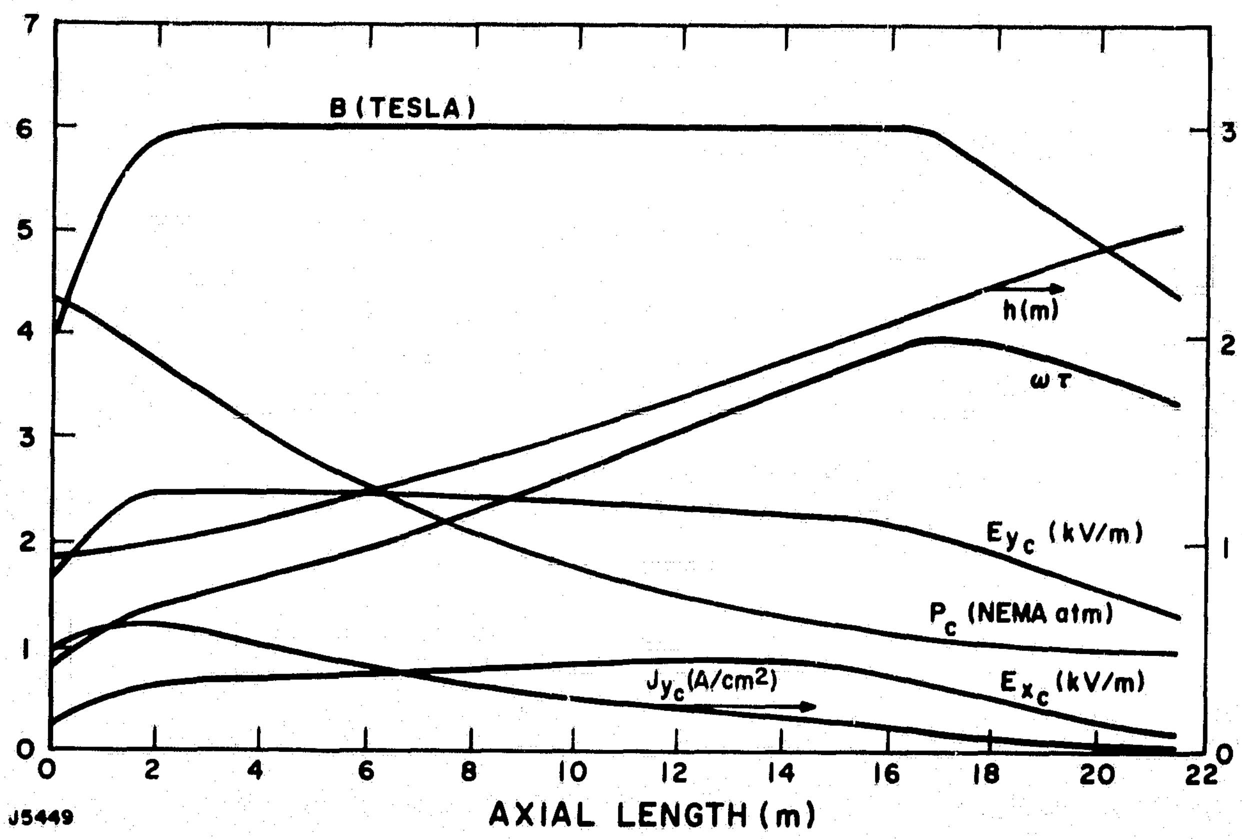


Figure 3-9 Channel Operating Characteristics at 50% Load with Analytical Magnet Design

Figures 3-10 to 3-15 show comparative variations of individual channel operating parameters at full and part load operation. The plotted curves for each parameter are labeled as follows:

Label	Load Conditions
BLD075	100% Coal Input
BLD105	75% Coal Input
BLD144	50% Coal Input

The axial static pressure distribution for the three cases is shown in Figure 3-10. The static pressure distribution at the inlet and middle regions of the channel is lowered as the mass flow rate is reduced at part load because of the corresponding reduction in combustor pressure.

Figure 3-11 shows the axial static temperature distribution. As seen, the channel inlet region temperatures distributions are nearly identical, while some divergence occurs at the exit region of the channel. This result occurs because the Mach number is significantly lower for the part load cases, and relative to the full load, this difference becomes larger at the exit end of the channel. The Mach number distribution is shown in Figure 3-12.

In Figure 3-13, the plasma electrical conductivity is presented. Higher values of electrical conductivity occur for the part load cases which have a higher static temperature distribution because of their lower Mach number.

The equi-potential surface angle is shown in Figure 3-14. This figure shows that, except for the exit region of the channel, the equi-potential surfaces are nearly identical for the full load and part load cases. Consequently, the angle selected for the bar wall channel design will be applicable for a range of channel operating conditions.

Figure 3-14A shows the electrode voltage drop distribution for full and part load operation of the channel.

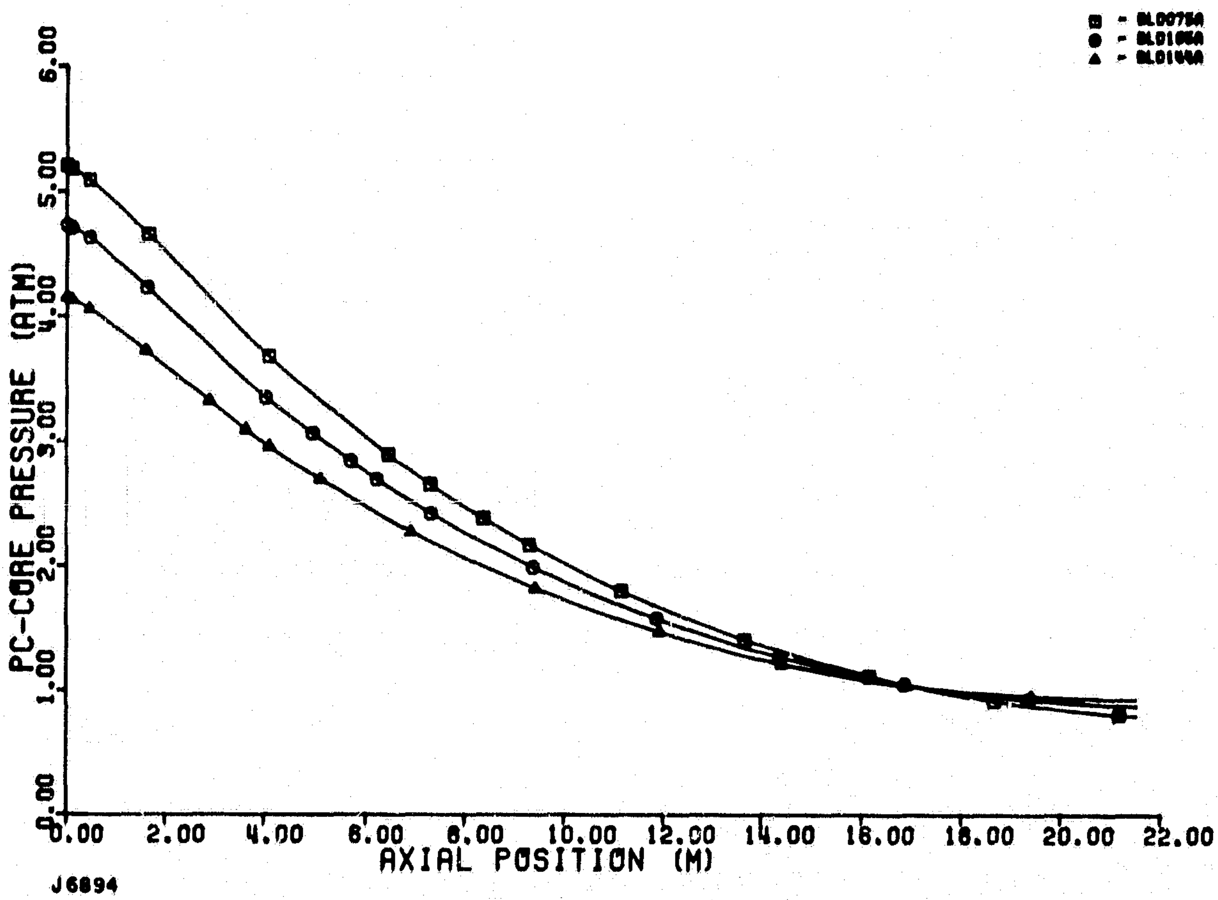


Figure 3-10 Axial Static Pressure Distribution

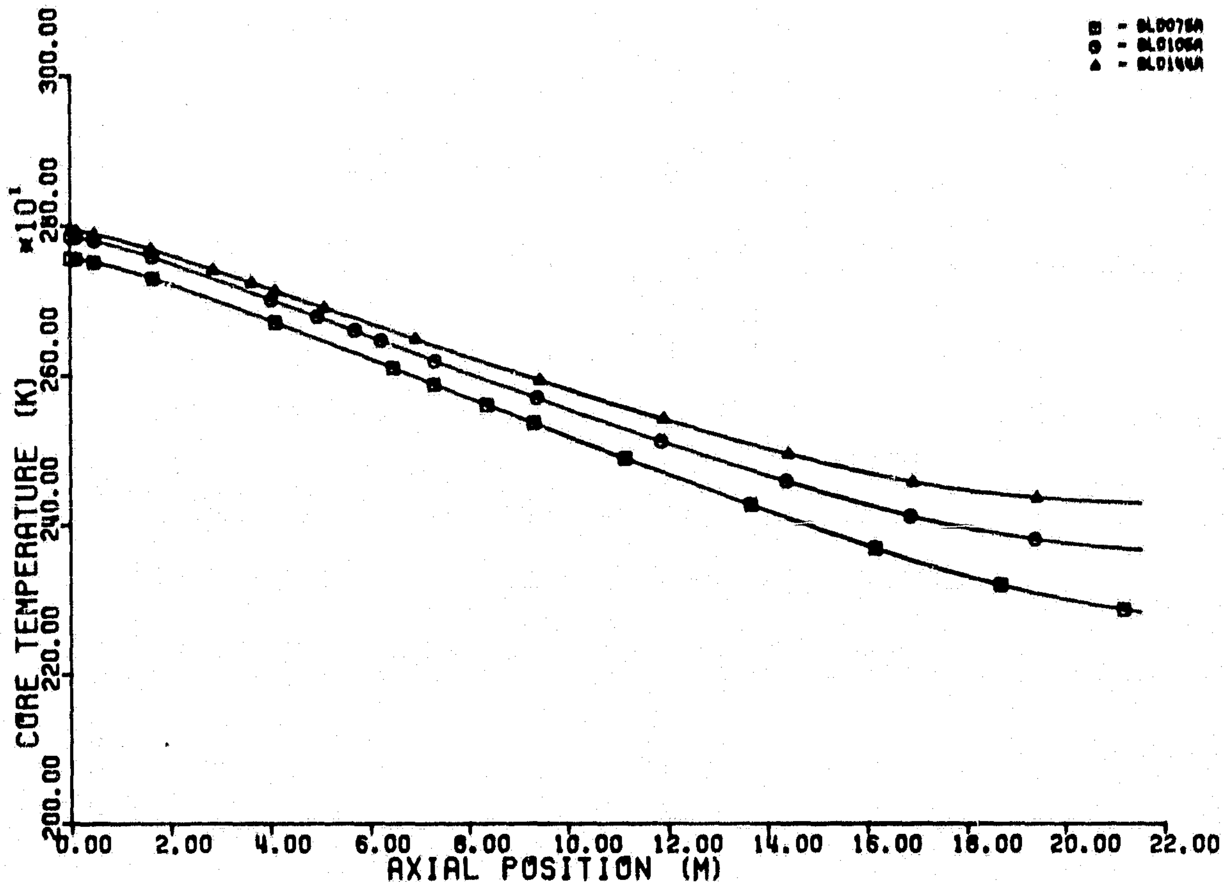


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Figure 3-11 Axial Static Temperature Distribution

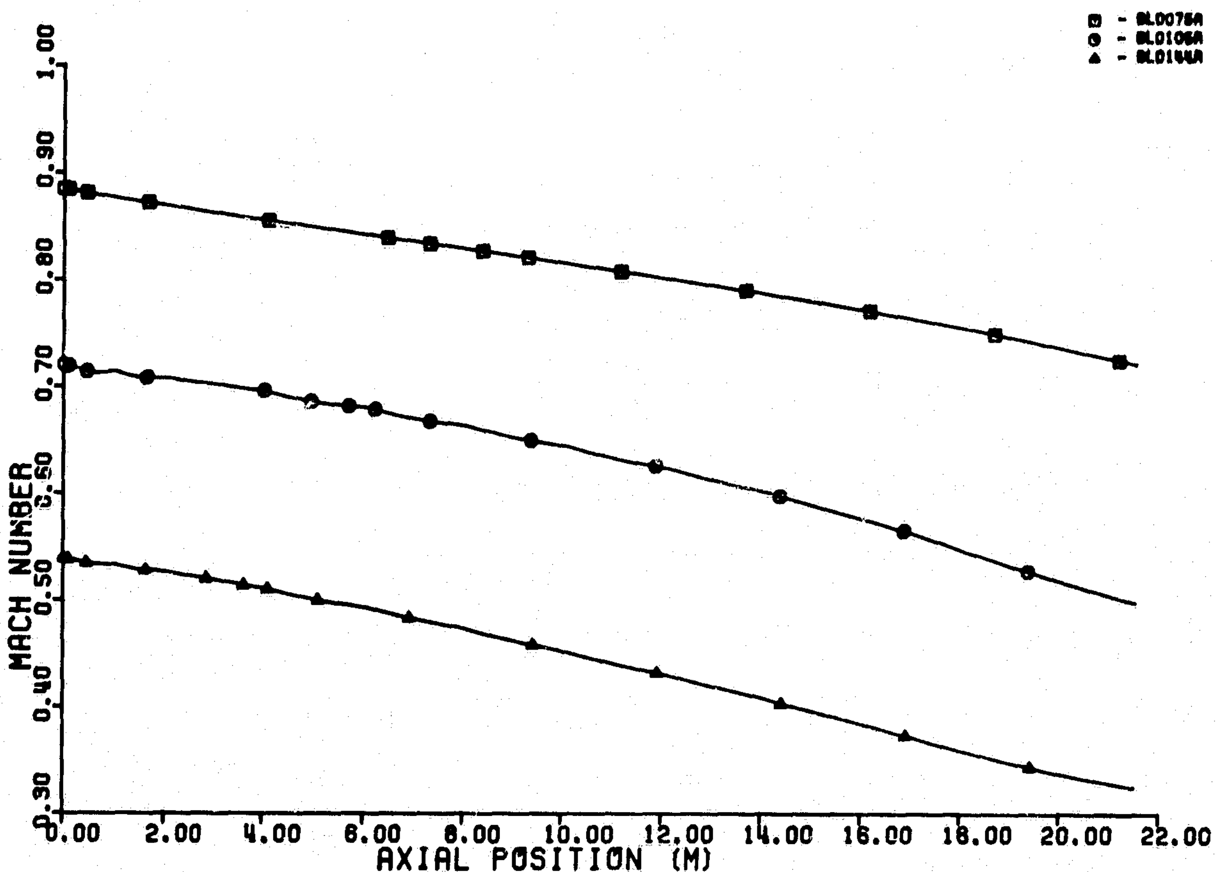

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Figure 3-12 Channel Mach Number Distribution

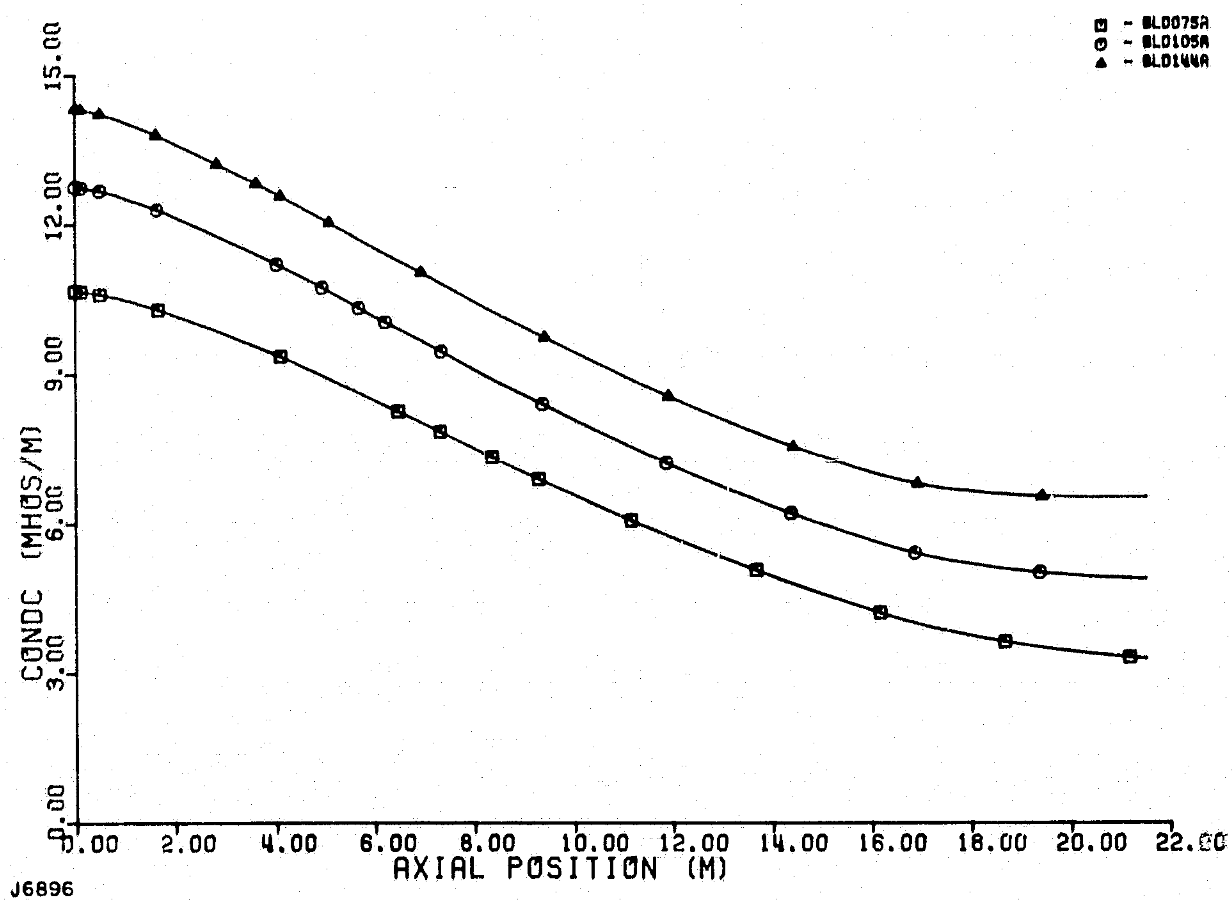

Figure 3-13 Plasma Electrical Conductivity Distribution

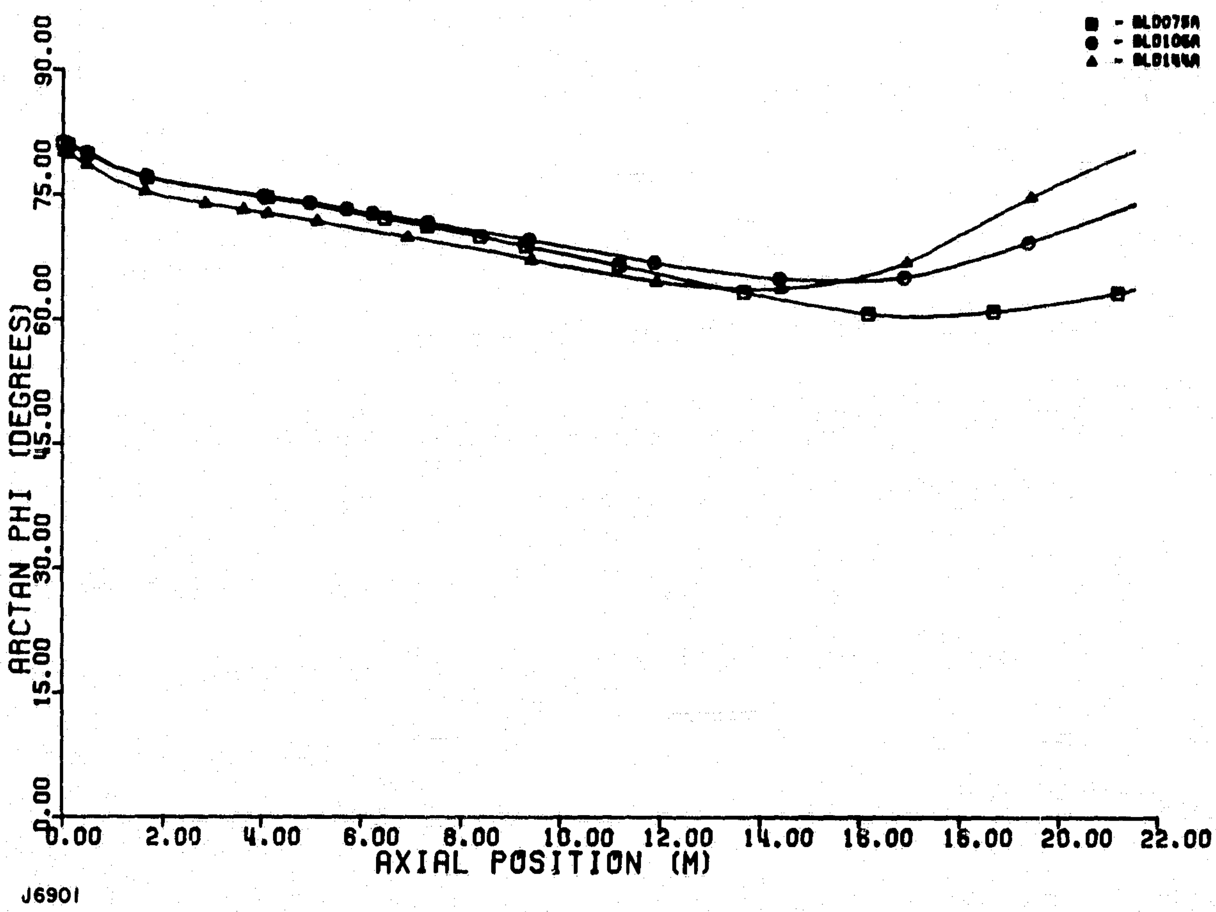

Figure 3-14 Equi-Potential Surface Angle Distribution

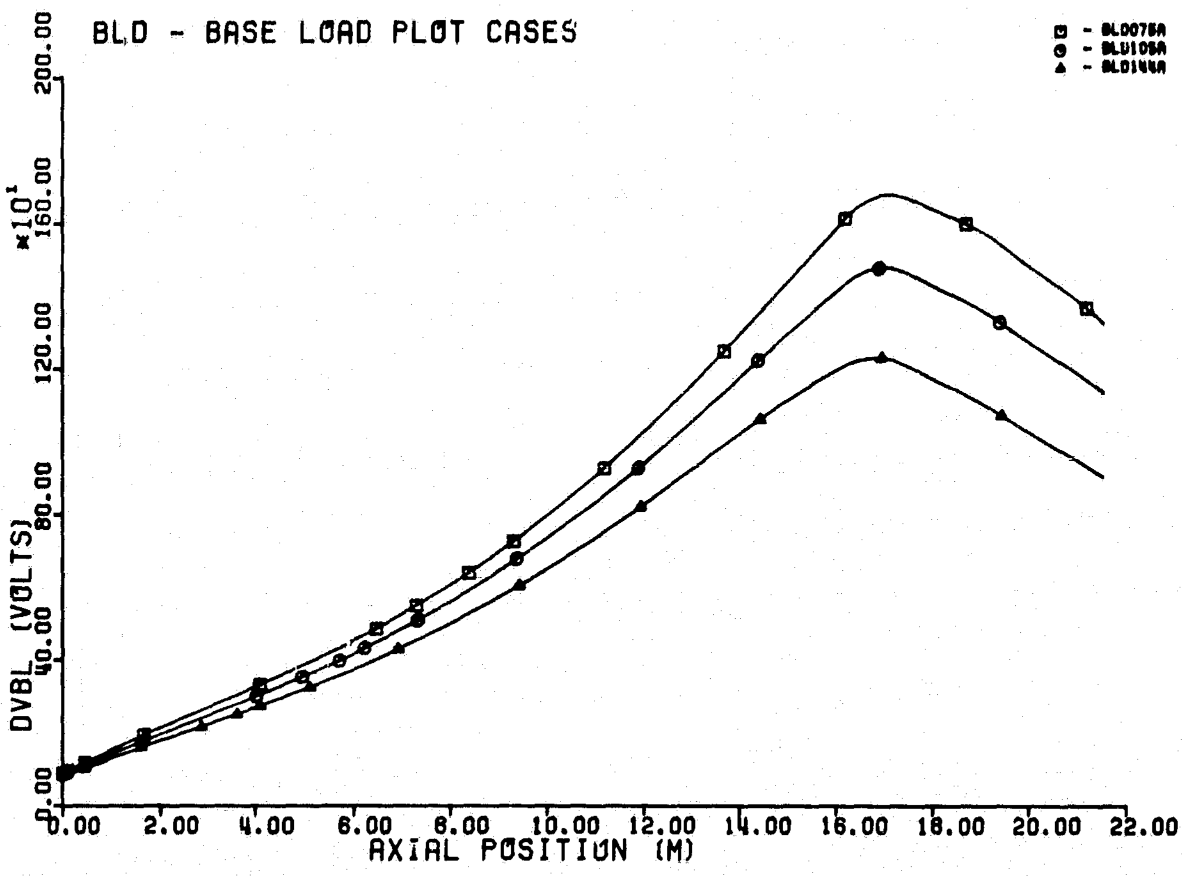

Figure 3-14a Electrode Voltage Drop Distribution

3.1.2 MHD Channel Mechanical Design

3.1.2.1 Design Basis

The mechanical design selected for the commercial MHD generator channel is essentially an extension of the channel design which has successfully logged several thousand hours of test operation in the Avco Mk VI and Mk VII Component Development Program. In essence, this consists of a rugged "box-type" structure made from reinforced fiberglass-epoxy material. This insulating box provides the principal structure support for the channel and also serves as a pressure vessel to contain the high-temperature gases in the channel. The individual metallic and insulating elements which constitute the gas-side surfaces of the channel are mounted directly to the insulating sidewalls. This type of construction has the following advantages:

a) The channel assembly consists of individual separable walls. This facilitates initial fabrication and assembly and makes subsequent repair or replacement of individual elements a relatively simple and inexpensive operation.

b) Gas sealing and interelectrode insulating functions are separate and independent. This minimizes the risk of high-temperature gas leakage from the channel in the event of interelectrode breakdown and arcing.

c) There are only four main gas seals along the corners of the box where the four individual walls are joined and these are located in a relatively low-temperature region thus further minimizing the risk of plasma leakage.

d) Permits the use of non current-carrying sidewalls, thus eliminating severe current concentrations at the corners and the potential damage which is generally a consequence of this condition.

e) This type of construction is verified by extensive experience with experimental MHD generator channels. Channels employing this type of construction will also be used in the CDIF test program and will provide additional operating experience. The physical properties of all the materials employed in the fabrication of the channel are well documented so that all the necessary detailed engineering design calculations can be performed with a high level of confidence.

The channel geometric dimensions are established from the channel performance calculations discussed in subsection 3.1.1. As previously shown in Figure 3-6 the distance between channel walls varies nearly uniformly from inlet to exit. The channel is divided into a number of sections so that the channel outer walls can be plane for each section and the inner walls contoured to give the required flow area by slight variations in the height of the insulator and electrode elements attached to the walls. Dividing the channel into a number of relatively short sections will also facilitate initial fabrication and assembly of the channel and simplify subsequent repair or replacement of the individual sections.

For this conceptual design, channel cooling was accomplished by employing low pressure and low temperature boiler feedwater to keep within the present state of the art in channel technology.

Electrical isolation of the elements of the cooling system is accomplished by using fabric-reinforced rubber hose rated for the appropriate pressure level. The rigid main supply lines are isolated by placing interflange insulators at appropriate locations.

3.1.2.2 Channel Gas Side Elements

The individual elements of the channel walls which are exposed to the seed and slag-laden high-temperature and high-velocity plasma must be designed to operate in a hostile environment with interrelated electrical, chemical, thermal, and mechanical stresses imposed upon the wall elements. The conceptual designs presented here are to a large degree based upon the experience gained from several years of MHD channel development at AERL.

3.1.2.3 Electrode Walls

The electrode walls are designed to be covered with a uniform slag layer. The slag layer is assumed to be $\sim$ 2-3 mm thick and to have a surface temperature of $\sim 1800^{\circ}K$. This slag layer reduces wall heat loss and also provides a renewable interface between the plasma and wall elements to minimize erosion damage.

The electrodes are fabricated from OFHC copper extrusions with an integral cooling passage. OFHC copper is selected as the base material for the electrodes primarily because of its high thermal diffusivity. The electrode design provides the following advantages:

1. Low temperature decreases anodic oxidation rates.
2. High diffusivity minimizes arc damage.
3. High diffusivity promotes low-temperature interelectrode gaps to increase breakdown strength.
4. Low-temperature copper is effective in quenching anode interelectrode arcs.
5. Small thermal gradients reduce thermal stresses.

As shown in Figure 3-15, the electrode elements are rectangular segments with a 0.250" diameter cooling passage. Brazed plugs are used to blank the ends of the cooling passage and holes are machined at each end to which brass tubes are inserted to provide inlet and outlet passages. Threaded stainless steel studs are provided at appropriate points to secure the electrode to the insulating wall and copper studs are used to provide a connection for the electrical power cable.

The electrodes are 0.625" wide which with a 0.075" thick insulator yields an electrode pitch of 0.70". This results in an interelectrode voltage of slightly more than 30 V in the region of maximum electric field towards the exit of the channel. This value of interelectrode voltage has been experimentally demonstrated to be below that which can be withstood by the BN insulator which separates the electrodes.

The nominal height of the electrode is one inch, however, the actual height will vary slightly from this nominal value to provide the required internal wall contour. The total electrode length will vary from 91 cm at the channel inlet to 249 cm at the channel exit. Transverse segmentation can be provided, if necessary, by cutting the electrode to the appropriate length and placing insulators between adjacent segments. The cooling circuit for each segment can be supplied by an integral internal or external manifold arrangement depending on the final electrode configuration selected.

A typical channel electrode wall cross section is shown in the schematic drawing in Figure 3-16. This illustrates how all the components which make up the wall are arranged. Boron Nitride strips typically 0.075" thick are placed between electrodes to provide interelectrode insulation. This material is chosen because of its excellent performance demonstrated in extensive channel testing at AERL. In addition to being an effective electrical insulator, it possesses high thermal conductivity which provides good resistance to thermal shock. Groups of electrodes are compressed with insulating tie rods to provide positive thermal contact between the electrodes and insulating strips. This avoids transmitting excessive heat to the plastic backing wall. Also, a mica mat is placed between the G-11 sidewalls and the electrode and insulator elements. This serves as a thermal barrier and also as a sacrificial element which delaminates readily when the channel wall is disassembled for repair or refurbishing. A layer of silicone rubber is also applied to the mica to provide a barrier against seed or gas penetration to the sidewalls.

Because BN is not readily wetted by slag, it is difficult to form a continuous slag layer over the electrode wall if the insulator extends the full height of the electrode. Therefore, the BN insultor is recessed and the resulting groove is filled with castable alumina. This provides an effective slag attachment area and

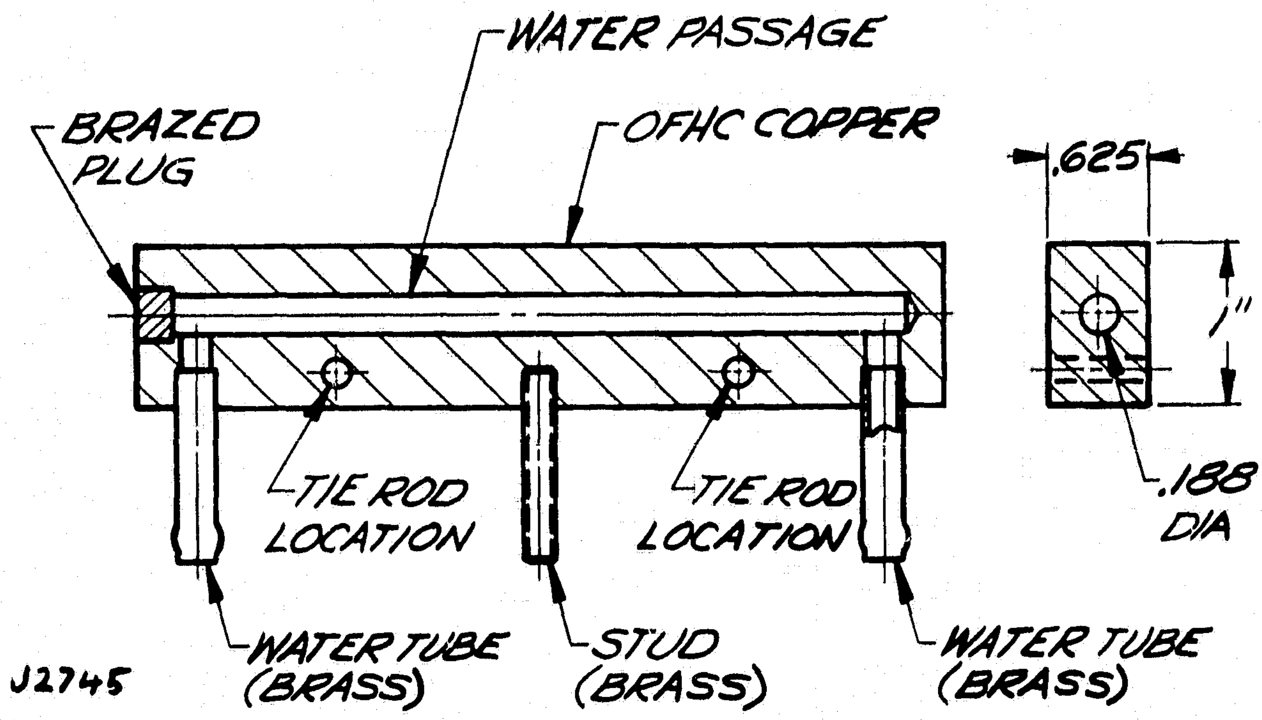

Figure 3-15 Electrode Structure (Schematic)

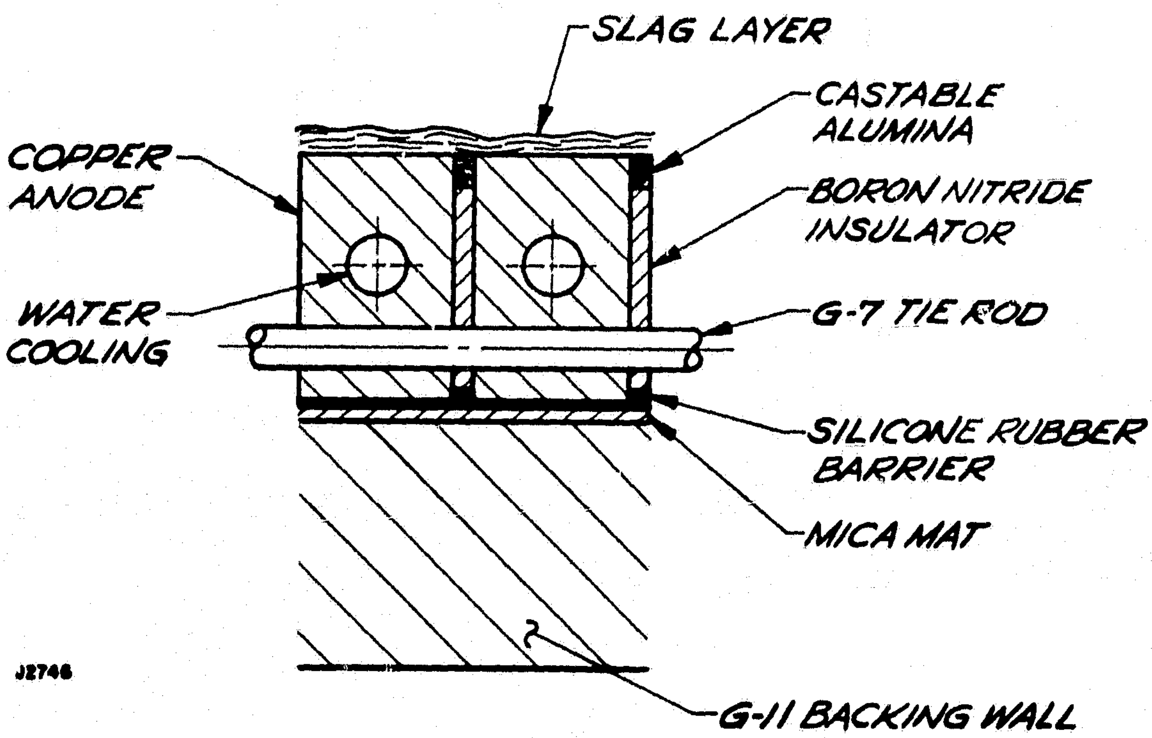

Figure 3-16 Electrode Assembly (Schematic)

enhances the formation of a stable slag layer. The alumina also protects the BN from thermal shock resulting from possible arcing and reduces the heat loading to the insulator.

3.1.2.4 Electrode Gas Side Surface

In this design effort, electrode designs which have provided the best long term performance to date were used. In the case of the cathodes, a 1/8-inch thick W-Cu cap is applied on the gas side surface. For the anodes, a 10 mil platinum cap is used. The use of Pt greatly increases the cost of the channel (~ 55% of total channel cost at currently quoted Pt price) but experience to date necessitates its use for required channel duration.

3.1.2.5 Channel Insulating Walls

The insulating sidewalls of the channel must be capable of withstanding a high electric field which is a function of the transverse and axial voltage gradients, Ey and Ex. These are indicated with the other channel characteristics in Figure 3-6. The orientation and magnitude of the electric field varies with axial position in the channel and channel load.

For this conceptual design effort the insulating sidewalls were considered to be made from short bar segments. A peg wall design concept represents an alternate insulating wall design. This type of wall has been used successfully in experimental MHD generators, but was not selected here because it requires a very large number of individual elements and further scale-up design considerations. The final selection of channel electrode and wall designs will be based on further channel development and test results.

The construction of the segmented bar sidewall as shown by the detail drawing in Figure 3-17 is very similar to that employed for the electrode walls except for the orientation and the length of the bars. The bars are placed on the sidewall so as to be closely aligned with the equi-potential field as established by arctan Ey/Ex. Because this angle changes somewhat along the length of the channel and with load, the bars are made sufficiently short to avoid excessive potential difference between adjacent bars and between the ends of bars in the same row. A detailed design analysis of the sidewall bars was beyond the scope of this study.

A summary of the materials used in the fabrication of the channel is given in Table 3-10.

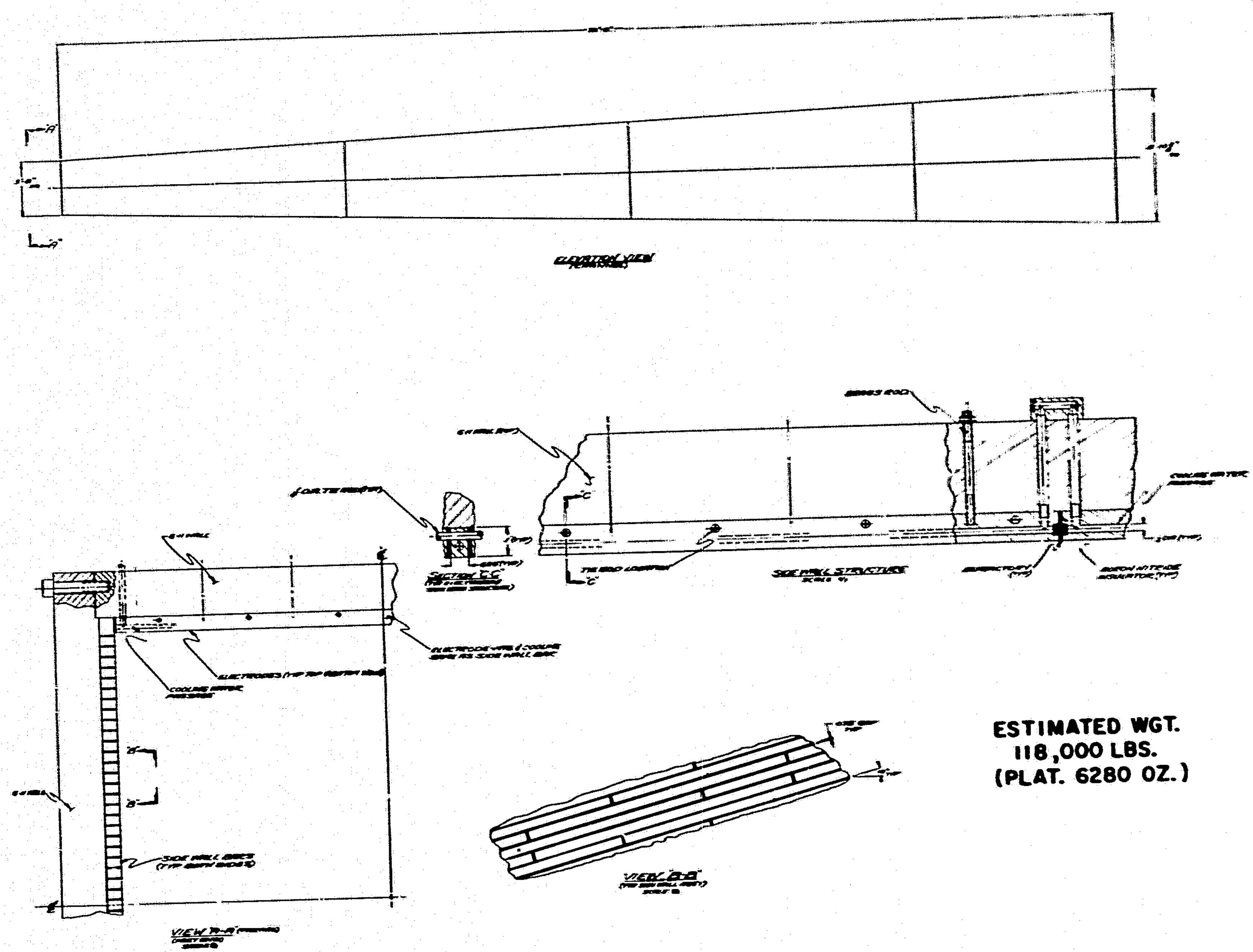

Figure 3-17 MHD Generator Channel

TABLE 3-10

CHANNEL WEIGHT SUMMARY

Copper Extrusions	65,000 lbs
G-11 Sidewalls	43,500
Tungsten-Copper	3,200
BN Insulators	1,950
Fasteners, Misc. Hardware	7,500
	121,150 lbs

(Platinum - 6280 oz.)

3.1.2.6 Magnet Warm Bore

Efficient utilization of the magnet warm bore volume is important because it effects the overall magnet size and, hence, the cost of the magnet. Therefore efforts were made to efficiently utilize the clearance volume between the magnet warm bore tube and the channel. This requires that the power cables, cooling lines, support members and transport mechanism be selected and arranged so as to minimize space. In essence, it is a complex packaging problem. It is an area which requires futher major attention and coordinated engineering development work between the channel and magnet designers.

The magnet warm bore size was determined by calculating the space required for the necessary coolant lines and power cables which must be provided. It was assumed that the power cables and coolant lines for the forward third of the channel would exit the magnet bore through the upstream end, and all the remaining through the downstream end. The size and number of the power cables was determined from the number of electrode pairs in each section and the average channel electrical characteristics. A packing factor of 25 percent was assigned to the cable bundles to provide for ohmic heating dissipation. The size of the coolant lines was determined from the flow rate and reasonable velocity of the coolant water. Optimization was not performed.

It was determined that 12" clearance space on all sides between the channel and magnet warm bore tube would accomodate all the piping, wiring and channel support and transport mechanism. This results in a magnet volume utilization factor of ~ 0.50 where this term is defined as the ratio between effective channel gas volume and magnet warm bore volume.

3.1.3 Loading and Consolidation Circuitry

For a large scale MHD generator, circuits interfacing with both the channel and the load inverters are contemplated. These circuits serve the dual function of controlling individual electrode currents, and consolidating power from several electrodes, each at a different potential, for conversion by a single inverter. The ultimate configuration of these control and consolidation networks will be determined by considerations of cost, efficiency, reliability, flexibility and effectiveness.

A successful control circuit must satisfy the following criteria: (1) the circuit must be essentially nondissipative; (2) it must not short the Hall field in the generator; (3) it must not induce destructive arcing along the channel wall; and (4) it must provide control over individual electrode currents so that the channel can be trimmed (i.e., the process of adjusting the electrical loading of the channel to achieve a desired electrical and gas-dynamic operating condition).

In this conceptual design a diagonal type channel with five terminal load connections in parallel was assumed. The circuitry with data for this five terminal diagonal load connection is shown in Figure 3-18. A simpler two terminal load connection can be considered to provide the same efficiency as a five terminal load connection at nomial design load, but more uncertainties remain regarding part load performance. Channel loading and controls is an area which requires further investigation and development work before a practical optimum design for commercial operation can be determined.

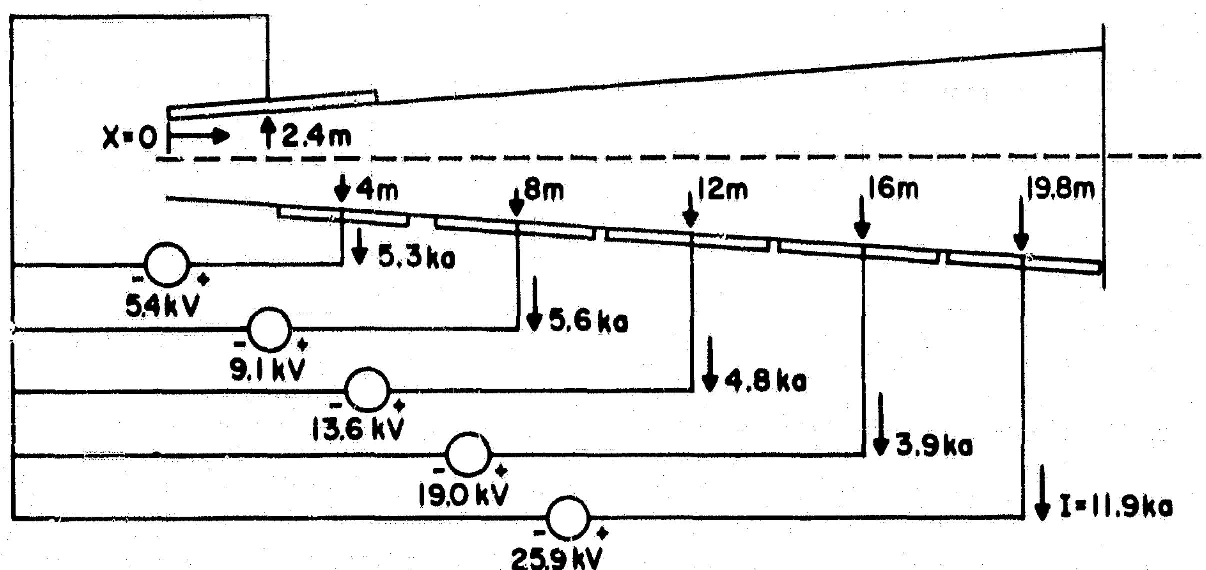

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Figure 3-18 Five Terminal Diagonal Load Connection

3.2 SUPERCONDUCTING MAGNET

The design and cost analyses of the superconducting magnet were a follow-on to the parametric analyses of Task I. They were all based on the magnet design concept previously developed in the Conceptual Design of the ETF (Reference 2).

Scaling from the ETF size to the large commercial size considered here was possible because the magnetic field in both magnets was about the same (~ 6 T) and the basic design principles used in estimating the cost, weight and dimensions of the magnet were applicable for both sizes. The dimensions of the warm bore were based on the channel design developed. Particular attention was given in the design of the magnet to matching it with the channel so as to achieve a compact and economic design with an effective utilization of the magnet bore volume. This is very important because the magnet represents a significant portion of the cost of an MHD power system.

It is mentioned that the ETF magnet conceptual design which formed the basis for the magnet design in this study represented a significant departure from earlier conceptual designs that had been made for both pilot scale and large-scale baseload MHD power plants. This new design concept offers the potential of a very significant reduction in the amount of labor and cost required for magnet construction and assembly.

In the current concept the magnet has been designed with modules which are small enough to be shipped to the site ready for assembly. Small size and light weight were not, in themselves, primary design objectives, but capital cost, and the need to conserve helium were considered important. The magnet design objectives were:

- All components (with the exception of the vacuum tank) should be of modular construction and of a size that permits shipment to the power plant site.

- The most difficult and the largest single item to be shipped is the winding. Therefore, the magnet design was aimed at shop prefabrication of the winding and for shipment of the winding in individual containers ready for final assembly.

- The Lorentz forces originating within the windings should be transferred via substructure within the winding container, to the container walls and then to a suitable superstructure.

- All forces except the weight should be contained within the support structure and not reacted either against the vacuum tank walls or the bore tube.

- The conductor splices should be brought to a separate splice box located in the low field region of the winding container where the individual conductor ends and winding instrumentation could be accessible for inspection or repair.

- All pressure and vacuum seals whether on the vacuum tank or on the helium container should be independent of the load transferring elements. In this way, the containers may be opened and resealed, without interferring with the structural integrity of the part.

- The vacuum tank would have a single wall with an $80^{O}K$ baffle and superinsulation. There would be removable covers that are large enough to permit magnet assembly or disassembly within the main frame of the tank.

- Emphasis on ease of assembly, disassembly, inspection, repair and maintenance.

In connection with the last item above, it is pointed out that provision for rapid replacement, repair and maintenance of the channel also is of key importance in magnet design. This is discussed further in Section 7.0.

Superconducting magnet design data with dimensions and weights are summarized in Table 3-11. The magnet size and the internal forces were established with a computer simulation of the electrical windings. This contained 48 current elements positioned to represent a 45^{O} rectangular saddle magnet. Also, two different grades of conductor were described in the winding, leading to efficient use of the winding space and conductor material.

Figure 3-19 shows the profile of the magnet field on the central axis of the channel.

A plan view of the magnet, is shown in Figure 3-20. Figure 3-21 is a cross-section view of the magnet. The magnet is housed in a cylindrical vacuum tank which has two large covers. It is assembled on its supports inside the tank. The central part of the tank is notched at the inlet side so that the combustor may be brought close to the channel. The magnet windings are housed in sealed helium containers which have a 45^{O} rectangular saddle shape. The principal direction of the magnet field is horizontal.

TABLE 3-11

SUPERCONDUCTING MAGNET DESIGN DATA

Superconductor		Copper Stabilized NbTi
Active Channel Length	m	21.5
Inlet Warm Bore Dim. (Square)	m	1.73
Outlet Warm Bore Dim. (Square)	m	3.30
Magnetic Field	Tesla	~6
Overall Height	m	18.0
Overall Length	m	26.5
Stored Energy	10^9 J	6.3
Winding Assembly Weight	ton (met)	2003.
Structure Assembly Weight	ton (met)	1937.
Tank Weight	ton (met)	1352.
Total Weight Including Refrigeration and Cryogenic Storage	ton (met)	5334.

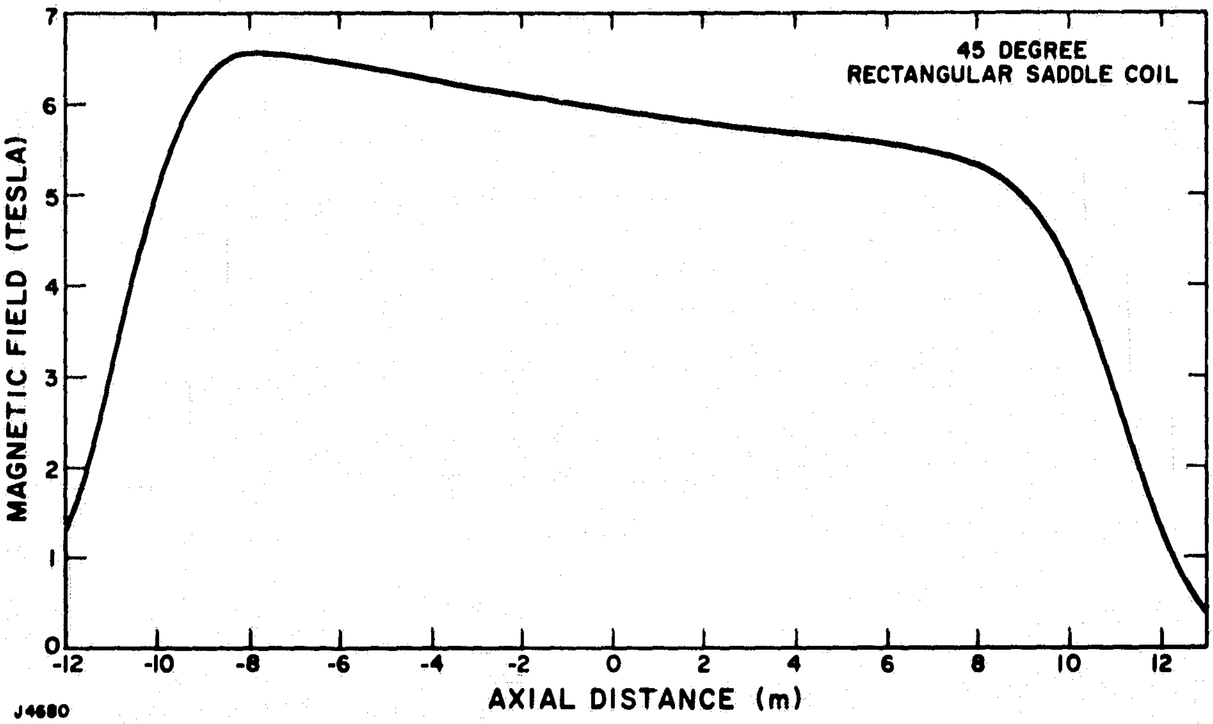

Figure 3-19 Magnetic Field Profile

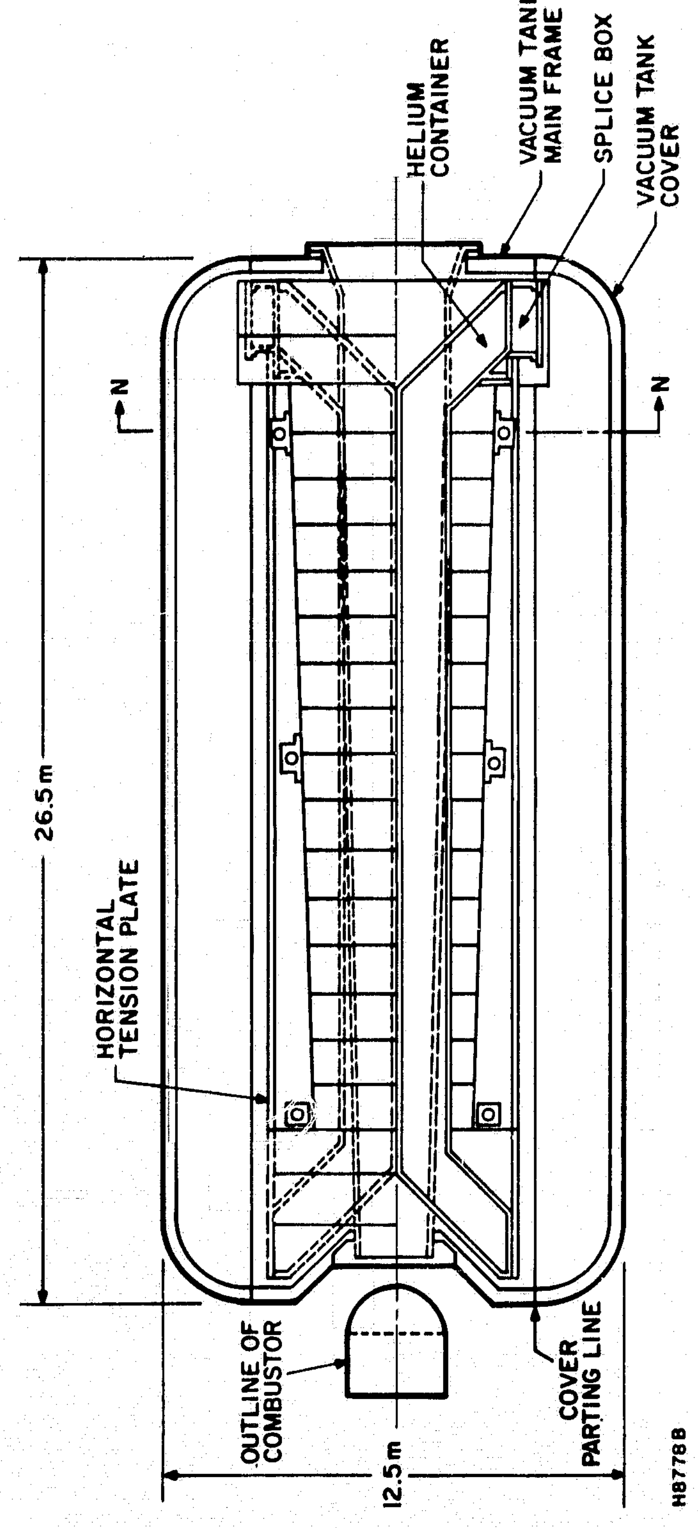

Figure 3-20   Magnet Plan View

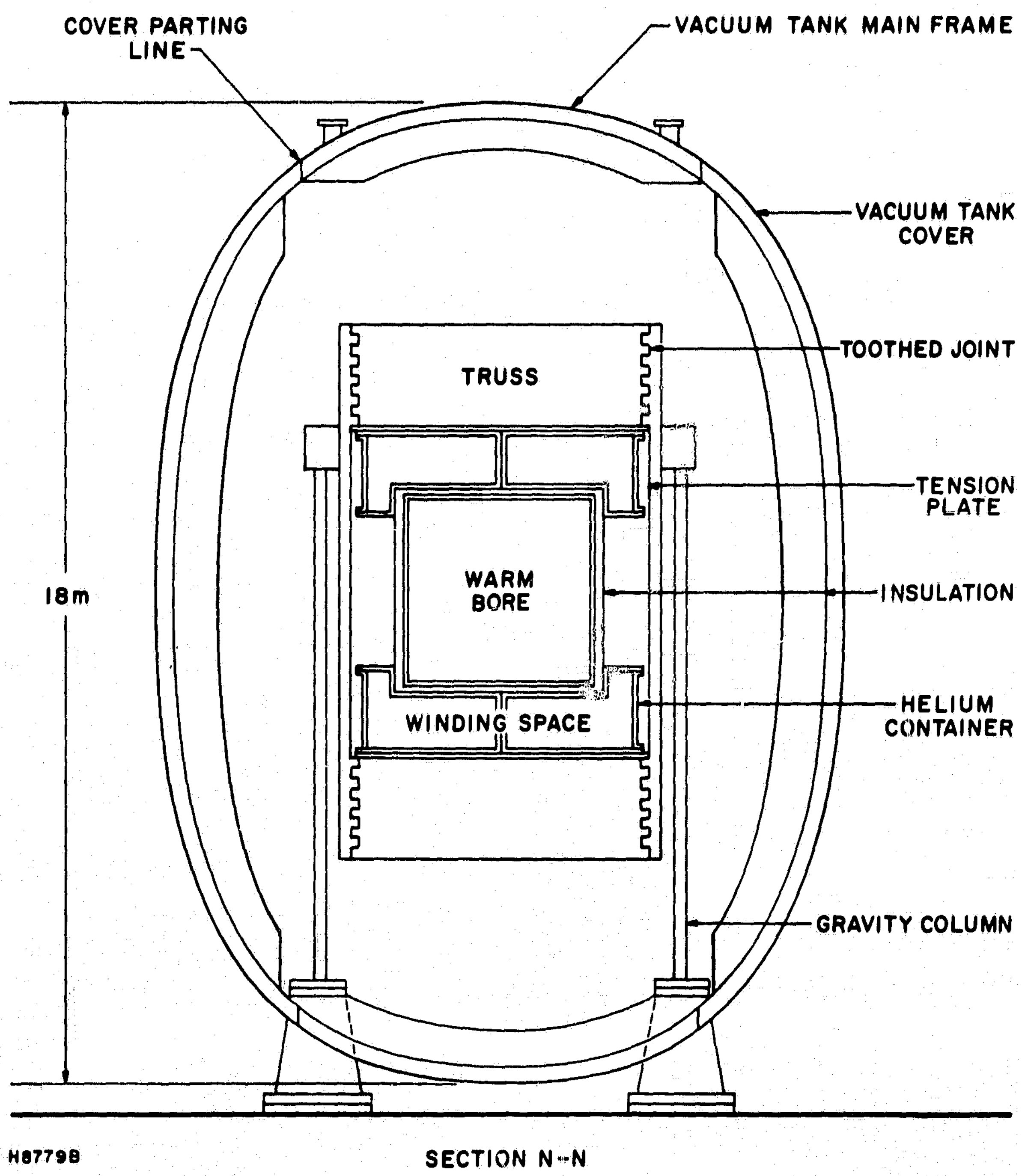

Figure 3-21 Magnet Cross Section

The force containment structure, consisting of trusses and the tension plates, is assembled from individual modules built up from flat aluminum plates without welding. In the mating faces of the trusses and tension plates, teeth are cut to transfer forces. As a result of this new design concept, significant savings in projected magnet costs are expected compared to other magnet designs that require extensive manufacturing and assembly at the power plant site.

The warm bore area is square to match the channel cross-section geometry.

The estimated costs of this commercial sized magnet was developed utilizing cost data from the ETF magnet obtained in 1977 and appropriate scaling. The estimated costs were subsequently escalated with an annual rate of 6 1/2% to mid-1978 dollars.

Table 3-12 shows a comparison of pertinent data of magnets of different sizes designed for the CDIF, ETF (modified design) and Early Commercial Plant here, respectively. All magnets are designed for about the same magnetic field of 6 T. The ratio of weights between the ETF size and CDIF size magnets is about 6 and between the commercial size and modified ETF size about 4. The corresponding stored energy ratios are about 10 and 4.5, respectively.

TABLE 3-12

COMPARISON OF MHD MAGNETS

		CDIF*	ETF**	EARLY*** COMM'L
Peak Magnetic Field	T	6.	6.	6.5
Warm Bore Area, Average,	m^2	0.86	3.57	6.33
Effective Length of Field,	m	3.	9.	21.5
Stored Energy,	10^9 J	0.18	1.7	6.3
Weight,	10^6 kg	0.18	1.1	5.3
Length, Overall,	m	8.9	14.9	26.5
Height, Overall,	m	4.8	11.0	12.5
Method of Construction		One Piece Sealed Unit	Modular	Modular
Repairability		Difficult	Easy	Easy
Copper for Conductor With Niob. Titan. Superconductor		Yes	Yes	Yes
Full Cryostatic Stability		Yes	Yes	Yes

* Gen. Elec. Preliminary Design

** Avco Conceptual Design (Modified ETF)

*** Avco Conceptual Design

3.3 COAL COMBUSTOR

3.3.1 General

The combustor design concept selected for this study is a single-stage configuration which is under development at AERL. The principal reasons for selecting a single-stage design are:

1. Relatively low heat loss.

2. Effective carbon utilization resulting from rapid particle heating and high volatile yield.

3. Mechanical simplicity.

4. Simplicity of operating controls.

The combustor assembly shown on the drawing in Figure 3-22 consists of two main sections: a cylindrical downward firing chamber where the combustion and slag separation processes are performed, and a side-mounted horizontal duct where the seed is introduced and through which the high-temperature plasma is delivered to the MHD channel. Addition of the seed to the combustion gases after the slag has been removed results in a minimal loss of seed to the discarded slag.

It is emphasized that serious efforts in coal combustion development work only recently have been undertaken, and that much further development work is required before a commercial MHD coal combustor can be defined. The coal combustor design concept and features presented here must be subjected to intensive testing and evaluation to determine their viability.

3.3.2 Mechanical Design

The combustor is designed to operate at a pressure level of ~ 8.5 atm. The oxidizer consisting of oxygen enriched air is preheated to a nominal temperature of 1200°F. The fuel is Montana subbituminous coal pulverized to 70% through 200 mesh and dried to a moisture content of 5% before firing. An air/fuel equivalence ratio of 0.9 is employed for NO_x emisssion control.

The coal and oxidizer are introduced through eight equally spaced coaxial injectors located near the top of the combustor. This type of fuel/oxidizer injection has been demonstrated to be an efficient and reliable means to achieve rapid and intimate mixing of the fuel particles with the high temperature oxidizer. It results in a high release of volatiles and efficient utilization of the carbon contained in the fuel. A toroidal shaped inlet manifold supplies the oxidizer to the individual injectors.

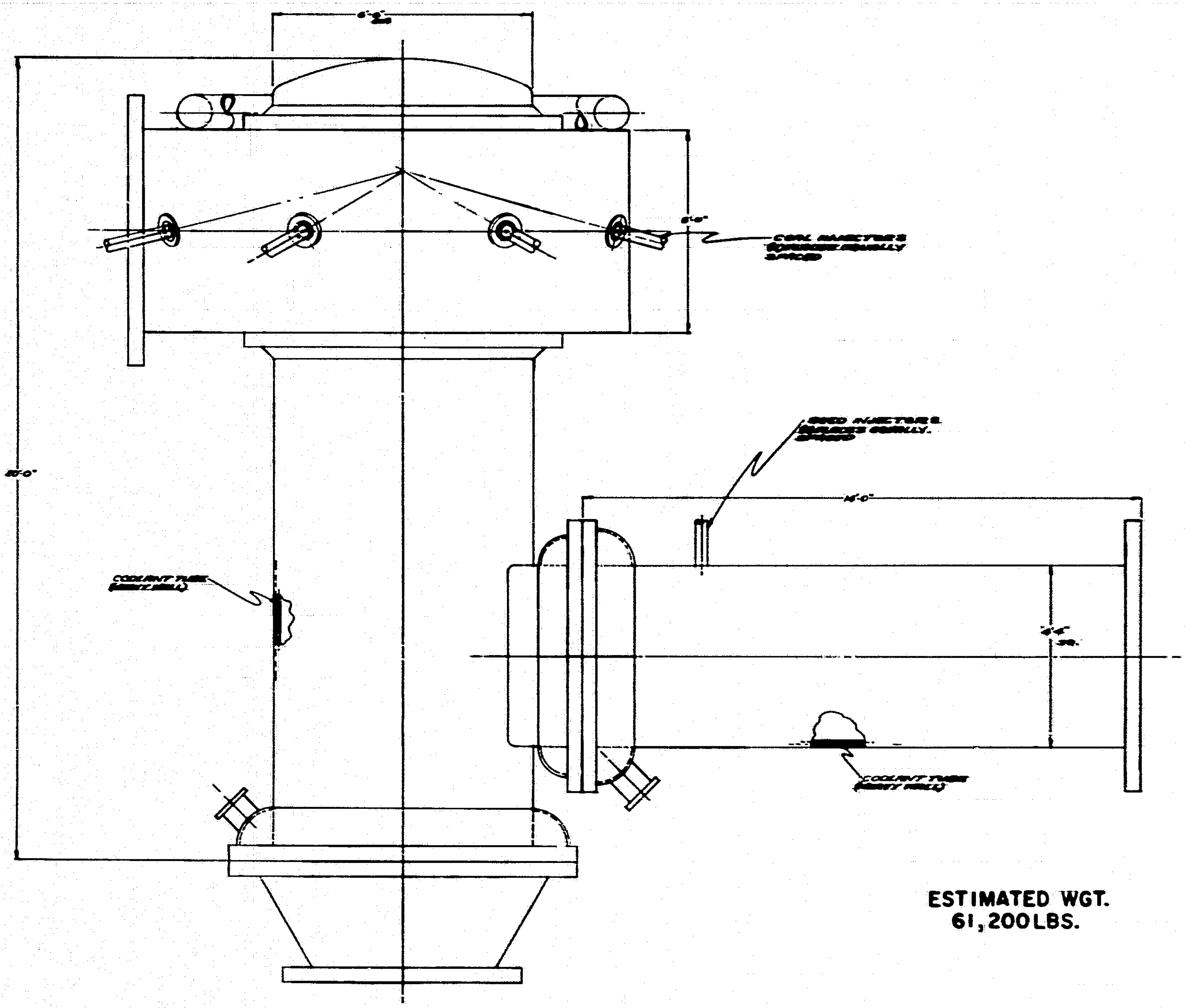

Figure 3-22 Coal Combustor

The injectors are equally spaced around the periphery of the combustor and directed radially at an angle of 30° above the horizontal plane. This orientation has been selected to provide optimum utilization of injection momentum, homogeneity of combustion products and separation of slag. The flow field produces a toroidal vortex flow pattern near the combustor dome which drives the slag particles to the water cooled walls. Additional baffles interrupt slag particles which were not initially separated from the flow and direct them toward the wall. Thickness of the slag layer which forms on the wall will be governed by backing wall temperature, slag thermal conductivity, local heat flux, slag viscosity and the viscous and gravitational forces acting upon the slag. The outer surface layer of liquid slag which forms flows down the combustor walls to the slag tap located at the bottom of the combustor. A slag rejection of 80% of total coal ash has been assumed. This has been experimentally achieved with a small-scale single stage combustor.

The overall size of the combustor was determined on the basis of necessary residence time to ensure complete burnout of the fuel and selection of a reasonable value for L/D ratio. The combustor was designed for a bulk residence time of 40 ms. This is in line with results from experimental coal combustion work for the combustion conditions and coal particle size (70% through 200 mesh) considered. A combustor L/D ratio of 3 was selected considering combustor flow fields, flow gas velocity, heat loss and slag rejection. The resulting combustion chamber is 6.5 ft in diameter and 20 ft long.

The combustion products exit the combustor through a horizontal duct which is 4 ft square and 14 ft long. The dimensions of the duct were essentially governed by the channel inlet geometry and the size of the SC magnet dewar which determined how close the combustor could be located to the channel inlet. Seed is injected near the inlet of the duct through eight nozzle type injectors which are mounted transverse to the flow. The seed is in slurry form and consists of liquid potassium formate and solid potassium sulfate particles. The injector nozzles are located to provide uniform distribution of the seed in the high temperature combustion gases. Residence time of the gases in the duct from the plane of seed injection to the nozzle inlet is calculated to be $\sim$17 ms. This is considered ample time to complete seed vaporization according to experimental work conducted.

A breakdown of the materials used in the fabrication of the combustor is given in Table 3-13.

TABLE 3-13

COMBUSTOR WEIGHT SUMMARY

Stainless Steel Plate	24,000 lbs
Inconel 600 Tubing	17,500
Flanges and Manifolds	10,000
Refractory	8,500
Fuel and Seed Injectors	1,200
	61,200 lbs

3.3.3 Combustor Cooling

Rough calculations of the convective and radiative heat loss from the gas were conducted with simplified assumptions. Particle radiation was omitted in these analyses because of the uncertainty and complexity involved.

The total heat loss was computed to be 54.5 MW at nominal operating conditions. It corresponds to an average specific heat loss per unit of combustor surface area of about 300,000 Btu/ft^2/hr. This value is in line with that expected from operation of smaller experimental coal combustors taking into account the higher radiant heat loss from the commercial combustor because of its larger size.

The burner is cooled by high pressure boiler feed water which enters the burner at 600^{o}F. The total flow rate is 1180 lb/sec and the bulk temperature rise is 30^{o}F. The cooling tubes will be heavy wall Inconel 600 tubes which will be welded to the outer shell of the combustor. Milled slots at the ends of the tubes will provide for water flow into and out from the tubes from circumferential cooling water manifolds. The various inlet and outlet manifolds will be interconnected to provide a balanced heat load for the entire combustor cooling system. The lines from the individual manifolds will be tied to a single supply and discharge header so that only a single electrical isolation segment will have to be provided for each of these lines.

3.3.4 Electrical Isolation

Because the combustor is directly connected to the upstream end of the MHD generator, it is subjected to the full axial Hall potential developed by the generator. Consequently, it is necessary to provide electrical isolation for all combustor support members, the slag collection system, and the feed lines supplying oxidizer, fuel, seed and cooling water.

Isolation of the structural support members is achieved by placing a section of dielectric material such as G-10 fiberglass epoxy between flanges in the support columns. This material has high compressive strength and a dielectric strength rating of ~ 400 V/mil. Therefore, an insulator of only a few inches in thickness will have the standoff capability several times the anticipated potential.

The oxidizer supply duct is isolated from the combustor by placing a section of G-10 between the flanges joining the supply duct and combustor. This insulator will have a protective layer of dense refractory on the gas side surface to protect it from the high-temperature gas stream.

Cooling water supply and discharge lines are isolated in the following manner: 1) an insulator made from polyimide resin will be placed between a pair of flanges to provide isolation between the sections of pipe, and 2) a thin layer of aluminum oxide or similar insulating material is flame sprayed to the inner wall of the pipe for a short distance to minimize current conduction through the deionized water. Polyimide was chosen as the insulator for this application because of its excellent mechanical and dielectric properties at elevated temperature. It must be protected from direct contact with the cooling water, however, and this is accomplished by bonding a thin ring of impervious ceramic to the inner surface of the insulator.

Isolation of the coal feed lines is accomplished by placing a section of Teflon-lined fabric-reinforced rubber hose in each of the individual injector lines. Previous tests have shown that a pulverized coal stream is not electrically conductive so that insulation has to be provided only in the transport line. The type of hose proposed has been used successfully for extended periods of time in the Mk VI development program.

Isolation of the seed feed lines is accomplished in a manner similar to that described for the coal feed lines. In this case, however, because the seed slurry is conductive, isolation of this flow must be provided for. This is discussed more fully in Section 3.10.5.

Electrical isolation of the combustor from the slag collection and removal system is accomplished by placing insulators between flanges connecting with the various elements of the system. Tests to determine the resistivity of a mixture of slag and partially deionized water have demonstrated that the resistivity is quite high. Consequently, electrical isolation of the slag handling system is quite practical. A more detailed description of this system is presented in subsection 3.12.2

3.4 MHD GENERATOR INLET NOZZLE

3.4.1 General Considerations

The primary function of the generator inlet nozzle is to accelerate the high-temperature gases produced in the burner to the velocity required at the channel inlet. Ideally the nozzle should be as short as possible to minimize heat transfer losses while maintaining an ample radius of curvature in the vicinity of the throat to avoid flow separation. An additional requirement for this application is the ability to form and sustain a uniform slag layer on the walls of the nozzle which will also carry over into the inlet of the channel. The slag layer serves the dual function of reducing wall heat loss and erosive damage to the walls from the particles entrained in the high velocity gas stream. Experimental work performed at AERL has demonstrated that a slag layer can be formed and sustained under these conditions by properly contouring the walls and providing means for slag attachment. This is accomplished by contouring the walls to provide large radii of curvature resulting in a low pressure gradient (dp/dx). The walls are also grooved and filled with a castable high-temperature ceramic such as zirconia to provide attachment points to which the slag can adhere.

3.4.2 Nozzle Design and Construction

In addition to providing the performance requirements discussed previously, the conceptual design developed for the nozzle was based on minimizing the cost for initial fabrication and subsequent repair or refurbishing.

To attain these objectives the nozzle is assembled from individual modules which are fabricated from conventional materials and formed by standard machining and fabrication techniques. A drawing of the nozzle assembly and some of the details of construction are shown on Figure 3-23. As indicated on the drawing, the nozzle is of square cross section and is made up of six separate modules. The modules consist of standard wide flange stainless steel channel members which povide the principal structural support. Nickel slab sections which are machined to the prescribed nozzle contour and which also contain the cooling water passages are mechanically fastened to the channel members. The 1/4 in. diameter cooling passages are machined in the slab sections by gun drilling. Grooves are also milled on the gas side surface of the slab which are subsequently filled with castable ceramic to serve as slag attachment areas.

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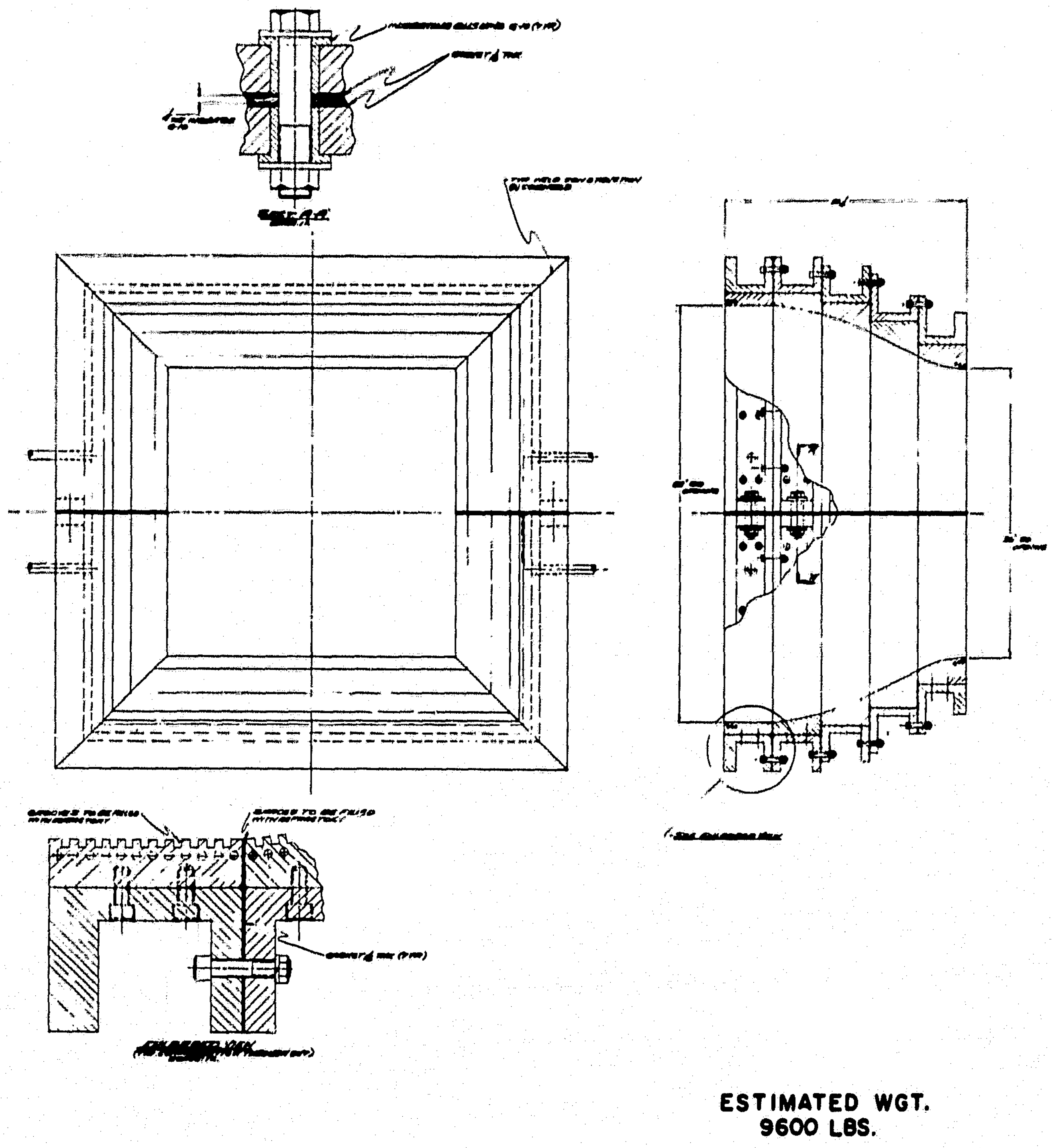

Figure 3-23 MHD Generator Inlet Nozzle

The nozzle is located in a region where the magnetic field is still sufficiently high to generate potentially damaging circulating currents in the nozzle. Therefore, the individual modules are split at the centerline and electrically isolated as shown by the detail on Figure 3-23.

3.4.3 Nozzle Cooling

The total heat load to the nozzle walls at full load design operating conditions has been calculated to be 6.15 MW. A wall slag layer at an average temperature of 1850°K was assumed. The average wall heat load is calculated as 180 W/cm^2 with a maximum of 240 W/cm^2 occurring in the region of the throat.

The heat load is absorbed by the high-pressure boiler feedwater which is circulated through the cooling passages at a high velocity to provide a high coefficient of heat transfer. At a velocity of 40 fps the quantity of water which will be circulated through the cooling system is calculated to be 130 pps. With an inlet temperature of 600°F, the heat absorbed by the water will result in an average temperature increase of 30°F. The system pressure drop is calculated to be of the order of 90 psi. Pressure in the cooling system will be maintained at a sufficiently high level to ensure that no local boiling will occur.

3.5 DIFFUSER AND TRANSITION SECTION

The primary function of the diffuser and transition section is to efficiently decelerate the high velocity gas exiting from the MHD generator channel. The diffuser must also provide acceptable gas entry conditions to the bottoming plant HRSR system. This requires that the gas be decelerated to a velocity of ~ 250 fps and 1 atm pressure as it enters the radiant furance.

The geometry selected for the diffuser is based upon the limited data available for diffuser performance with nonsymmetric flows having relatively thick boundary layers. The design therefore consists of a two dimensional diverging duct with plane walls having an exit to inlet ratio of 4.0 and a wall half-angle of 2.5°. A drawing of the proposed design is shown in Figure 3-24.

The diffuser consists of an outer pressure vessel fabricated from 1/4 in. steel plate with an inner membrane tube wall to provide the required wall cooling. I-beams are welded to the outer surface of the diffuser at 4 ft. intervals to provide sufficient rigidity and support. Because the upstream section of the diffuser is located in a region of relatively high magnetic field, this section will be made from nonmagnetic materials. The outer wall will be stainless steel and the cooling tubes will be Inconel 600 which is acceptable to the ASME Boiler Code Section 1. The remaining downstream sections of the diffuser as well as the transition section will be fabricated from conventional carbon steel.

Simplified calculations of the convective and radiant heat loss were conducted. Particle radiation was omitted because of the uncertainty and complexity involved. It was assumed that the diffuser walls were coated with a slag layer with a surface temperature of 1850°K. The total heat loss from the diffuser and transition section was calculated to be 52 MW. The wall cooling system was incorporated as part of the evaporative boiler circuit. The heat flux levels encountered in the walls of the diffuser and transition section make this feasible.

The linear thermal expansion of the channel and diffuser from ambient to full load operation is calculated to be slightly less than 5 in. This horizontal expansion along with a vertical downward thermal expansion of 5 in. in the radiant boiler must be accomodated by expansion joints in the flow train. A product search revealed that large stainless steel bellows-type expansion joints are available and suitable for this function. As shown in Figure 3-24, it is proposed that expansion joints be placed between the first and second sections and the second and third sections of the diffuser and also between the diffuser and transition section. The diffuser support structure incorporates rollers to accomodate the horizontal movement and hydraulic actuators to compensate for the vertical movement and to maintain proper alignment.

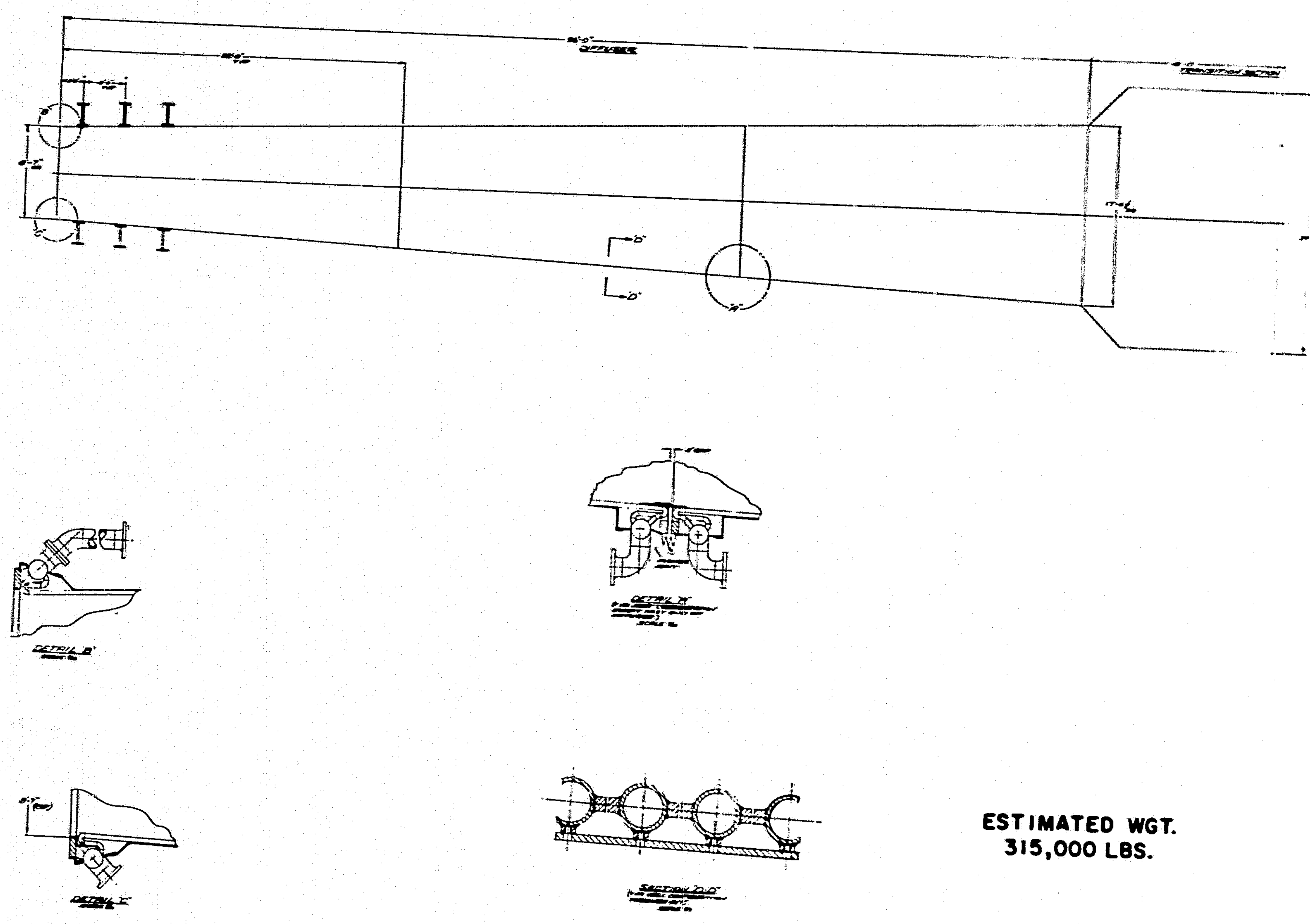

Figure 3-24 Diffuser and Transition Section

A weight summary of the primary materials used in the fabrication of the diffuser and transition section is given in Table 3-14.

TABLE 3-14

DIFFUSER AND TRANSITION SECTION WEIGHTS

Stainless Steel Plate	14,000 lbs
Carbon Steel Plate	91,000
Coolant Tubing	116,000
Coolant Manifolds	54,000
I-Beams	40,000
	315,000 lbs

3.6 HEAT RECOVERY, SEED RECOVERY SYSTEM (HRSR)

3.6.1 Steam Generator Including Intermediate Temperature Oxidizer Preheater, Low-Temperature, Secondary Air and Nitrogen Heaters and Economizer

MHD operation imposes unusual and severe design requirements on the steam generator. Because of this, the conceptual steam generator design is a significant departure from conventional utility boiler practice. The design evolved from considerations of the several MHD-related problems and it draws heavily from both utility and industrial recovery boiler state of the art. The steam generator is a balanced draft, controlled circulation multichamber unit, divided into:

- Radiant Slag Furnace
- Seed Condenser/Recovery Section
- Convective Section and Rear Pass
- Economizer Section
- Low-Temperature Air and Nitrogen Heaters

Key factors which influenced the steam generator design included:

1) NO$_x$ Control - A gas residence time of 2 sec above 2900^{o}F is provided in the primary radiant furnace by reducing the gas velocity through the furnace and by lining the chamber walls with refractory to reduce heat transfer and the gas cooling rate. This is expected to reduce the NO$_x$ concentration in the gas to a level well below NSPS standards.

2) Final Combustion - Provision for final and complete combustion of the substoichiometric MHD generator exhaust gas with the introduction of preheated secondary (or burnout) air to the gas entering the secondary furnace. Combustion is completed in the secondary furnace at temperatures sufficiently high to ensure complete oxidation of all unburned species and still below temperatures at which NO$_x$ can be reformed.

3) Seed Recovery - Economic operation necessitates efficient recovery of seed. Therefore, careful consideration was given to this problem in the design of the HRSR system. Potassium seed will react with sulfur in the gas to form potassium sulfate (K_2SO_4). The condensation temperature for K_2SO_4 in the gas is roughly 2300^{o}F and the

solidification temperature for K_2SO_4 is 1970°F. By maintaining the temperature of the gas relatively high in the primary slag furnace chamber and leaving this furnace at about 2900°F, the amount of seed lost in that chamber is minimized. The seed will condense and solidify as the gas is cooled in the secondary furnace. Some of the seed, together with some of the remaining fly-ash will deposit on the various walls and hanging surfaces throughout the secondary furnace (seed condenser), convective, and rear pass sections. Provision for recovery of this material is included in the steam generator design by incorporation of a large number of sootblowers. The seed material that is removed from the steam generator surfaces will be collected in dry bottom hoppers provided in these sections. It is expected that roughly one-quarter to one-third of the total solids entering the steam generator will be removed in this manner. Essentially all of the solids remaining in the gas after leaving the heat recovery sections will be removed in the gas cleanup device (electrostatic precipitator) before the gas is emitted to the stack. All of the collected material (from the ESP and hoppers) will be processed as necessary and recycled.

4) <u>Materials</u> - High metal temperatures are expected in some sections of the superheater, the reheater, and the oxidant preheater. High-temperature alloy steels are used in these sections. Operation in a reducing (substoichiometric) environment with potassium seed presents a potentially severe corrosion problem. The refractory selected for the slag furnace chamber is a high alumina ram material which offers both high-temperature protection and resistance to degradation from seed attack in a reducing atmosphere. The carbon steel waterwall tubes are aluminized to protect against corrosion in the seed condenser section and to provide added corrosion protection in the event of refractory cracking in the slag furnace.

5) <u>System Operating Conditions</u> - The design is based on steam turbine inlet conditions of 2500 psig/1000°F/1000°F. These steam conditions were considered preferable for early commercial MHD power plant applications to avoid possible associated operational complexities of supercritical conditions. The oxidant preheater is designed to heat the oxygen-enriched air to 1200°F. To assure even distribution throughout the complex steam generator waterwall circuitry, the design was based on the concept of controlled circulation. This permits smaller diameter and thinner tubes than required with natural circulation.

6) Fouling of Convective Sections - The presence of the seed material in the flue gas greatly increases the tendency towards fouling in the convective sections. The steam generator incorporates a number of design features that address this (anticipated) critical problem:

   a) The gas is cooled below the potassium sulfate melting point (1970°F) before entering any closely spaced tube assemblies.

   b) The seed condenser and convective sections are designed for low gas velocities and tube assemblies are vertically oriented (recovery boiler design practice for sodium sulfate-laden gases employs these approaches).

   c) Numerous rotary sootblowers are provided in the convective and rear pass sections to permit periodic cleaning of the assemblies.

3.6.1.1 HRSR System Design

Figure 3-25 is a key plan of the HRSR system, and Figure 3-26 shows the heat recovery steam generator system arrangement. The HRSR system consists of a multisection unit with conventional water and steam cooled walls. Data for the heat absorbing surfaces, including materials, are summarized in Table 3-15. Surface assembly details are presented in Table 3-16. Maximum expected metal temperatures in the high-temperature sections of the superheater, reheater and oxidant preheater are 1115°F, 1150°F and 1285°F, respectively.

3.6.1.2 Primary Radiant Slag Furnace

The slag furnace chamber is designed to cool the MHD gas in a controlled manner from about 3700°F to 2900°F. This chamber, 48' x 46.3' x 115', has a wet bottom and is lined with a high alumina refractory (1-4" thick). The gas enters horizontally through a single opening near the bottom of the chamber and moves upwards at a velocity of roughly 40 fps. The average uniform gas cooling rate will be less than 400°F/sec. This provides a gas dwell time of about 2 sec above 2900°F to ensure NO_x emission control. The waterwalls are formed by 2" OD SA 210 C carbon steel tubes fusion welded on 2-1/2" centers, with aluminizing on the furnace side for corrosion protection.

Six oil guns (rated at a total output of 1700 x 10^6 Btu/hr) are located in the lower region of the slag furnace chamber. These guns are used to provide sufficient heat input to the chamber during startup and shutdown to prevent excessive temperature gradients. The oil guns can also be used independently to start up and

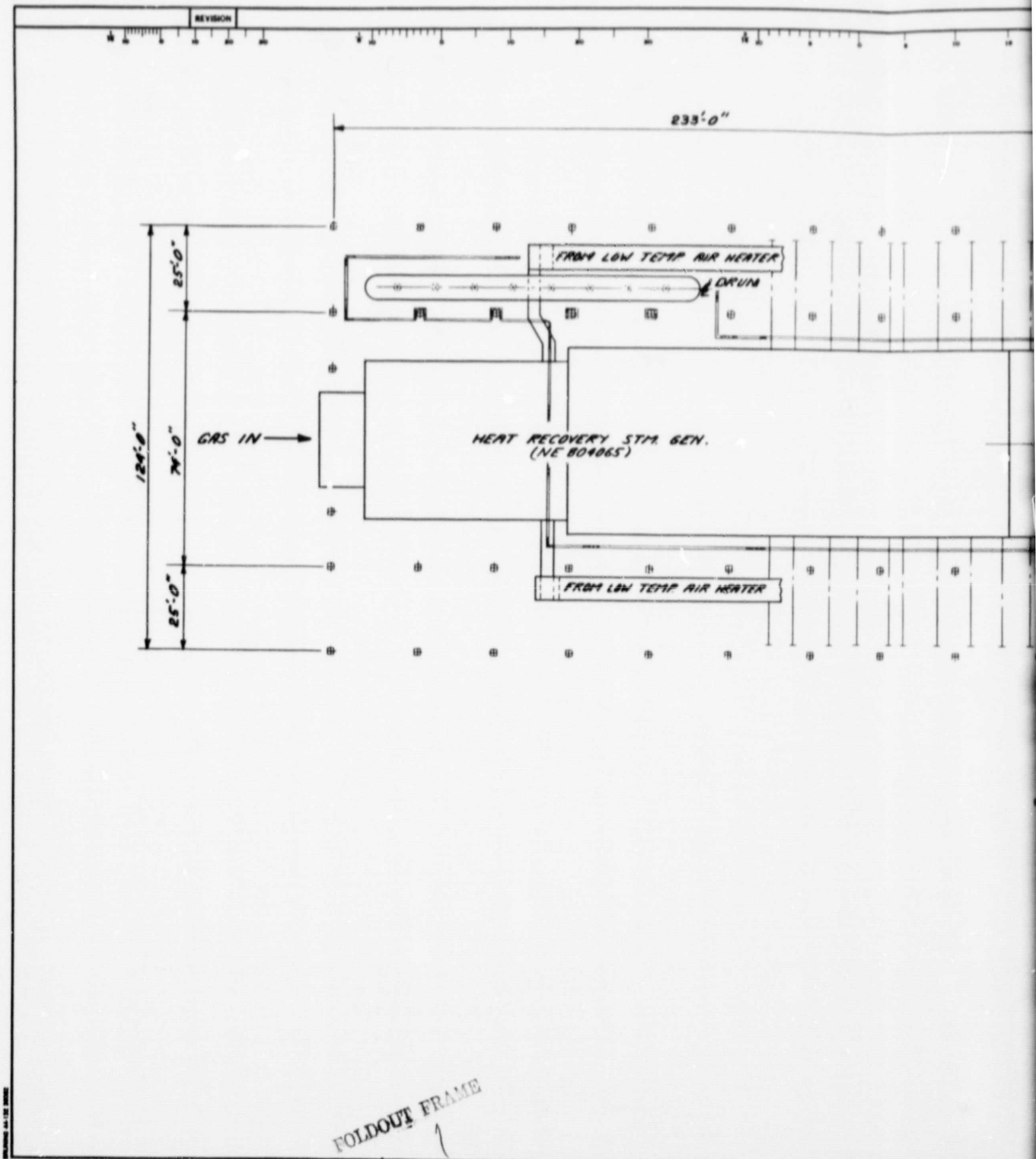

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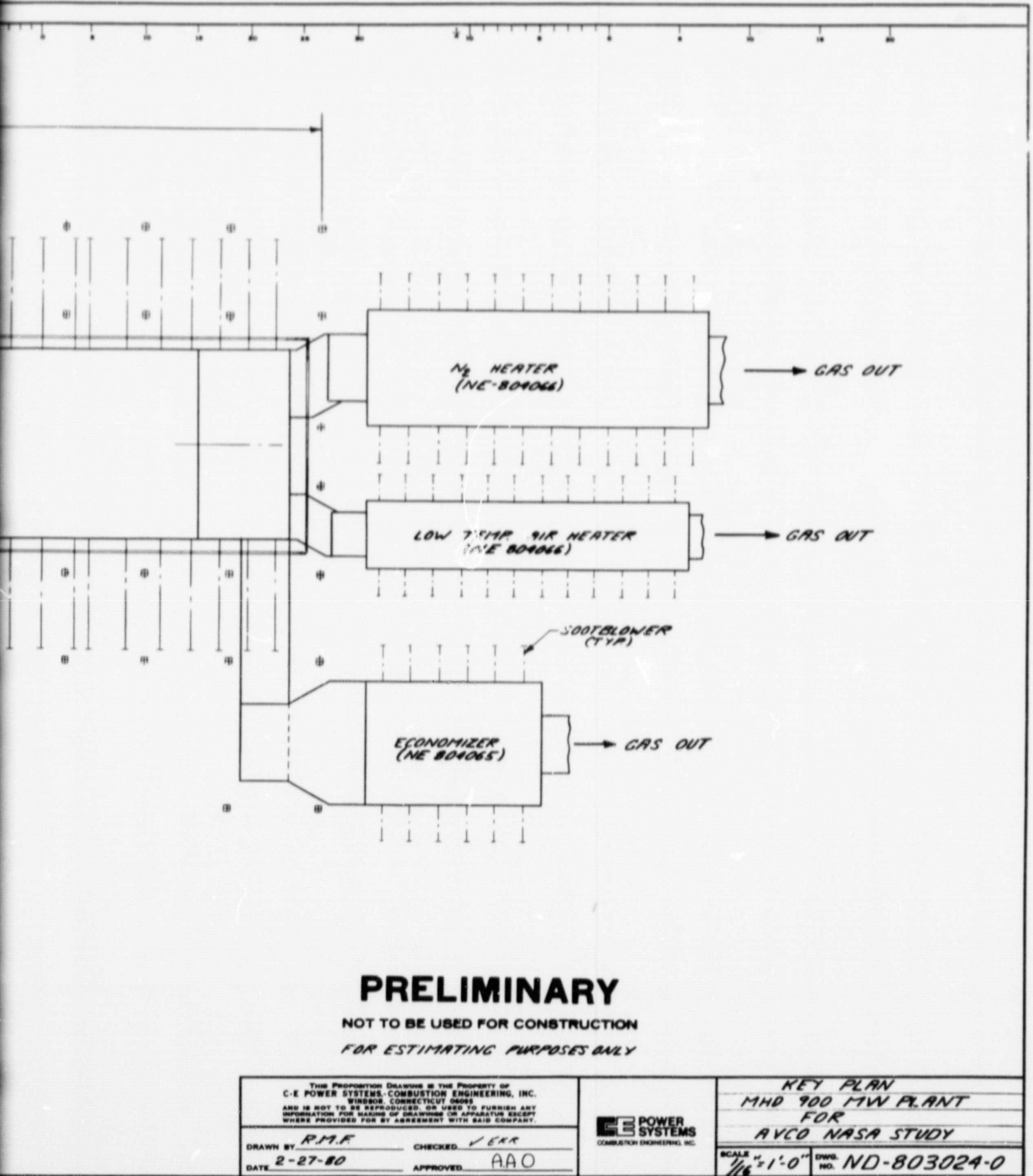
Figure 3-25 HRSR System Ke



-25 HRSR System Key Plan

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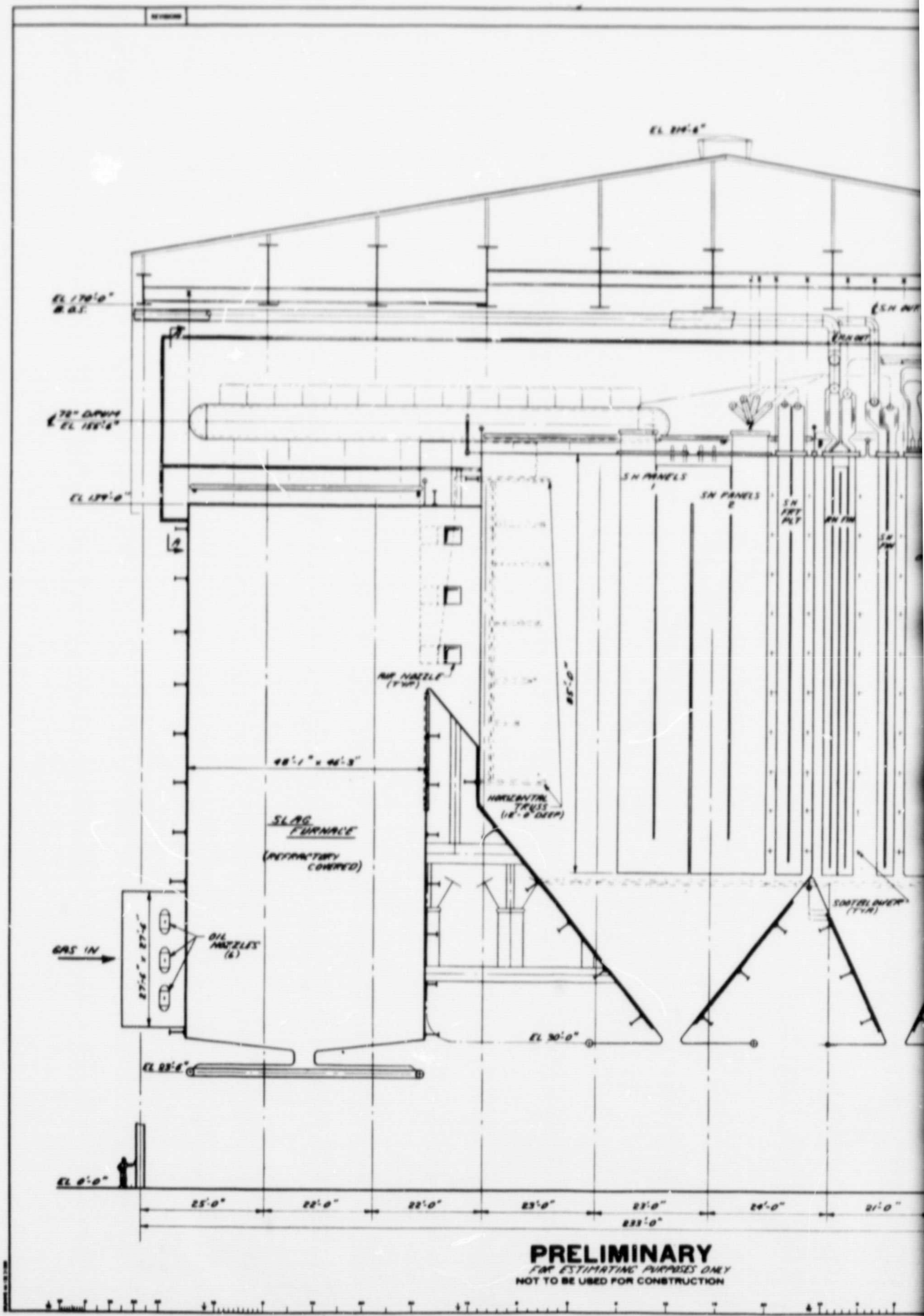

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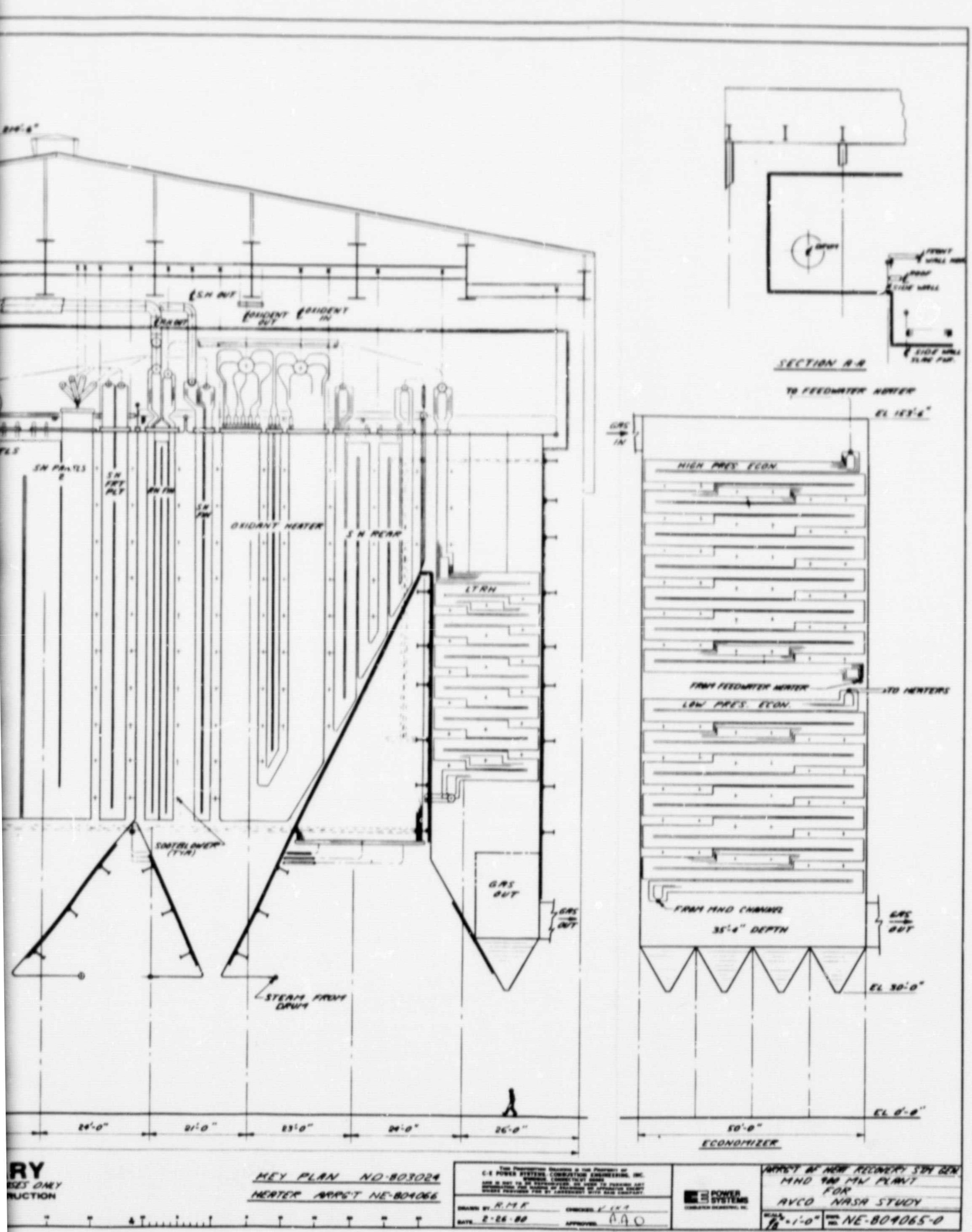
Figure 3-26 Arrangement of Heat Reco



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...gement of Heat Recovery Steam Generator System

TABLE 3-15

HRSR SYSTEM DESIGN SUMMARY

Section	Surface, ft^2	Material
Superheater	301,758	192,213T22, 213 T11, 213 TP347H
Reheater	269,830	192,213T22, 213T9, 213TP 304H
Oxidant Heater	301,403	192,213 T22, 213 TP 304H
Economizer	448,855	192
Low-Temperature Air Heater	305,585	192
Low-Temperature N_2 Heater	569,217	192
Evaporator and Steam Cooled Walls	72,182	210C

TABLE 3-16

HRSR SYSTEM ASSEMBLY DETAILS

	Location	Tube OD	Transverse Spacing	Longitudinal Spacing
SH-Finishing	CS	2	6"	4-1/2"
SH-Front Platen	SRS	2-1/8	22-1/2"	2-3/8"
SH-Panels	SRS	2	45"	2-1/4", 2-3/8"
SH-Rear Pendant	CS	2	6"	4-1/2"
RH-Finishing	CS	2-1/2	9"	2-3/4"
RH-Low Temperature	RP	2-1/2	6"	4-1/2"
Oxidant Heater	CS	2-1/2	6"	4-1/[illegible]
Econ-LP	E	2	5-1/2"	4-1/2"
Econ-HP	E	2-1/2	5"	4"
Lt Air Htr	LA	1-1/4	4-1/4"	3-1/4"
Lt N_2 Htr	LN	1-1/4	4-1/4"	3-1/4"

SRS - Seed Recovery System

CS - Convective Section

RP - Rear Pass

E - Economizer Section

LA - LT Air Section

LN - LT N_2 Section

warm up the steam generator. (Consideration should be given in future studies as to whether a direct pulverized coal ignition system can be used for these purposes as well as for carrying some load on the steam generator independent of the MHD system.)

3.6.1.3 Secondary Section

At the exit of the transition duct from the slag furnace, the 2900°F substoichiometric MHD gas is mixed with preheated burnout air (600°F) for the completion of combustion. The air is introduced through six nozzles located in the sidewalls of the duct. It is expected that burnout will be very rapid at these relatively high temperatures. The final flue gas composition contains 5% excess air.

The gas mixture enters the secondary section through a 46.3' x 48.8' opening in the front wall. As the gas passes through this section, it passes over the superheat panels and the superheat front platen before entering the convective section. It is expected that some of the seed material will condense on the walls and surfaces in this region. As the material gradually solidifies and accumulates, it will either fall off or be knocked off by the sootblowers located between the panels and the platen. The material will be collected in the hopper below.

The waterwalls are formed by 2" OD SA 210C carbon steel tubes fusion welded on 2-1/2" centers. The tubes will be approximately 70% aluminized for corrosion protection.

3.6.1.4 Convective Section and Rear Pass

The convective section and rear pass contain most of the various hanging surfaces. As the gas passes through the convective section, it passes over the finishing reheat, finishing superheat, oxidant preheat, and rear superheat surfaces prior to entering the rear pass. The roof and walls are steam cooled.

It is expected that additional seed material will fall out of the gas stream throughout these sections, adhering to the walls and surfaces. Numerous retractable sootblowers will be used to remove the seed material, which will be collected in the hoppers for reprocessing.

As the gas passes through the rear pass, which contains the low temperature reheat sections, the gas temperature is lowered to about 700°F. At the rear pass exit, the gas splits into three streams. Roughly half of the gas goes to the economizer section. The remaining gas goes to the low temperature air and nitrogen heaters.

3.6.1.5 Economizer Section

The economizer section, which contains the high-pressure and low-pressure economizers, cools the gas to about 300°F. The economizer section also contains numerous sootblowers and dry bottom hoppers for removal and collection of the seed material that might adhere to the surfaces.

3.6.1.6 Superheater Design

The superheater is divided into several sections located throughout the seed recovery, convective, and rear pass sections. The saturated steam leaves the drum and flows through the roof tubes in the three sections. The walls of the convective pass are also steam cooled in parallel with the roof. The steam then proceeds in sequence, to: the rear pendant located in the convective section; the panels, located in the secondary (seed condenser) section; the front platen, also located in secondary section; and the finishing superheater, located in the convective section. Steam temperature is controlled by two spray desuperheaters located at the exit of the front platens. The desuperheaters will be sized to provide up to 75°F temperature control at design point conditions. Steam conditions leaving the finishing sections are 2530 psig and 1005°F.

3.6.1.7 Reheater Design

The reheater is divided into two sections: the low-temperature reheater, located in the rear pass section, and the finishing reheater, located in the convective section.

Steam enters the low-temperature reheat sections from the exit of the high-pressure turbine at roughly 495 psig and 607°F. After leaving the low-temperature section, the steam passes through the finishing section, leaving at 455 psig and 1005°F. Desuperheat capability, with up to 75°F temperature control, is provided at the inlet to the low temperature section.

3.6.1.8 Oxidant Preheater Design

The oxidant preheater, located in the convective section, is designed to preheat the oxygen-enriched air for the MHD combustor. The oxidant, at the compressor outlet condition of 8.8 atm and 593°F, enters and leaves the preheater through manifolds at the top of the unit. The preheater outlet temperature is 1200°F.

3.6.1.9 Economizer Design

Approximately one-half of the 700°F MHD gas is sent from the rear pass exit to the economizer section located diagonally behind the rear pass. The gas enters the economizer section at the top, passes downward over the high-pressure and low-pressure economizers, and exits at the bottom at about 300°F. The economizer tubes are oriented horizontally, since particle loadings and temperatures are expected to be low enough to preclude deposition problems.

Water conditions entering the economizers are 235 psig/262°F into the low pressure section and 3000 psig/459°F into the high-pressure section.

3.6.1.10 Low-Temperature Air and Nitrogen Heater Design

The low-temperature air and nitrogen heaters are shown in Figure 3-27. They are located behind the steam generator rear pass section and operate in parallel with the economizer. The air heater preheats ambient air to 600°F for completion of combustion of MHD exhaust gas in the steam generator. The nitrogen heater preheats nitrogen supplied from the oxygen plant to 600°F for use in coal drying. MHD gas at 700°F enters the heaters at the bottom, makes four passes over the interior tubes, and leaves at the bottom at roughly 200°F. The air and nitrogen enter their respective inlet tube manifolds and leave their respective exit manifolds through openings at the top. The inlet temperature for both gases is about 100°F.

The heaters are dry bottom sections. They are equipped with numerous sootblowers for removal and collection of any seed material that deposits on the surfaces.

3.6.1.11 Part Load Performance

Analysis of the steam generator performance at part-load operation was also performed. Iterative performance analyses became necessary and these concentrated on 75% load (75% of coal input or gas mass flow). It was first found that significant reductions in superheater, reheater, and oxidant preheater outlet temperatures would result with the reduction in gas flow for the proposed steam generator design. In addition, the difference between superheater and reheater outlet temperatures (112°F) exceeded the maximum limit (75°F) specified by the steam turbine manufacturer. Further analysis showed that these problems could be alleviated by recirculating roughly 650,000 pph of MHD flue gas taken after the ESP. This recirculated gas was introduced along with the secondary air for completion of combustion. Final steam conditions at 75% load would be 1038°F superheater outlet, 955°F reheater outlet, and 1060°F for the oxidant heater outlet. The superheater steam outlet temperature would be sprayed down to 1005°F to keep the superheater/reheater temperature difference within turbine manufacturer's limits.

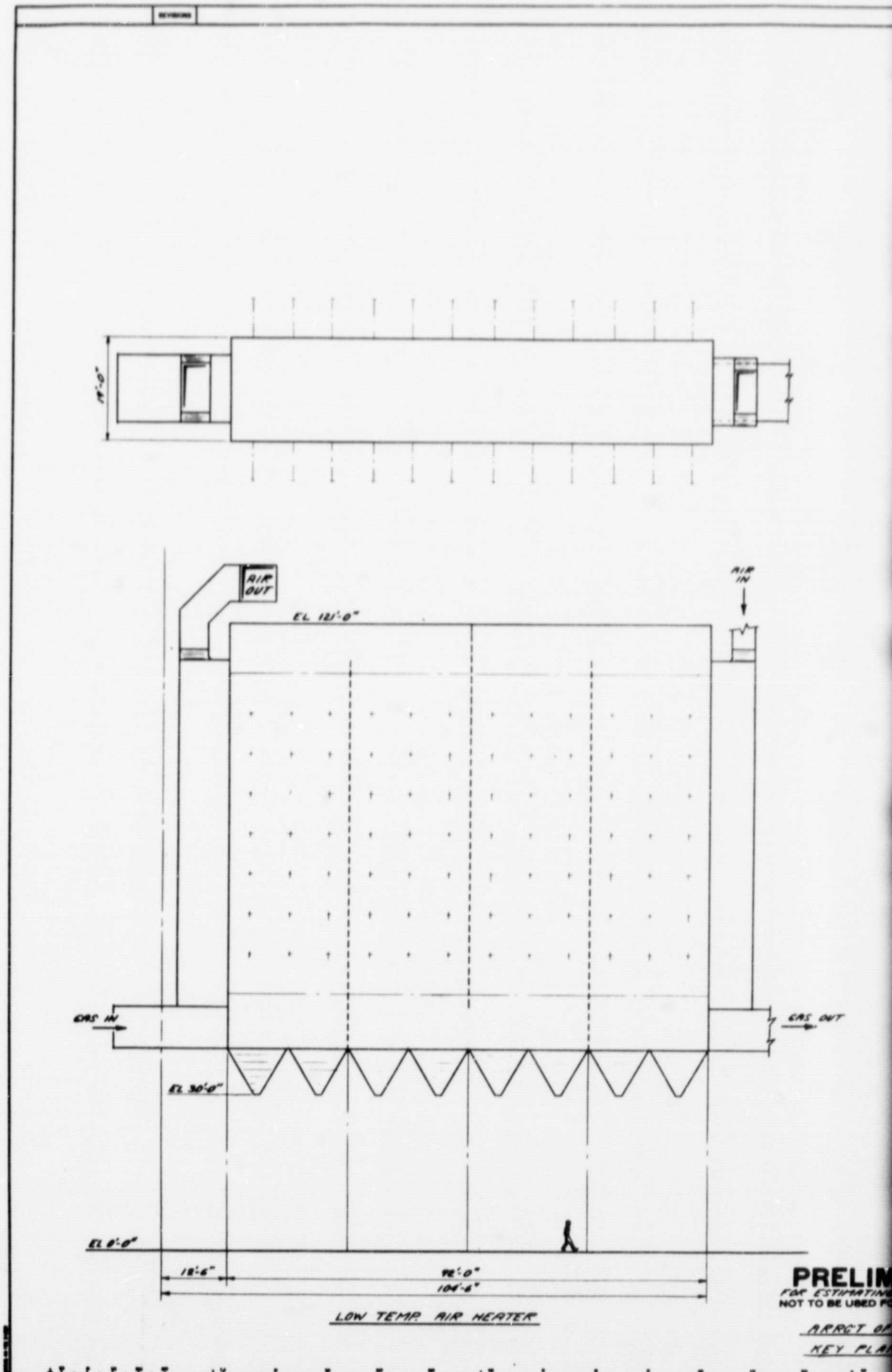

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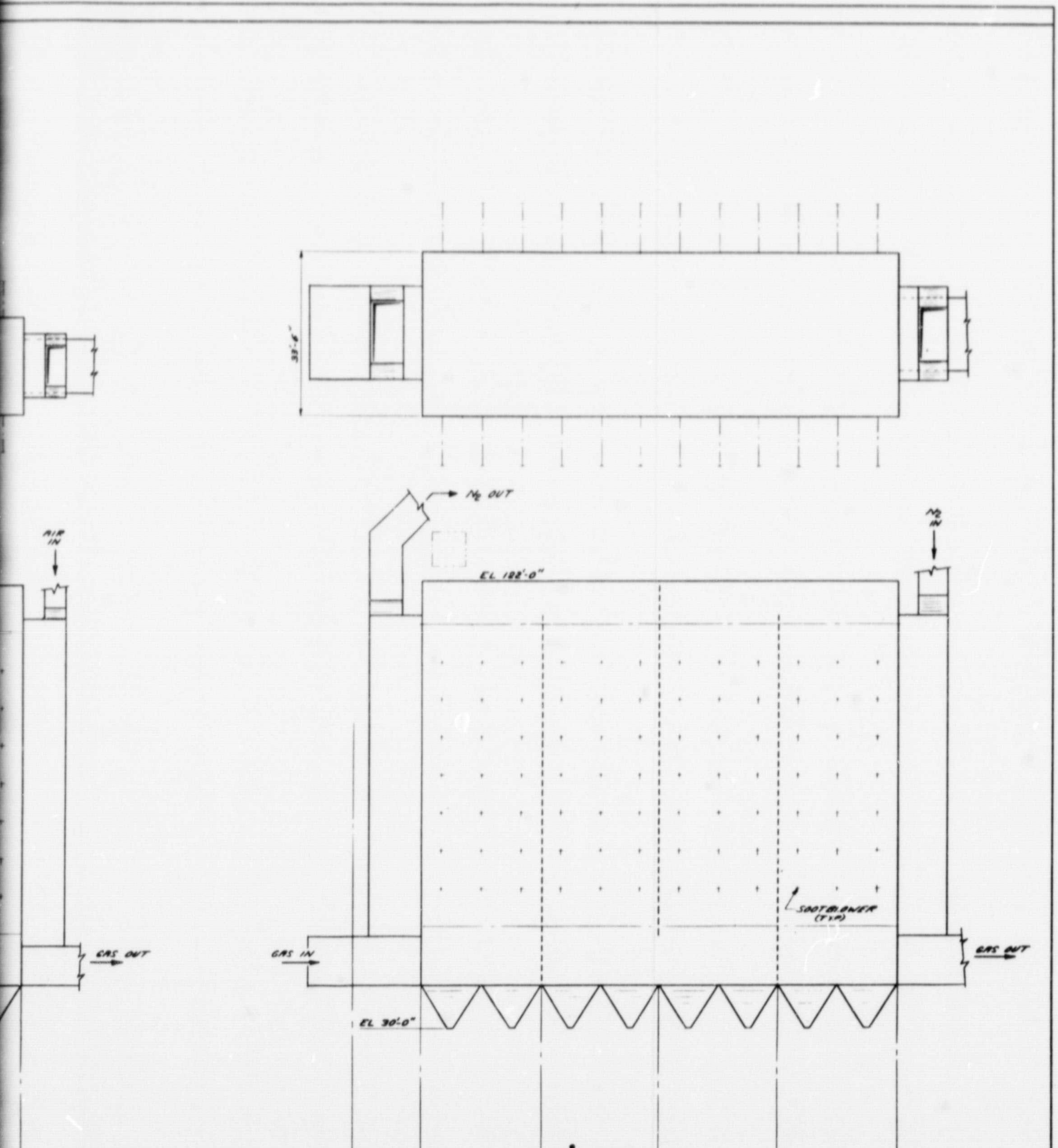
Figure 3-27 N_2 Heater and Air H



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2

eater and Air Heater Arrangement

It is anticipated that further reductions in outlet temperatures, together with increased recirculation requirements, would result from operation at lower power levels. Because this is an unfired boiler, gas recirculation is the most readily available method to increase the net heat available to the finishing superheater and reheater sections and high-temperature section of the oxidizer preheater.

However it is likely that refinements and optimization studies of the steam generator design could minimize the gas recirculation requirements while maintaining performance. These refinements and design optimizations would require tradeoff analyses between full and part load operation. Such tradeoff analyses were beyond the scope of this design effort, but could be conducted later to examine the effects of surface rearrangements and other design changes on steam generator performance at various performance levels.

3.6.1.12 Instrumentation and Controls

The steam generator is a balanced draft, controlled circulation unit with reheat. Other than during warmup, there will be no conventional fuel input to the boiler.

The control system will consist of two parts: the digital controls and the analog controls. The digital control system will provide coordination, safety supervision, monitoring, and remote status display. The analog control system will provide continuous control of the controlled variables such as furnace draft, steam temperature, fuel flow, oxidant flow and feedwater flow.

3.6.1.13 The Digital Control System

The digital management system, usually called the furnace safeguard supervisory system (FSSS), will provide remote-manual startup with safety interlocks.

3.6.1.14 Furnace Draft Controls

The furnace will be a balanced draft unit. The furnace draft will be controlled by the 1D fan. A conceptual schematic is shown in Figure 3-28.

The furnace draft control system will be similar to the draft control on a conventional boiler. Three pressure transmitters feeding into a median selecting circuit will be used to protect against the loss of any one pressure transmitter. The median furnace pressure will be sensed and compared to the setpoint. The furnace pressure error is used to regulate the ID fan. Oxidant compressor vane position is used as an anticipation signal for the basic ID fan demand, thereby minimizing the integral action from furnace draft.

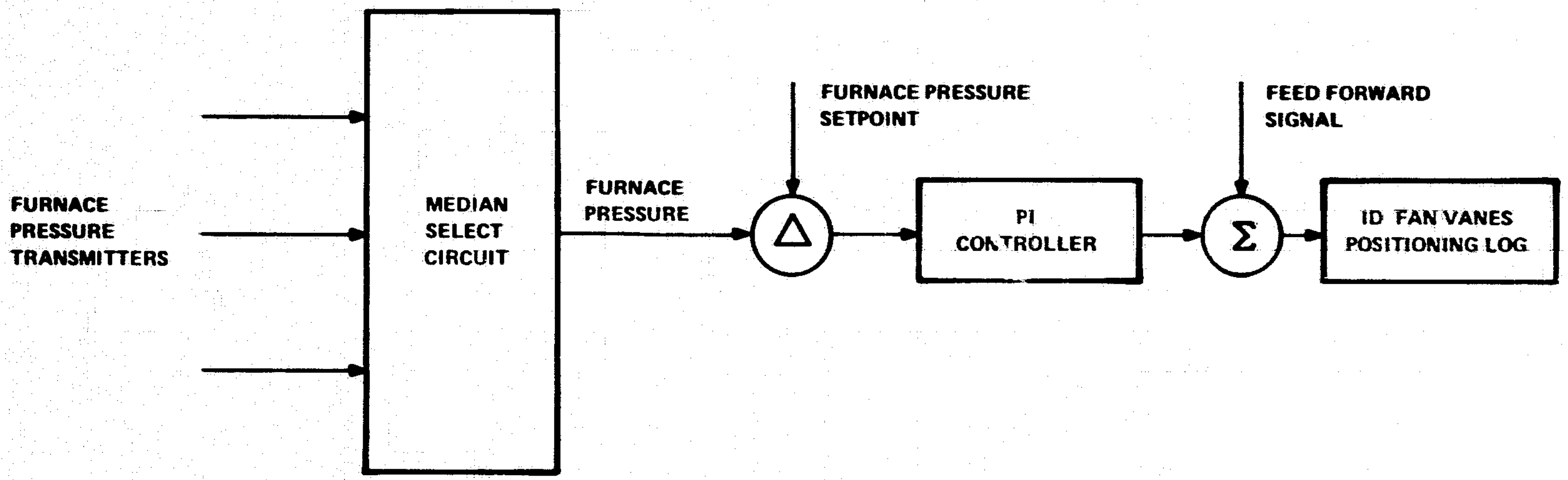

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Figure 3-28 Furnace Draft Control

Directional blocking circuits will be included. Excessively high furnace vacuum will block further opening of primary ID controls; a signal will be available to block further closing of the oxidant compressor controls. Conversely, excessively high furnace pressure blocks further closing of primary ID fan controls; a signal will be available to block further opening of the oxidant compressor controls.

When gas input to the MHD channel ceases abruptly, exhaust gas from the channel and heat input to the furnace also drops abruptly. Under these conditions, a feed forward signal is to be given to the ID fan control dampers. This command is to result in the dampers closing ~ 10% of total travel. This command is to decay over an adjustable time period. This action is to be taken if the furnace draft control is either in automatic or in manual.

3.6.1.15 Steam Temperature Control

The function of the superheater steam temperature control is to maintain the superheater outlet temperature at setpoint. In order to minimize temperature deviations during transients affecting steam temperature as well as to maintain the superheater outlet temperature at setpoint during steady-state operation, a desuperheater spray, located between two sections of the superheater, will be employed utilizing superheater outlet steam temperature and the steam temperature at the desuperheater outlet as shown schematically in Figure 3-29.

The spray valve will control the temperature downstream of the desuperheater utilizing anticipatory action to maintain the superheater outlet temperature at its design setpoint. A steam temperature change will first be detected by a change in desuperheater outlet steam temperature; this meansurement will initiate the corrective control action. The outlet steam temperature error signal will then trim the desuperheater spray valve position to maintain superheater outlet temperature.

A block valve in the spray piping will be interlocked to close when there is no spray demand signal.

A similar steam temperature control system is used to maintain the reheater outlet temperature at setpoint. The reheater desuperheater is located at the inlet to the low temperature section.

3.6.1.16 Combustion Controls

There will be two modes in the combustion control system. The first mode will be a combustion control system that monitors and limits the rate of increase of refractory lining temperature and will be used for warmup of the boiler.

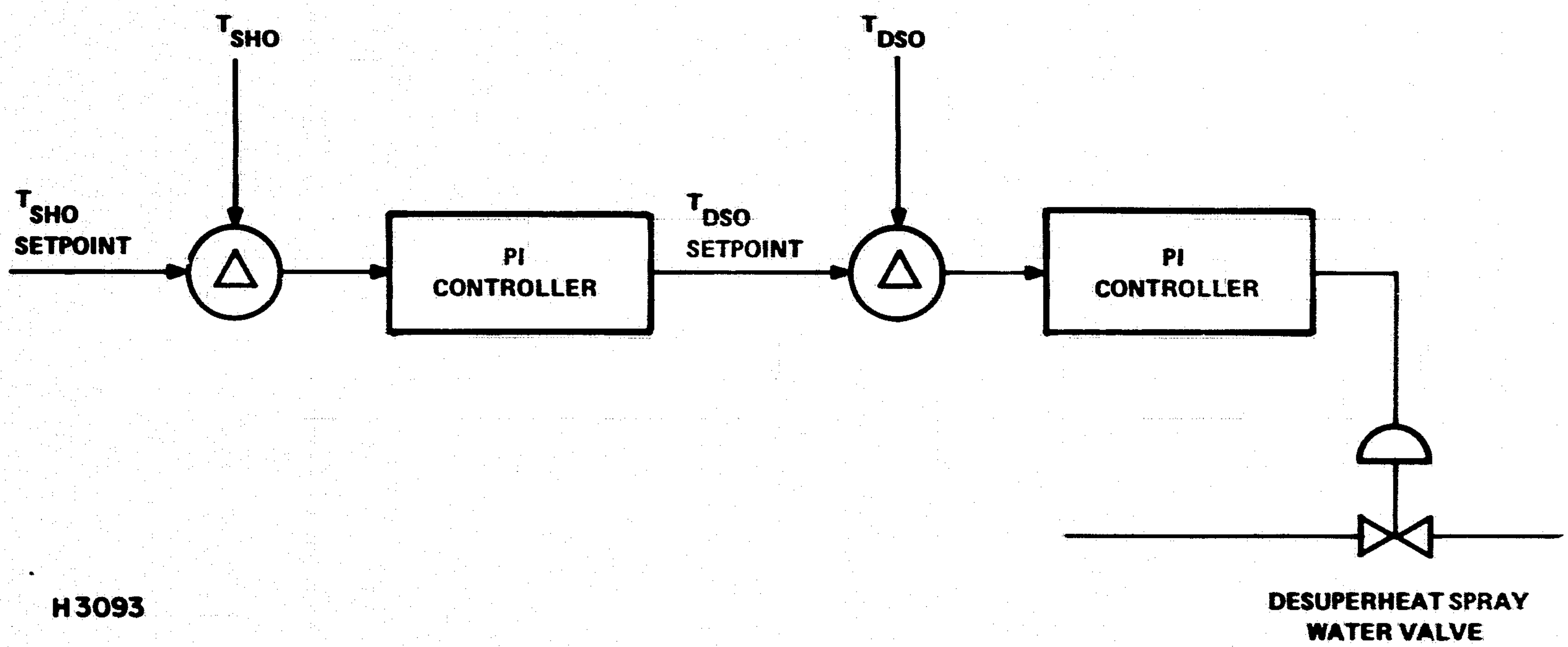

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Figure 3-29 Steam Temperature Control

Six oil guns, located in the walls of the refractory-lined furnace, will be provided to warm up the refractory prior to starting the MHD system. Each gun will be capable of firing 280 x 10^6 Btu/hr of air-atomized Number 2 oil. There will be 6 air atomized ionic flame monitor ignitors and 6 flame scanners.

Thermocouples will be used to monitor refractory temperatures during the warmup. Warmup will include synchronizing the turbine-generator and carrying up to $\sim$20% electrical load capability. When the MHD channel is fired the warmup oil will cease and the combustion control system will switch to the second mode of supplying sufficient preheated air to allow complete combustion of the MHD exhaust gases. The air required in the second mode will be 15% of the air required for complete combustion of the pulverized coal being fired in the MHD combustor as the exhaust products of the MHD channel are about 90% stoichiometric and the flue gas exits the boiler at 5% excess air.

Before firing the MHD system, the combustion control system is similar to the combustion control system on a conventional drum unit. During firing of the MHD combustor, air flow will be trimmed by an O_2 measurement in the exhaust gas.

Figure 3-30 shows conceptually how the combustion control system will operate.

3.6.1.17 Feedwater Controls

The feedwater control system will be a standard 3 element feedwater control system. The feedwater flow is adjusted to maintain drum level at setpoint as shown conceptually in the diagram of Figure 3-31.

3.6.2 Stack Gas Cleaning

The particulate removal system was designed such that the total plant particulate emissions would be below the 0.03lb/10^6 Btu total fuel input EPA limit. Since it is expected that a small amount of particulate material will be sent to the stack from the coal processing system, the cleanup equipment for the main MHD gas stream will be required to remove a very high percentage of the total solid material entrained in this stream.

The selection of an electrostatic precipitator (ESP) was made, based upon required particulate removal efficiency, gas flow rates, compatability with seed regeneration systems and wide-spread use in utility power plants.

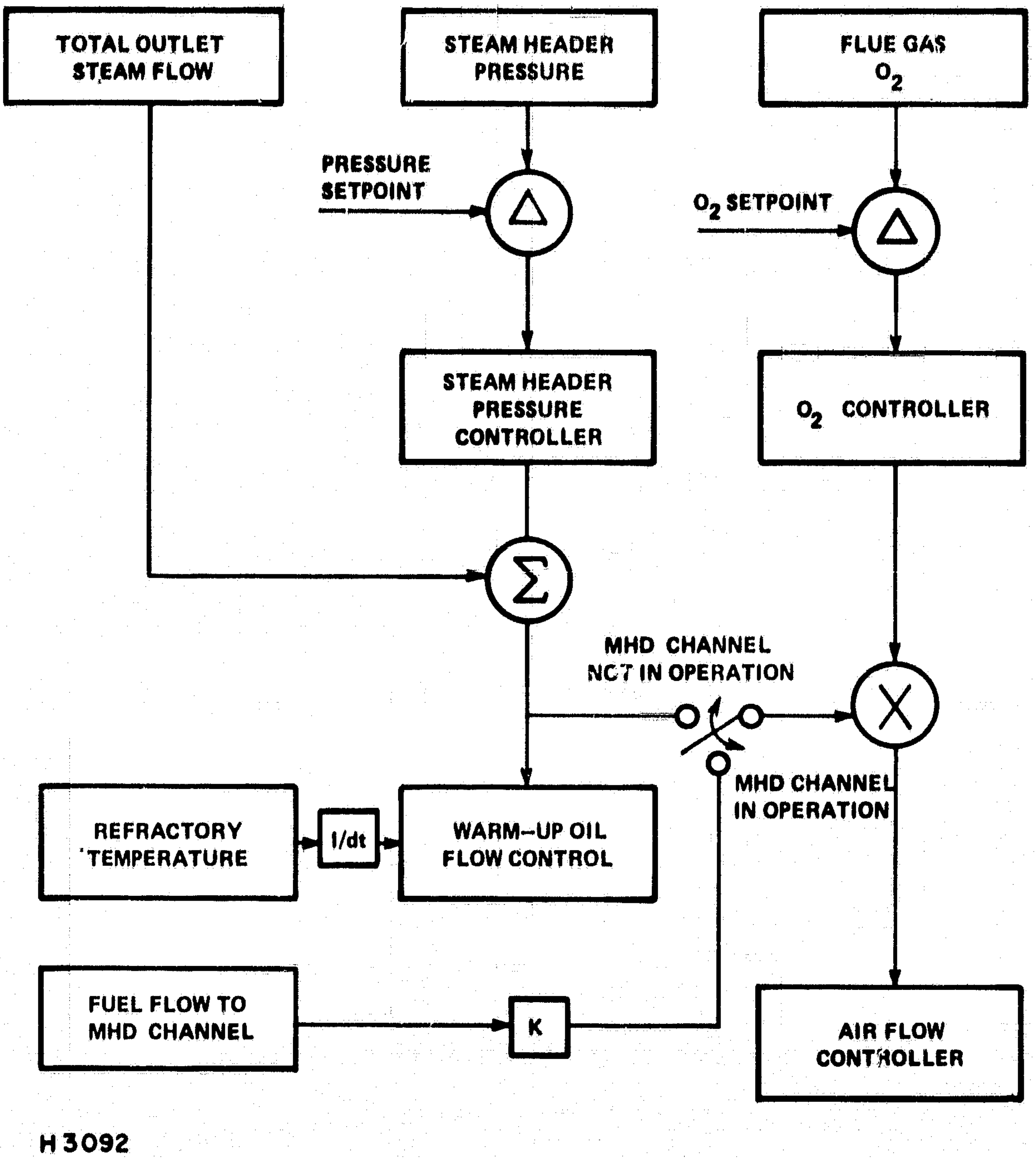

Figure 3-30 Combustion Controls

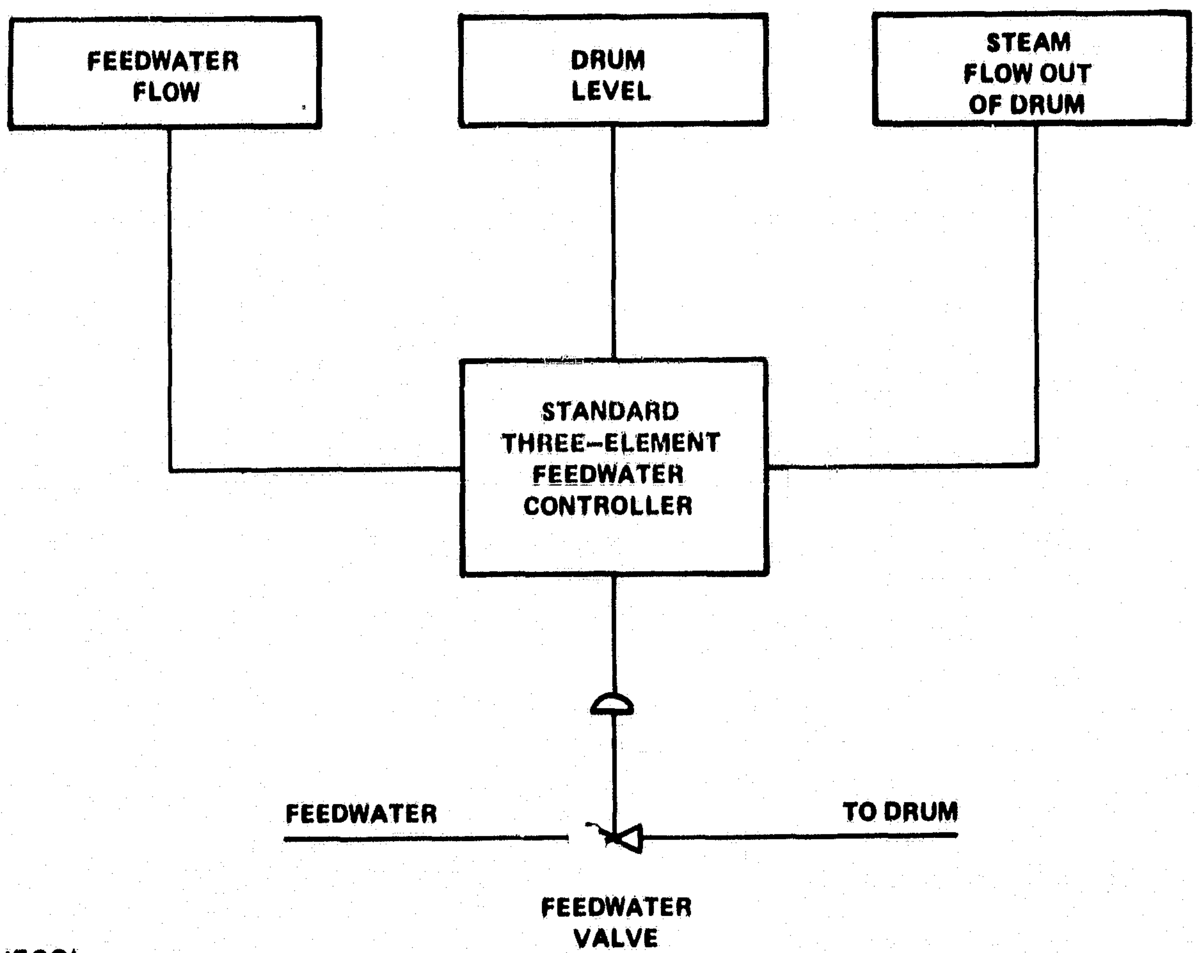

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Figure 3-31 Feedwater Controls

3.6.2.1 ESP Design

The ESP was designed for a collection efficiency of 99.83% with a gas flow of approximately 1.4×10^6 ACFM. This corresponds to a particulate emission of 0.018 lbs/MBtu which is 60% of that permitted by NSPS. A preliminary design is shown in Figure 3-32. Figure 3-33 shows the precipitator inlet and outlet nozzles. Design details are shown in Table 3-17.

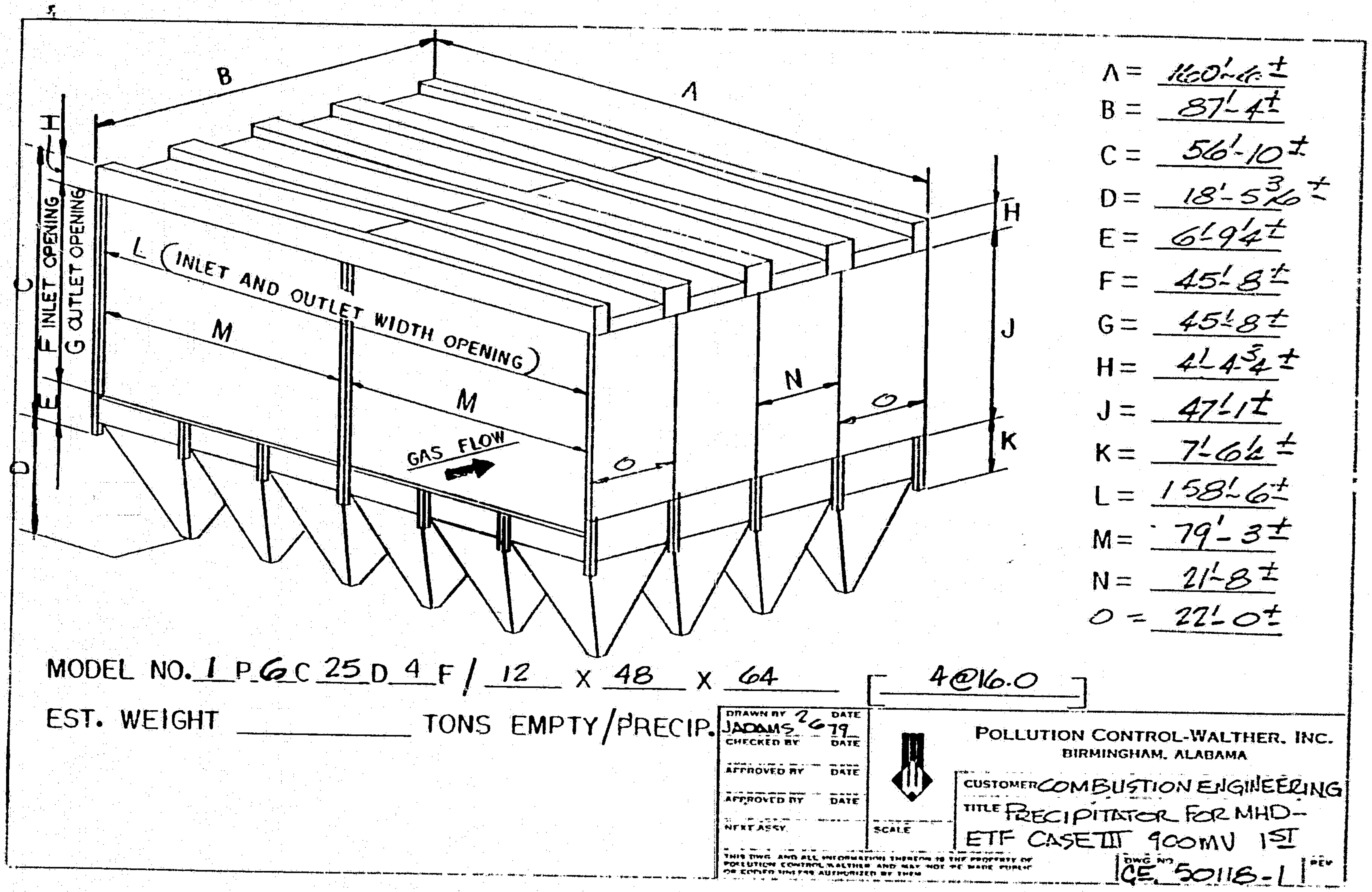
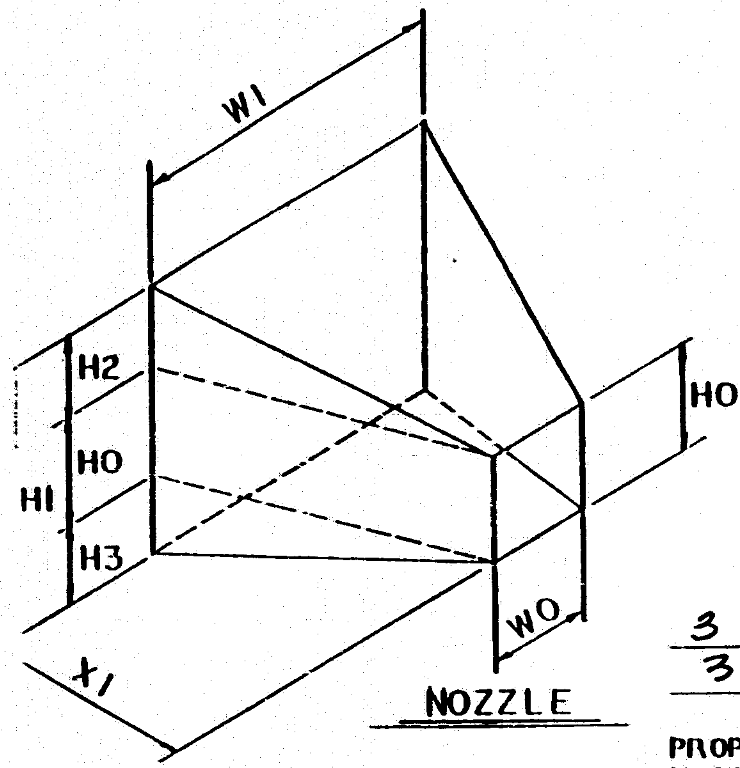


Figure 3-32 Precipitator for MHD-ETF Case III 900 MW



NOZZLE

W1 = 52'-6±
H1 = 45'-8±
H2 = 1'-6±
H3 = 32'-9±
HO = 11'-5±
WO = 11'-5±
X1 = 22'-1±

3 INLET NOZZLE REQ'D./PRECIP.
3 OUTLET NOZZLE REQ'D./PRECIP.

PROPOSAL NO.
MODEL NO. 1 P 6 C 25 D 4 F/ 12 x 48 x 64 [4@16.0]

DRAWN BY ADAMS DATE		POLLUTION CONTROL-WALTHER, INC. BIRMINGHAM, ALABAMA
CHECKED BY DATE		CUSTOMER COMBUSTION ENGINEERING
APPROVED BY DATE		TITLE INLET AND OUTLET NOZZLE FOR MHD-ETF CASE III 900MV
APPROVED BY DATE	SCALE	
NEXT ASSY.		DWG. NO. CE 50118-1 REV -

Figure 3-33 Inlet and Outlet Nozzle for MHD-ETF Case III 900 MV

TABLE 3-17

ELECTROSTATIC PRECIPITATOR DESIGN DETAILS

Gas Volume	1.36×10^6 ACFM @ 250°F
Efficiency	99.82%
Model Number	1P6C25D4F/12 x 48 x 64 (4 @ 16.0)
No. of Precipitators	1
No. of Chambers/Precipitator	1
No. of Ducts/Precipitator	150
Duct Spacing	12"
Number of Fields	4 @ 16.0' L x 48' H
Total Collecting Plate Area	921,600 ft^2 = 38,400 ft^2/T.R.
Total Discharge Electrode Length	546,000 ft
Number of T/R's	24 FW sets/precipitator @ 1450 MW each
SCA	655
Migration Velocity	4.95 cm/sec
Gas Velocity	3.26 ft/sec
Total expected R/R Power Consumption	1400 kW
Total Approximate Precipitator Weight	5,300,000 lbs

3.7 STEAM TURBINE GENERATOR

The steam turbine for the electric generator will share the boiler main steam supply with the turbine drivers for the cycle air compressor and oxygen plant air compressor. The steam turbine-generator is rated at ~ 475 MW.

The turbine selected will be a tandem compound, multiflow, condensing, single reheat unit. Steam throttle conditions are 2400 psig, 1000°F main steam and 1000°F reheat steam. These conditions of pressure and temperature are typical of modern, central electric-generating stations and will allow high steam plant efficiencies to be attained.

As discussed in Subsection 3.12.1, the steam cycle performance has been calculated based on a turbine backpressure of 2 in. HgA. The steam cycle has been arranged for seven turbine extraction points. Steam to seven feedwater heaters, the heat loss from the MHD components, and the boiler high and low pressure economizers heat the feedwater to within 50°F of boiler drum saturation temperature at full load. Steam to drive the boiler feed pump turbine is taken from the crossover between the intermediate and low pressure turbines. Steam to drive the main air compressor and oxygen plant air compressor is taken from the main steam line.

The extraction points from the turbine were chosen to make best use of the available heat losses from the MHD components and the boiler economizer. High-temperature heat from the MHD burner was used to heat feedwater just prior to entering the boiler. The location of the MHD channel coolant in the feedwater circuit is dictated by the requirement for relatively low-pressure and low-temperature cooling water. Cooling water temperature out of the channel will not exceed 265°F. The economizer was split into high and low-temperature sections to make better use of the available heat in the flue gases. The economizer sections are located in the condensate and feedwater lines such that a minimum temperature difference of 50°F between the water and flue gas is maintained. Seven extraction points from the turbine will accommodate the six closed feedwater heaters and one open dearating heater.

3.8 CYCLE COMPRESSOR AND DRIVE

An axial flow air compressor will be provided, with its steam turbine drive, inlet filter and silencer. This equipment is located on the operating floor with the main turbine-generator set.

The air compressor flow rate is ~ 3.1 x (10^6) lb/hr. The pressure ratio is 8.89 and the power required to drive the compressor is 111.5 MW. The compressor is a multistage axial flow machine without intercooling. Quotes from major manufacturers have been solicited for this equipment. One manufacturer indicated he would use a fifteen-stage machine without intercooling. Due to the high work per stage, blades other than what is now standard will be required for this machine. In addition, the downstream portion of the compressor casing will be steel rather than cast iron to accommodate the higher discharge temperatures.

The flow rate from the compressor is controlled by varying the speed and stator vane angle on the compressor. To decrease the flow below design, the compressor stator vane angle is varied while maintaining rated speed. For flows ~ 70% of design flow, the stator vane angle remains at the minimum setting while the speed is decreased. Performance curves indicate surge (upper limit) and choke (lower limit) lines which become progressively closer as the flow decreases. To operate within these lines, particularly at lower flows, requires a blowoff valve to stay below the surge line and a throttling valve to stay above the choke line.

The steam turbine drive is a multistage, condensing machine designed for a back-pressure of 2 in. HgA. The turbine throttle conditions are 2400 psig, 1000°F.

3.9 COAL DRYING, PULVERIZING AND FEEDING

The coal drying, pulverizing, and feeding system will be required to handle nearly 820,000 pph of Montana Rosebud subbituminous coal. The system layout will be similar to that used in the ETF design. A typical equipment arrangement schematic is shown in Figure 3-34.

The coal will be thermally dried from the as-received condition of 23% moisture to 5% moisture using preheated nitrogen obtained from the oxygen plant. The bulk of the drying will occur in the mills.

Crushed coal from the raw storage bins will be fed into the CE-supplied bowl mills (#1003RP bowl mills with 600 hp/900 rpm motors) by gravimetric feeders. The nitrogen, preheated to 600°F in the nitrogen heater, is also fed into the mills. The coal will be pulverized to 70% through 200 mesh. The gas with the entrained pulverized coal will be sent next to the cyclone separators where ~ 85% of the coal will be removed. Approximately 99.9% of the remaining coal will be removed in baghouses downstream of the cyclones. The filtered gas, now at about 200°F and nearly dust-free, will be sent to the stack.

Pulverized coal from the cyclones plus the fines from the baghouse collection system will enter the prepared coal storage bins. Total capacity of the bins will be roughly equivalent to one hour of full load running to provide for temporary outages or overload operation.

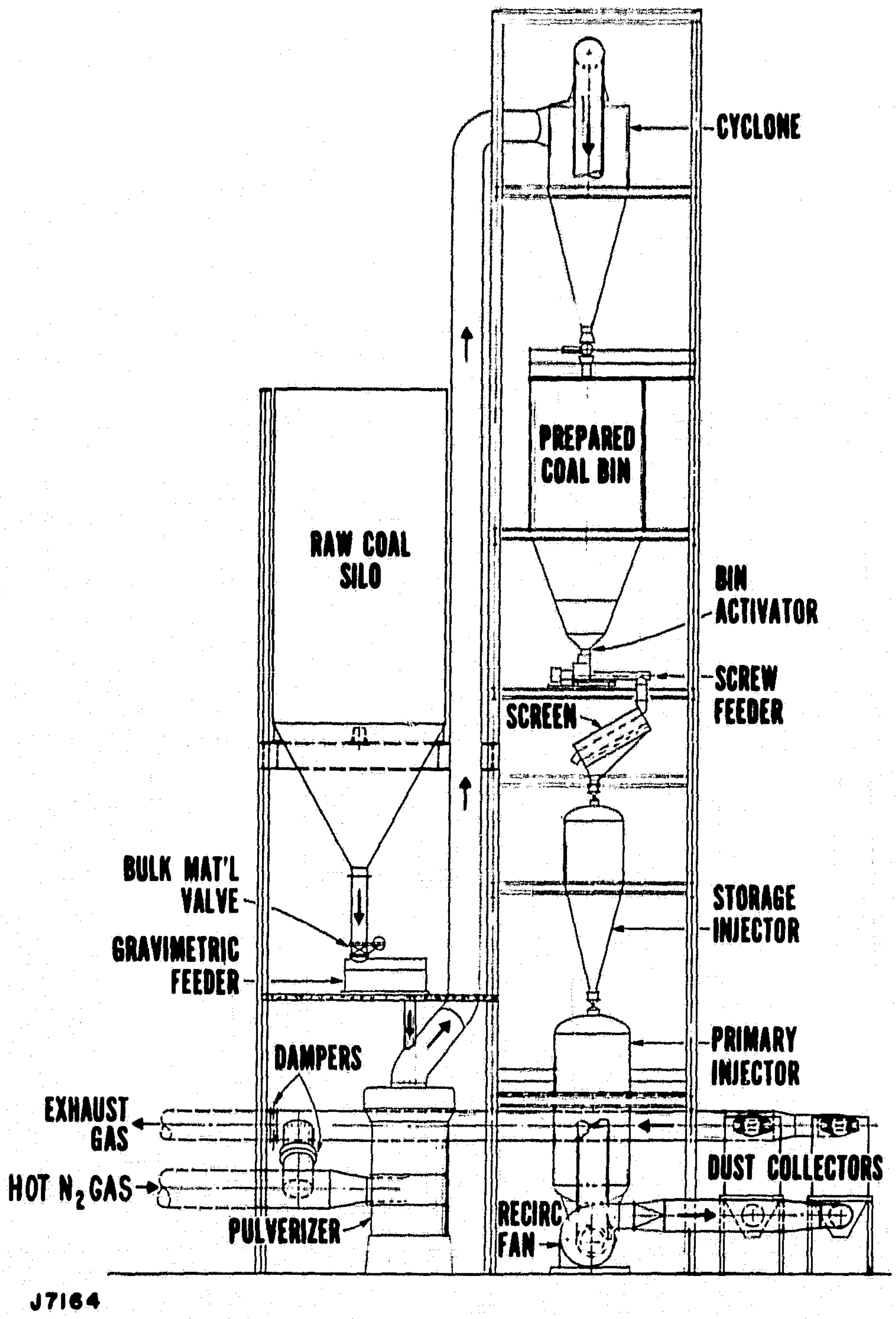


Figure 3-34 Arrangement of Coal Processing Equipment

For operation of the MHD combustor, the coal must be delivered against a pressure of ~ 8.5 atm. To accomplish this, the Petrocarb lock hopper system will be used. This is considered the only proven commercially available injection system which can deliver controlled quantities of coal against the 5-10 atm combustor pressure used in the open cycle MHD system. The coal will be fed from the storage bins on demand via bin activators and screw feeders to scalping screens and finally to the Petrocarb Lockhopper systems. When the upper hoppers of the Petrocarb systems are filled, they will be sealed and pressurized to 200-250 psig using nitrogen from the oxygen plant. With upper and lower lockhopper pressures equalized, the isolating valves will be opened, allowing the coal to drop into the lower bins. When the upper bins are empty, they will be depressurized, ready to be recharged. Each complete Petrocarb cycle will take about 20-30 min. Coal will leave the lower bins via two 1 1/2 in. feed pipes per bin. Compressed air will be used in the pipes to convey the fuel and inject it into the combustor.

The system consists of seven bowl mills (plus one spare) feeding into four pressurized feed trains. Half the total flow of drying gas will be passed through each of two baghouse filters prior to being sent to the stack.

3.10 SEED MANAGEMENT AND PROCESSING

3.10.1 Seed Management

Efficient seed recovery is necessary for economical commercial operation. Seed recovery is also combined with effective removal of sulfur from the MHD combustion gases. This is feasible because of the known high chemical affinity of potasium seed to sulfur in the gas.

The behavior and chemistry of seed and ash is complex. It depends upon several factors such as thermochemistry, mass and heat transfer, condensation phenomena, particle mechanics and compositions of the gas, seed material used and coal ash. It has been studied by several investigators in the MHD field and is part of the ongoing HRSR development program and other MHD development support efforts. Past investigations have revealed that alkali seed is more volatile than mineral matter in coal ash and that the amount of seed which can be dissolved in ash is a strong function of temperature and that it depends upon seed and ash chemistry including kinetics and the coal ash composition. These seed characteristics can be utilized in the recovery of seed.

A large fraction of the coal ash (80%) is assumed to be removed in the MHD combustion process. Furthermore, as described in Section 3.3 of the MHD coal combustor design, seed is added to the high-temperature MHD combustion gases produced in the combustor in such a way so as to avoid seed loss with molten ash removed from the coal combustor. The boiler design has also been developed with careful consideration for attaining efficient recovery of seed as described in Section 3.6. Slag is removed from the primary radiant furnace at the highest MHD exhaust gas temperature in order to minimize the amount of seed dissolved and lost in the molten slag removed from this furnace. The gas exit temperature from this primary furnace (2900°F) is well above the dew point of seed in the gas ($\sim$2300°F), and the furnace wall boiler tubes are refractory lined. Condensation of seed occurs as the gas is subsequently cooled in passing through the secondary furnace. The gas is cooled down to below the melting point for K_2SO_4 (1970°F) for solidification of condensed potassium sulfate before entering any tightly spaced tubes in the convective sections. Part of the condensed seed with some additional fly-ash is recovered from this secondary furnace and also from the subsequent sections of the boiler including the economizer. The remaining portion of the condensed seed in the gas is removed in electrostatic precipitators at stack gas temperatures of 250°F together with a small fraction of fly-ash in the gas.

Recovered seed is processed for removal of sulfur. This permits utilization of seed recovery for removal of sulfur from the gas for air pollution control. The particular aspect of processing and recycling of recovered seed is described in Section 3.11.

The New Source Performance Standards (NSPS) requires that 70% of the sulfur contained in the coal type considered as fuel (subbituminous, Montana Rosebud) be removed. This level of sulfur removal was used as the basis for seed processing and plant design. As an alternate, essentially 100% sulfur removal was also considered. The latter consideration of essentially complete sulfur removal reduces the sulfur concentration in the gas to a minimum. This would ideally minimize the potential corrosion problems related to sulfur in the gas both of MHD components and of bottoming plant components and hence could increase component lifetime and reliability.

Table 3-18 lists pertinent data of seed and sulfur mass flow rates in the system for 70% and 100% sulfur removal. The seed regeneration process considered is the formate process (see Subsection 3.10.2). For the alternate consideration with 100% sulfur removal there is an excess amount of potassium in the gas compared to the stoichiometric ratio of potassium and sulfur (K_2SO_4). This excess amount of potasssium is listed as K_2CO_3 for this alternate case.

Seed and ash mass balances for 70% (NSPS) and 100% sulfur removal are listed in Table 3-19. Seed losses and makeup requirements and costs for the same two levels of sulfur removal are presented in Table 3-20. For 70% sulfur removal about 1/3 of the recovered seed is processed. The remaining 2/3 of the recovered seed with its ash impurities is considered recycled directly without processing. For 100% sulfur removal all of the recovered seed is processed and all ash impurties are considered removed from the recovered seed in the seed regeneration process before recycling.

The calculated loss of potassium seed in liquid slag removed from the primary radiant boiler furnace is based upon 15% K_2O dissolved in this slag. For the remaining ash removed from the HRSR system a potassium content of 17% as K_2O has been assumed for calculation of additional seed losses with ash. These values of seed content in slag and ash are in line with values reported elsewhere from simplified model predictions.(2) Uncertainties still exist related to seed and ash chemistry and whether equilibrium is reached under actual operating conditions. It has been reported by investigators in the MHD field that simple seed-slag equilibrium models can overestimate the amount of seed captured by slag significantly and experimental results reported also support this. The total amount of seed lost with slag and ash is calculated to be 5.0% and 5.1% of total seed for 70% and 100% sulfur removal, respectively.

TABLE 3-18

SEED DATA FOR 70% (NSPS) AND 100% SULFUR REMOVAL

Coal:			
Coal Flow Rate (5% Moisture)	pph	665,005	
Thermal Input (10,692 Btu/lb)	MBtu/hr	7289.78	
Sulfur in Coal (1.045%)	pph	6,949	
Sulfur Input	lbs SO_2/MBtu	1.905	
Seed:			
Potassium seed flow rate (1%K)	pph	37,178	
All seed as K_2SO_4	pph	82,840	
Sulfur Removal	pph	70%	100%
Sulfur Removed	pph	4,864	6,949
K required for S-removal	pph	11,865	16,950
K_2SO_4 required processed	pph	26,440	37,770
KCO_2H produced for recycle	pph	25,520	36,460
K_2SO_4 recycled	pph	56,405	
K_2CO_3 recycled	pph		35,740
Total sulfur in gas (s)	pph	17,339	6,949
Sulfur in stack gas (s)	pph	2,085	trace
SO_2 in stack gas	pph	4,170	"
SO_x-conc. in stack gas	ppm	440	"
SO_x-emission	lbs SO_2/MBtu	0.57	"

TABLE 3-19

SEED AND ASH MASS BALANCES FOR HRSR SYSTEM

Sulfur Removal	%	70 (NSPS)	100
Raw coal feed rate to MHD burner	pph	665,005	
Ash contained in MHD burner coal feed	pph	71,150	
Seed feed rate (as K_2SO_4)	pph	82,840	
MHD Coal Combustor Ash Removal	%	80	80
Total amount of Ash to bottoming plant	pph	23,480	14,230
Slag removed in primary boiler furnace (40%)	pph	9,400	5,690
Seed loss in slag from primary boiler furnace (maximum):*			
as K_2O	pph	1,410	854
converted to K_2SO_4	pph	2,608	1,256
as per cent of total	%	3.1	1.5
Seed and ash removed in balance of boiler: (30%)			
Seed as K_2SO_4	pph	24,070	24,475
Ash	pph	4,224	2,562
Seed and ash removed in ESP: (99.8% Eff.)			
Seed as K_2SO_4	pph	56,150	56,995
Ash	pph	9,836	5,966
Particulates in stack gas with 99.8% ESP Eff.:	pph	132	126
as lbs/MBtu coal input to MHD combustor		0.018	0.017
Seed loss in stack gas with 99.8% ESP Eff.:			
as K_2SO_4	pph	112	114
as per cent of total	%	0.2	0.2

*Based on 15% K_2O in slag

TABLE 3-20

SEED LOSSES AND MAKE-UP COSTS

Seed Feed Rate as K_2SO_4: 82,840 pph

	70% S-Removal (NSPS)		100% S-Removal	
	pph K_2SO_4	% of Total	pph K_2SO_4	% of Total
With Slag from Slagging Furnace (15% K_2O in Slag)	2,608	3.1	1,580	1.9
With Ash Removed from HRSR (17% K_2O in Ash)	1,520	1.9	2,685	3.2
With Stack Gas	112	0.1	112	0.1
From Seed regeneration Process (1% Loss)	270	0.3	785	1.0
Total	4,510	5.4	5,162	6.2
Supplied with Coal Ash (0.55% K_2O in Ash)	390	0.5	390	0.5
Make-Up required	4,120	4.9	4,772	5.7
Contingency Loss	1,350	1.7	1,350	1.7
Total Make-Up Assumed	5,470	6.6	6,122	7.4
Seed Make-Up Cost at \$102/T K_2SO_4 Mills/kWhr	0.29		0.33	

Seed loss with stack gas is 0.1% for both degrees of sulfur removal. One percent loss has been assumed for the amount of seed processed for sulfur removal. For 70% sulfur removal this corresponds to a seed loss of 0.3% of total seed and for 100% sulfur removal to a seed loss of 1% of total seed because in this case all of the recovered seed is processed.

The total loss of seed for 70% and 100% sulfur removal adds up to 5.4% and 6.2% of total seed. A smaller amount of seed is contained in the coal ash which is assumed liberated in the MHD combustion process and thus provides some makeup. Deducting this smaller amount, the total remaining seed makeup requirement is 4.9% and 5.7%, respectively, for the two levels of sulfur removal. A contingency loss of about 30% of makeup requirements has been added which results in a total assumed makeup requirement of 6.6% and 7.4% of total seed for 70% and 100% sulfur removal. This corresponds to a total seed makeup cost of 0.29 mills/kWhr and 0.33 mills/kWhr. With seed makeup at $102/T K_2SO_4, the calcuated seed losses and costs are considered acceptable for both cases.

3.10.2 Seed Reprocessing

Recovered seed (K_2SO_4) must be reprocessed in a seed regeneration plant to a sulfur-free form for recycle into the combustion gas stream to meet the sulfur removal requirements on a continuous basis.

3.10.2.1 Design Criteria

a. Seed Flow Rates and Sulfur Removal

The coal feed rate is defined as 665,005 pph of Montana Rosebud subbituminous at 5% moisture content and the feed potassium feed rate is defined as 82,870 pph computed as K_2SO_4 or 951.05 pound moles/hour. The CO producer for the seed reprocessing plant in this conceptual design was considered to be coal fed and air blown. To meet New Source Performance Standards (NSPS) 70% of the sulfur injected with the coal must be removed from the combustion gas stream and the stoichiometric equivalent of recovered seed must be reprocessed. The NSPS with 70% sulfur removal formed the basis for the conceptual design, and as an alternate 100% sulfur removal was considered as previously discussed in Subsection 3.10.1. Seed processing requirements with flow rates for 70% (NSPS) and 100% sulfur removal are listed in Table 3-21.

TABLE 3-21

SULFUR FLOWS AND SEED REPROCESSING REQUIREMENTS

Basis: 665,005 pph Montana Rosebud Coal (5% H_2O) Feed to MHD Combustor

70% Sulfur Removal	pph	lb Mole/hr	% of Feed	% of Recovered Seed
Total Sulfur Flow	7,032	219.34	100	---
Sulfur Removal Required by EPA Regulation	4,922	153.54	70	---
Seed Required for Conductivity Computed as:				
K	37,186	951.05	100	100
K_2SO_4	82,870	475.53	100	100
Seed Reprocessing Required Computed as:				
K	12,007	307.08	32.3	32.3
K_2SO_4	26,757	153.54	---	32.3
KCO_2H	25,832	307.08	---	---
100% Sulfur Removal				
Total Sulfur Flow	7,068	220.47	100	---
Sulfur Removed	7,068	220.47	100	---
Seed Required for Conductivity Computed as:				
K	37,186	951.05	100	100
K_2SO_4	82,870	475.53	100	100
Seed Reprocessed Computed as:				
K	17,241	440.94	46.4	46.4
K_2SO_4	38,421	220.47	---	52.2*
KCO2H	37,092	440.94	---	---

* Weight % of K_2SO_4 + K_2CO_3 Recovered

b. Seed Regeneration Process

The Formate Process developed and described in the ETF Reference System Design Report[2] was chosen for the Task II study. Among all the seed regeneration processes studied, it is the only one suggested to date which offers the combined advantages of technical viability, large-scale industrial use experience, excellent energy efficiency and favorable capital cost. In this process, reaction in an aqueous medium between potassium sulfate (K_2SO_4), lime ($Ca(OH)_2$), and carbon monoxide (CO) is carried out at 30 atm and 392°F to produce potassium formate (KCO_2H) and gypsum ($CaSO_4 \cdot 2H_2O$):

$$K_2SO_4 + Ca(OH)_2 + 2CO = 2\ KCO_2H + CaSO_4 \cdot 2\ H_2O,\ \Delta H = -7\ \text{Kcal}$$

The gypsum is removed by filtration and water is removed from the potassium formate solution by evaporative drying. The gypsum can preferably be used as a construction material or disposed of as solid waste in a landfill. The potassium formate is recycled as sulfur-free seed to the MHD combustion gases. Modifications of the Formate Process described in the ETF Report are suggested on the basis of more recent information and, alternatively, to meet the requirements of 100% sulfur removal.

c. Allowable Technology Level

The technology level for this conceptual design is defined as "moderately advanced." Therefore, a somewhat developmental approach has been assumed for the gasifier and reactor systems. Although both have been used at capacities comparable to the requirements of the conceptual design, the Texaco pressurized coal gasifier proposed has been used only in pilot plant operations. The largest Bethlehem pressurized, multistage, continuous reactor used industrially has a 5 ft working diameter. Also, additional data must be gathered on the formate reaction before detailed reactor design can proceed. Vendor trials of proposed standard equipment (gypsum filter, evaporator and/or spray drier) should be made before incorporating them in a final plant design.

3.10.2.2 Methodology

a. 70% Sulfur Removal Reference Case

The process concepts developed for the ETF were applied with modifications required by the design criteria. A comprehensive flow diagram was prepared. Mass flow and enthalpy data were computed by drawing appropriate balances around major elements of equipment. The latter were specifically identified and sized after communication with equipment vendors and reference to the technical literature. A very preliminary equipment arrangement plan was prepared to determine space and building requirements. A capital cost estimate was made by combining vendor budget estimates for major equipment with estimates of subordinate equipment scaled from ETF cost data.

b. 100% Sulfur Removal Alternative

A sulfur-free seed feed mixture of potassium formate (KCO_2H) and potassium carbonate (K_2CO_3) was assumed, which inherently mandates 100% sulfur removal from the combustion gases. To permit application of the Formate Process and to effect minimum sulfur concentration in the combustion gases, a procedure was developed for separating K_2SO_4 from K_2CO_3 in the recovered seed mixture and K_2SO_4 from KCO_2H in the regenerated seed mixture. The remainder of the seed regeneration procedure is based on the Formate Process described for the ETF. A comprehensive flow diagram was developed and mass flow data were computed. A complete heat balance was not developed for this alternate case although an approximate comparison of probable net energy requirements was made with the 70% sulfur removal reference case.

3.10.2.3 Conceptual Design - 70% Sulfur Removal Reference Case

a. K_2SO_4 Solubility

The basic reaction described in the ETF Design Report[2] and in Subsection 3.10.2.1 of this report requires preparation of an aqueous solution of K_2SO_4 in which the required stoichiometric quantity of $Ca(OH)_2$ is dispersed. To minimize evaporation requirements, a saturated solution of K_2SO_4 at the reaction temperature of 392°F is presumed. Thus, per Figure 3-35, a 23% solution of K_2SO_4 is injected into the reactor.*

---

*It is not known whether mixtures with lesser amounts of water can be used. The patent literature on the Formate Process[12] seems to imply that it can. Also, a possible reaction scenario with perhaps negligible quantities of water has been proposed.[13] In any case, water present in the reactor discharge solution must be removed before the dry product KCO_2H can be recycled to the MHD combustion gases.

SOURCES: (1) SEIDELL, A. & LINKE, W.F., SOLUBILITIES OF INORGANIC AND METAL ORGANIC COMPOUNDS, 4th EDITION, PP. 81, 296

(2) INTERNATIONAL CRITICAL TABLES

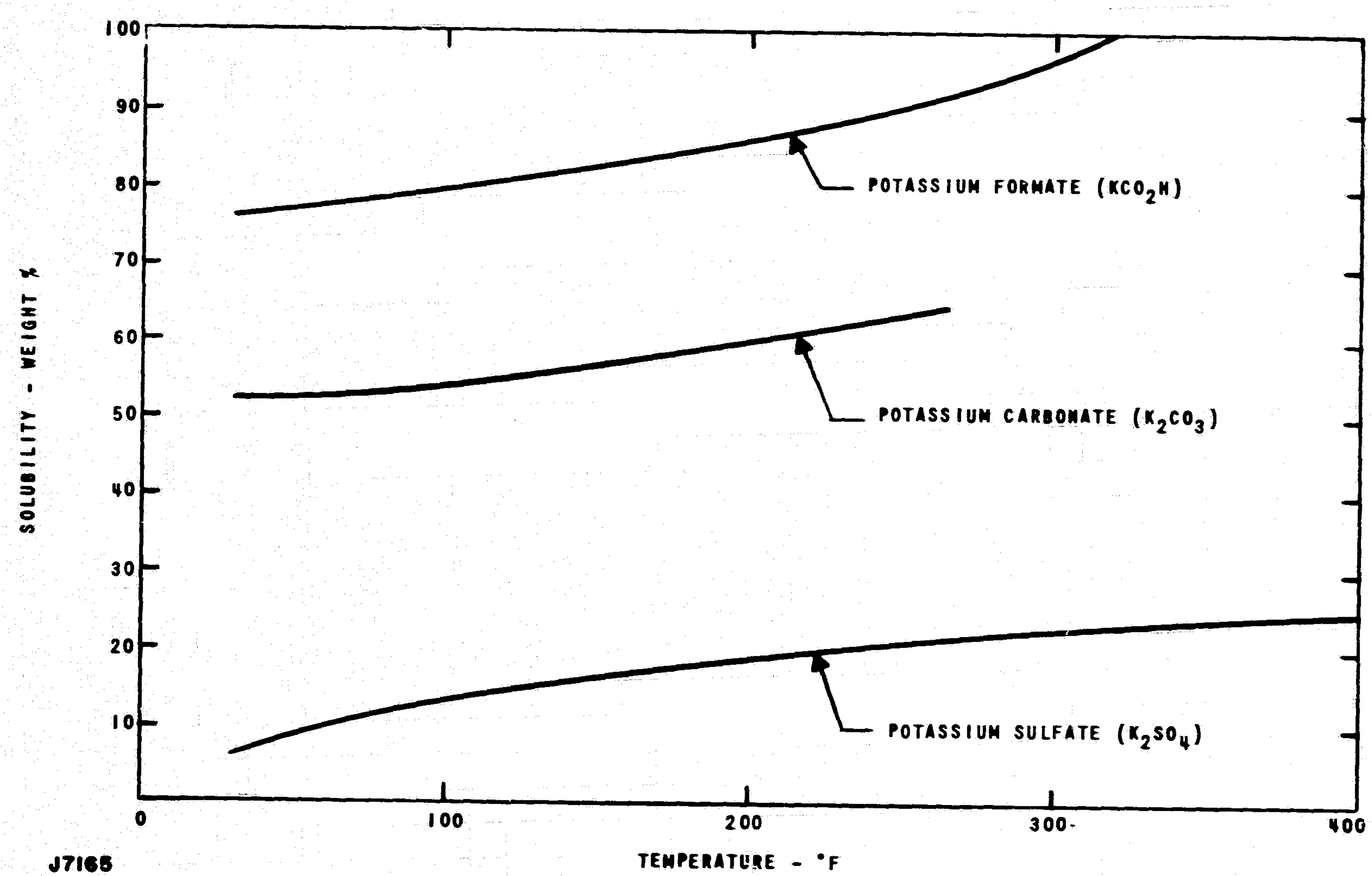


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Figure 3-35 Solubility in Water of Potassium Sulfate (K_2SO_4), Potassium Carbonate (K_2CO_3) and Potassium Formate (KCO_2H)

b. Total Sulfur Flow and Seed Reprocessing Requirement

Table 3-21 shows the quantity of sulfur introduced by the combined coal feed to the MHD combustor and to the seed regeneration plant gasifier, and the proportion of recovered K_2SO_4 seed which must be reprocessed to meet current EPA SO_2 emission regulations. Thus, 7032 pph (219.34 lb moles/hr) of sulfur are fed to the entire system and 70% or 4922 pph (153.54 lb moles/hr) must be removed from the combustion gas stream. Therefore, 26,757 pph (153.54 lb moles/hr) of K_2SO_4 must be reprocessed to yield 25,832 pph (307.09 lb moles/hr) of KCO_2H.

c. Process Flow Diagram

Figure 3-36 with accompanying tables presents the basic flow diagram and mass flows and enthalpies for individual process streams. The major processing sequences are:

1. Coal gasification to supply CO to the reactor
2. Air compression to supply oxidant to the gasifier
3. Dissolving to prepare the reactor solution
4. Reaction to produce the KCO_2H product
5. Filtration to separate the $CaSO_4 \cdot 2H_2O$ by-product
6. Drying to remove water from the KCO_2H product

Figure 3-37 presents a preliminary equipment arrangement plan.

(1) Gasification

A Texaco pressurized coal gasifier is proposed to produce the CO required for the formate reaction. Although this type of equipment is still under development, it has been operated extensively on a pilot plant scale at 100 TPD.[14] The design is a modification of partial combustion oil gasification technology developed by Texaco Development Corporation (also by Shell Development Corporation as licensed to Lurgi Kohle and Mineraloeltechnik GmbH). The oil fired process has been in large-scale industrial use for many years throughout the world. Lurgi's coal fired version has been used on an industrial scale at the SASOL synthetic fuel plant in South Africa.

The Texaco concept employs a coal-water slurry feed, either oxygen or air, a high-temperature gasification furnace pressurized in the range of 300 to 1200 psi and a proprietary waste heat recovery system.

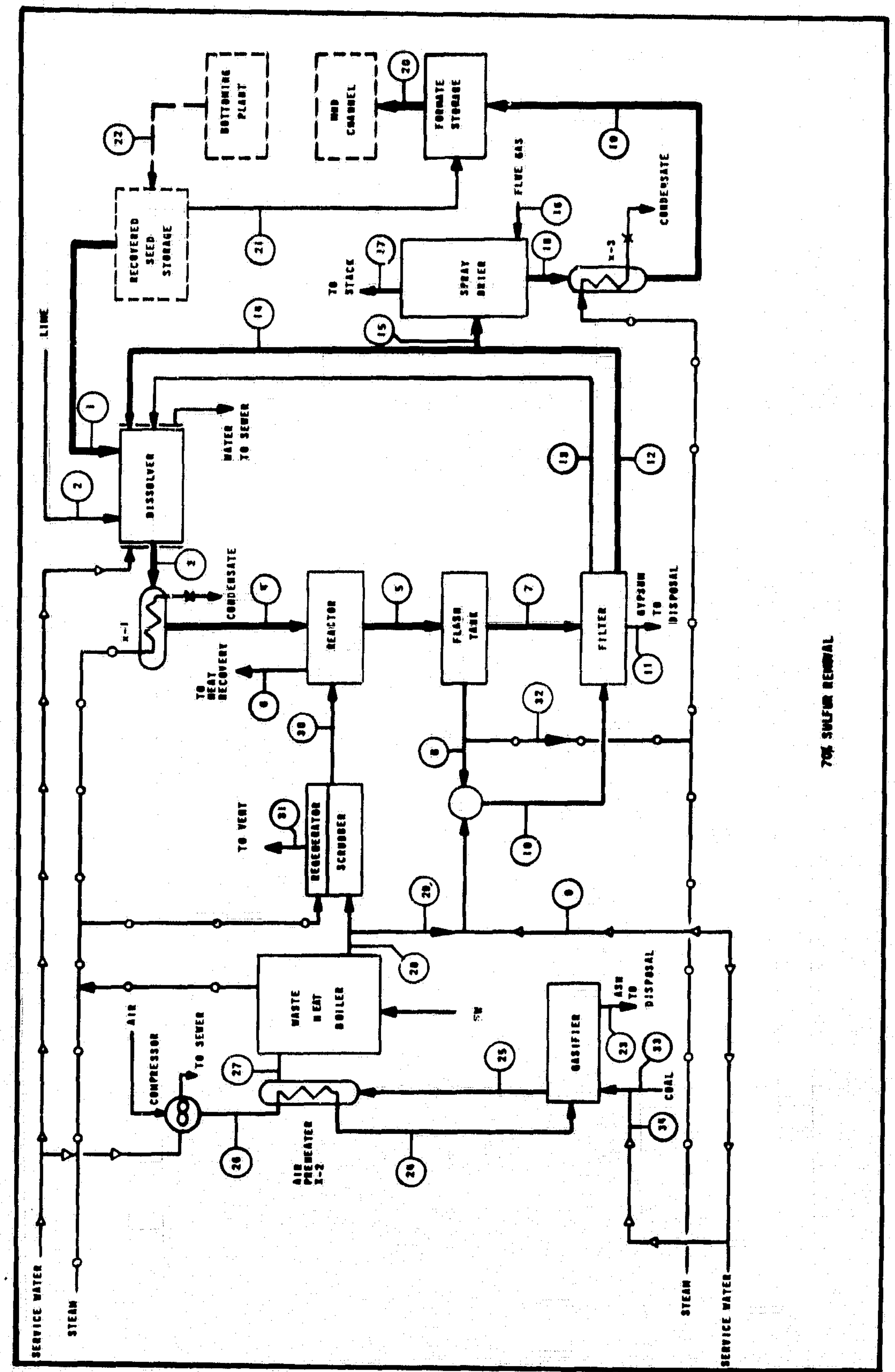

Figure 3-36a Process Flow Diagram for Seed Regeneration System for 70% Sulfur Removal

MASS FLOW (PPH)

STREAM NO.:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
AIR																		
Ar						524												
ASH																		
CaO		8,611																
$Ca(OH)_2$			11,376	11,376														
$CaSO_4 \cdot 2H_2O$					26,435		26,435				26,435							
CO						1,276												
CO_2																		
COAL*																		
FLUE GAS																2,516,590	2,516,590	
H_2						418												
H_2O_l			108,945	108,945	90,831		73,476		91,577	109,017	6,609	68,962	106,922	2,780	66,172			
H_2O_g						10,479		12,734									66,172	
KCO_2H			2,591	2,591	28,423		28,423					28,921	1,502	1,089	25,832			25,832
K_2SO_4	31,923		32,442	32,442	5,685		5,685					5,384	301	218	5,166			5,166
$MISC._g$																		
N_2						30,382												

STREAM NO.:	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
AIR						40,121		40,121								
Ar							524		524	524		524				
ASH					854											
CaO																
$CaSO_4 \cdot 2H_2O$																
CO							9,877		9,877	9,877		9,877				
CO_2							6,114		6,114	6,114			6,114			
COAL*															8,543	
FLUE GAS																
H_2							418		418	418						
H_2O_l														4,722		4,537**
H_2O_g							4,537		4,537	4,537	4,537		?			
KCO_2H	25,832	25,832														
K_2SO_4	5,166	55,947	50,781	82,704												
$MISC._g$							418		418	418		418				
N_2							30,382		30,382	30,382		30,382				

STREAM NO.:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Temp. °F	70	70	200	342	382	382	212	212	70	200	205	200	200	205	205	252	150	150	334	334	70	70
Press.-ATM	1	1	30	30	30	30	1	1	5	5	1	1	1	1	1	1	1	1	1	8+	1	1
Enthalpy- (10^6 Btu/hr)	0	4.59	14.34	29.84	25.86	15.24	11.45	14.17	0	14.17	25.60	8.97	13.90	0.38	8.60	114	122.08	0.53	1.74	1.74	0	0

STREAM NO.:	23	24	25	26	27	28	29	30	31	32	33	34
Temp. °F	2450	800	2450	500	2244	392	392	392	212	212	70	70
Press.-ATM	1	30	30	30	30	30		20	1	1	1	5
Enthalpy- (10^6 Btu/hr)	0.43	7.60	41.38	4.48	38.26	9.68	5.40	3.80	47+	5.96	0	0

FORMATE PROCESS
MASS FLOW/TEMPERATURE/PRESSURE/ENTHALPY
PLANT SIZE BASIS: 665,005 PPH MONTANA ROSEBUD COAL (5% H_2O) TO MHD COMBUSTOR

70% SULFUR REMOVAL

6 May 1980 MAIN Fig. 3.10.3-2

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Figure 3-36b Mass Flows and State Data for Figure 3-36a

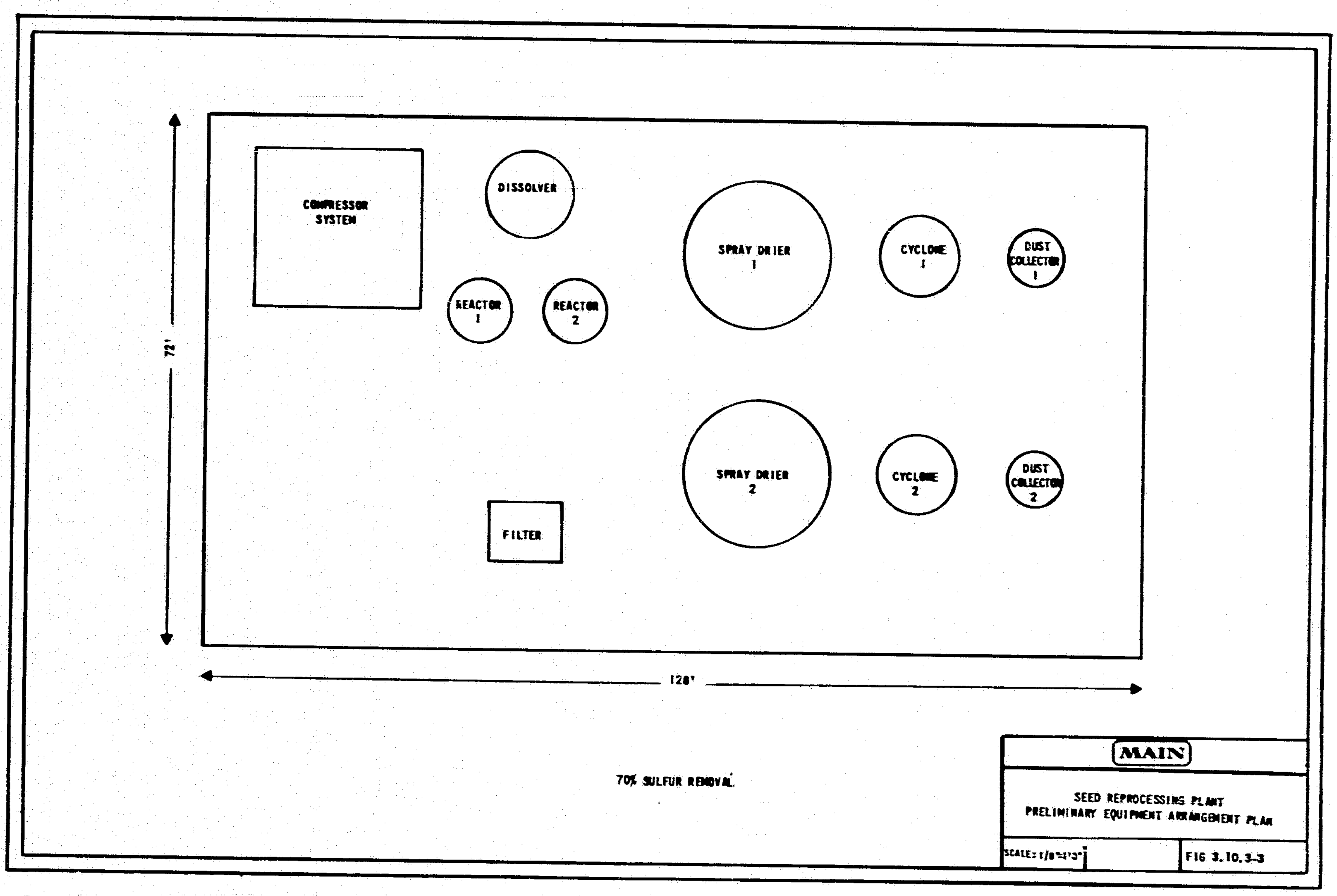

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Figure 3-37 Preliminary Equipment Arrangement Plan for Seed Reprocessing Plant

For this conceptual design, coal feed and air oxidant was an operational precondition. Illinois No. 6 coal instead of Montana Rosebud subbitumonous is shown as the gasifier feed in the process flow diagram because published data on operation of the Texaco coal gasifier is available only for that type. However, the sulfur content assumed to be introduced by the gasifier coal was computed as though it were Montana Rosebud. The mass flows and enthalpies shown were computed from Texaco data for a much larger unit.(15)

Raw gas composition from the Texaco gasifier unit is:

CO	18.9% by weight
CO_2	11.7
H_2	0.8
N_2	58.1
Ar	1.0
H_2O	8.7
misc.	0.8
TOTAL	100.0%

CO_2 is removed by an ethanolamine scrubber-regenerator system which follows the gasifier heat recovery units.

(2) <u>Compression</u>

For the ETF conceptual design a Wellman-Galusha atmospheric coal gasifier followed by a gas compressor was selected because it was the only hardware option which could meet the requirement of industrial availability. The selection of the moderately advanced Texaco gasifier for this early commercial plant permits the substitution of a simpler air compressor for the gas compressor.

(3) <u>Dissolving</u>

The equipment proposed for this operation is a 12 ft in diameter x 23 ft high stainless steel, stirred jacketed tank with a one-hour capacity into which recovered seed (K_2SO_4) and unslaked lime (CaO) are proportioned by gravimetric feeders. Recycle and wash water streams from the gypsum filter supply the requisite quantity of water to meet the saturated solution condition specified in Subsection 3.10.3-a. The sum of the sensible heat in the feed streams plus the net exothermic heat from CaO hydration and heat of solution for K_2SO_4 requires a moderate amount of jacket cooling to limit the outlet temperature as shown to 200°F.

(4) Reaction

The exothermic formate reaction

$$K_2SO_4 + 2\ CO + Ca(OH)_2 = KCO_2H + CaSO_4 \cdot 2H_2O,\ \Delta H = -7\ Kcal$$

is conducted at 30 atm and 392°F to prevent formation of insoluble K-Ca double salts. The equipment proposed comprises two 9 ft inside diamter x 36 ft high three-stage Type 316 stainless steel, jacketed, stirred, pressurized continuous reacctors of the type manufactured by Bethelhem Equipment Corporation. The equipment has been sized for a one-hour reaction time although it is probable that smaller units can be used. Feeds injected at 30 atm to the reactor are the $Ca(OH)_2$ slurry-K_2SO_4 solution (containing KCO_2H + K_2SO_4 recycle) and the gas mixture of CO, H_2, N_2 and small quantities of miscellaneous other gases not removed by the scrubber. Enough CO is injected to allow a small excess beyond the stoichiometric requirement to bleed with the off-gas and to be used to detect and control the extent of reaction.

Other gases pass through unreacted and are discharged collectively with the excess CO to heat recovery via combustion in the bottoming plant radiant furnace. The product KCO_2H solution containing $CaSO_4$ $2H_2O$ by-product is discharged to the flash tank for depressurizing and then to the rotary filter for gypsum removal.

(5) Filtration

The insoluble gypsum by-product is removed from the KCO_2H product solution in a Bird-Yound Type 316 stainless steel, unpressurized 3 ft in diameter x 3 ft long rotary filter. Applications experience obtained with this unit since 1978 when the ETF conceptual design was prepared indicate that capacity per square foot of filter area is much larger than assumed earlier. The filter unit has been sized on the basis of this new information. Also, further study since 1978 has indicated that the filtration probably does not have to be pressurized. Verification in vendor tests will ultimately have to be performed.

(6) Drying

An evaporative drying system is required to remove all water from the KCO_2H product solution. To minimize energy requirements, a recompression evaporator has been studied for concentrating the product solution from 32% to about 60% solids. Spray driers are known to be most effective for this level of solids concentration in the feed. However, the solubility of unreacted K_2SO_4 present in the product solution is probably too low to avoid crystallization which would complicate operation of a recompression evaporator. Therefore in the process flow diagram (Figure 3-36) only spray drying is shown. Assuming a discharge dry bulb temperature of 150°F, enough flue gas is theoretically available at 252°F for the evaporation. About 56% (2,516,590 pph) of the flue gas available from the ESP discharge (4,515, 830 pph) of the bottoming plant is required. The equipment proposed for this operation comprises two Type 316 stainless steel, Swenson spray drier systems (drier plus cyclone plus dust collector).

Each spray drier has a capacity of 250,000 SCFM and is 20 ft in diameter x 35 ft high. Since the melting point of KCO_2H is 334°F and its vapor pressure in that temperature region is extremely low, a liquid formate storage and seed injection system is proposed. Heat exchanger x-3 converts solid KCO_2H to a liquid and steam coils in the formate storage system will maintain the liquid phase. Unreprocessed recovered seed may be fed at the required rate (50,781 pph) to form a pumpable slurry of K_2SO_4 in molten KCO_2H for continuous reinjection into the combustion gases.

d. Overall Energy Requirements

The enthalpies of individual streams are shown in the data which accompanies Figure 3-36. A tabulation of the overall energy inputs and outputs for the process as a whole is shown in Table 3-22. Excess energy from the seed regeneration plant includes:

1. Steam from the waste heat boiler
2. Combustible CO and H_2 discharged in the reactor off-gas
3. Sensible heat in the reactor off-gas
4. Steam contained in the reactor off-gas
5. Steam contained in the gasifier off-gas
6. Low pressure saturated steam from the flash tank

TABLE 3-22

OVERALL ENERGY REQUIREMENTS

(70% Sulfur Removal - See Figure 3-36)

Thermal Input (10^6 Btu/hr)		Thermal Output (10^6 Btu/hr)	
x-1 (steam)	15.61*	Waste Heat Recovery (steam)	28.58**
x-3 (steam	1.22*	Flash (steam) 32	5.96**
Lime Hydration 2	4.59*	Reactor Discharge (gas-sensible) 6	3.10**
K_2SO_4 Heat of solution	-2.09	Reactor Discharge (steam) 6	12.18**
Fuel Gas 16	114.00	Heat of Combustion (CO) 6	5.55**
Coal 33	105.68*	Gasifier Discharge (steam) 29	5.40
Compressed Air	4.48	Gypsum Discharge 11	25.60
		Formate Discharge 19	1.74
TOTAL	243.5	Ash Discharge 19	0.43
		Dissolver Cooling Water	2.43
		Spray Drier Discharge 17	122.08
		x-1 + x-3 Condensate	2.39
		Scrubber Discharge (CO_2)	0.47
		Heat of Combustion (H_2) 6	21.57**
		Balance Error	6.02
		TOTAL	243.5

ELECTRICAL INPUT

Auxiliary Motors (9773 hp) 7.3 MWe Compressor Cooling Water 10.93

* System Debit = 127.1 x 10^6/Btu/hr

** System Credit = 82.3 x 10^6/Btu/hr

Net System Debit = 44.8 x 10^6/Btu/hr = 13.4 MWt

Of these, only steam from the waste heat boiler in excess of that used internally for seed reprocessing (11.8 x 10^6 Btu/hr) and combustibles in the off-gas from the reactor (27.1 x 10^6 Btu/hr) can be readily utilized for energy recovery, i.e., a total of 38.9 x 10^6 Btu/hr. Power for about 10,000 hp is required for continuously running motors, of which 4,000 hp or 40% is required for the gasifier air compressor.

3.10.2.4 Preliminary Conceptual Design - 100% Sulfur Removal Case

a. Rationale

As previously mentioned the alternate case of 100% sulfur removal was considered to minimize the sulfur concentration in the gas and its potential corrosion problems. Reactions bewtween sulfur-free potassium seed and sulfur produced in combustion of the coal fuel are assumed to produce K_2SO_4 in the gas which is removed by the seed recovery system. As shown in Table 3-21 for the selected coal (Montana Rosebud subbituminous) and seed feed rate (1%K), at least about 1/3 of the seed feed must be introduced as a sulfur-free compound to satisfy NSPS sulfur removal requirements. With continuous processing, and conversion of all of the seed recovered as K_2SO_4 to a sulfur-free compound for reinjection essentially 100% sulfur removal from the gas is accomplished. In this case seed in excess of that reacting to form K_2SO_4 is assumed to be recovered as K_2CO_3 from the gas. Since recovered K_2CO_3 does not need to be reprocessed for sulfur removal, a prodcedure for separating recovered K_2CO_3 from K_2SO_4 before the latter is processed for sulfur removal is proposed. The recovered seed will now be recycled and reinjected as a mixture of K_2CO_3 and KCO_2H.

b. Solubilities for the System $K_2SO_4/K_2CO_3/H_2O$

The solubility of K_2SO_4 in saturated K_2CO_3 solutions is shown in Table 3-23. Since at ambient temperatures, K_2SO_4 is virtually insoluble in a saturated solution containing more then 50% K_2CO_3, a separation procedure based on differential solubilities is possible.

c. Process Flow Diagram

Table 3-21 shows the total quantity of sulfur introduced by the combined coal feeds to the MHD combustor and to the

TABLE 3-23

SOLUBILITIES FOR THE SYSTEM K_2CO_3-K_2SO_4-H_2O

Temperature (°C)	Sat'd Solution - Wt %	
	K_2SO_4	K_2CO_3
25	0.03	52.8
50	0.08	54.1
150	0.2	68.6

Source: Seidell, A. and Linke, W.F., Solubilities of Inorganic and Metal Organic Compounds, 4th Edition, Van Nostrand, Princeton, p. 89.

seed regeneration gasifier. Thus a total of 7068 pph* (220.47 lb moles/hr) of sulfur are fed, all of which will be removed from the combustion gas stream. Figure 3-38 presents a preliminary conceptual flow diagram plus mass flows, temperatures and pressures for individual process streams.

To separate K_2CO_3 from K_2SO_4, 100% of seed recovered from the bottoming plant is fed to a dissolver where a saturated solution of K_2CO_3 is prepared. The K_2SO_4 remains undissolved and is separated by Filter 'A'. Residual K_2CO_3 solution remaining on the filter cake is removed, as shown, by displacement washing. The 52.3% saturated K_2CO_3 filtrate solution is dried by spray drying for recycle to the combustion gases. The K_2SO_4 filter cake is processed via a regeneration system analagous to the 70% sulfur removal reference case described in Subsection 3.10.3.

A two-stage KCO_2H solution evaporation system is shown in which the filtrate from the gypsum filter is first concentrated from 32% to 64% solids and then evaporated to dryness by spray drying. Excess K_2SO_4 introduced in the reactor feed is mixed with the dried KCO_2H in the spray drier output. It can be removed by hot melt filtration in K_2SO_4 Filter 'B' and recycled** to the K_2SO_4 dissolver. Pure KCO_2H liquid is recycled to the combustion gases as regenerated sulfur-free seed.

d. Mass Flow and Energy Utilization

The extra processing burden of 100% sulfur removal versus 70% sulfur removal requires nominally a 43% larger seed regeneration plant. The stream mass flows computed for the process described in Subsection 3.10.4-c above are shown in Figure 3-38. Stream enthalpies were not computed. However, it follows that the overall energy utilization requirement will be no more than proportionally

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* Excluding coal fed for CO bleed from reactor

** The small amount of KCO_2H retained on the filter cake was not shown in the mass flow data. It was assumed to be completely separated.

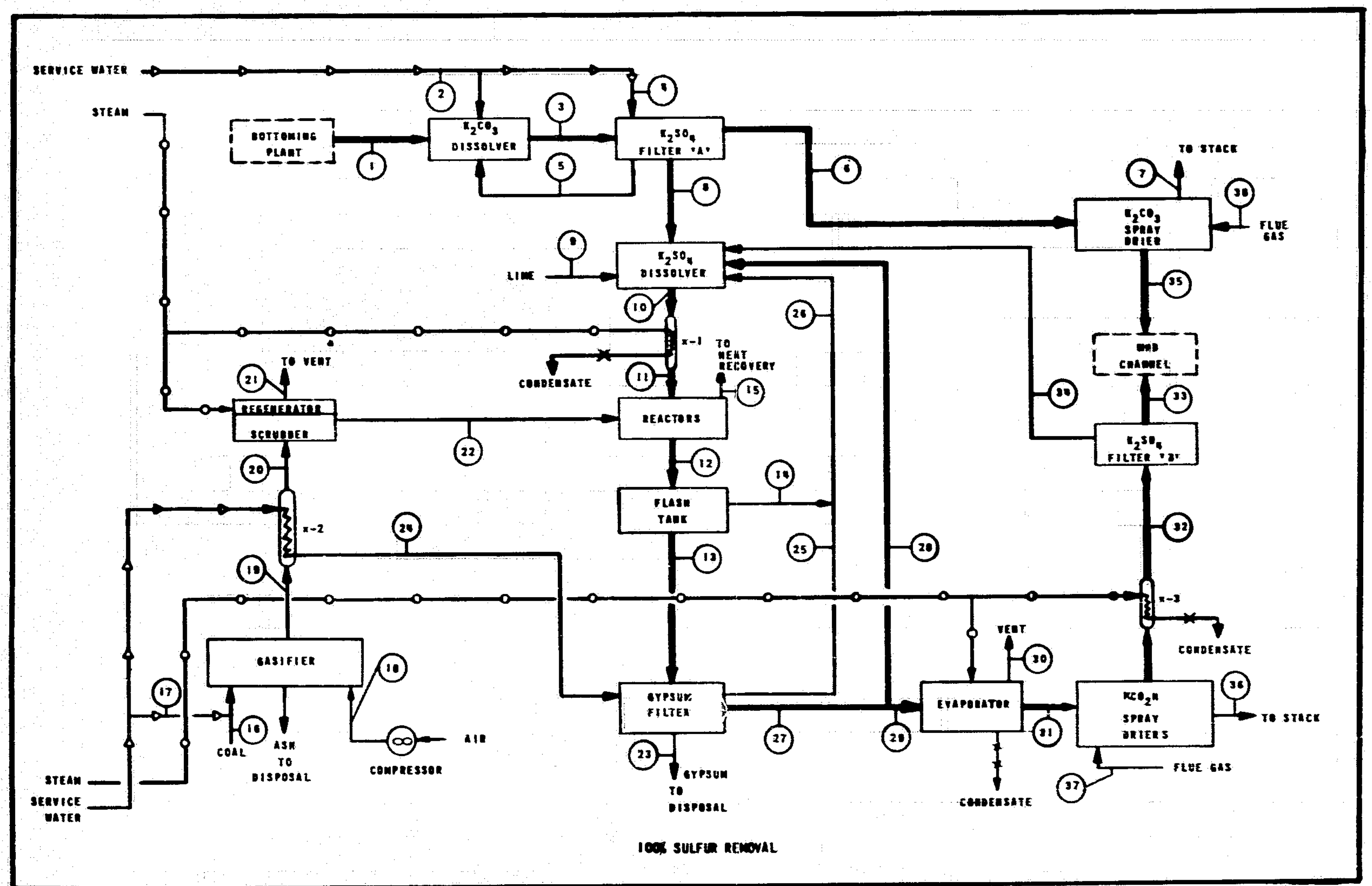

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Figure 3-38a Process Flow Diagram for Seed Regeneration System for 100% Sulfur Removal

MASS FLOW (PPH)

LIQUID-SOLID

Stream:	1	2	3	4	5	6	8	9	10	11	12	13	16	17	23	24	25
K_2SO_4	38,421		38,421				38,421		46,835	46,835	8,414	8,414					442
K_2CO_3	35,251		35,251		2,245	35,251											
KCO_2H									3,709	3,709	40,801	40,801					2,143
H_2O		36,035	36,035	18,018	18,018	31,766	4,269		154,423	154,423	131,435	106,202		6,811	9,490	121,924	118,007
$CaSO_4 \cdot 2H_2O$											37,958	37,958			37,958		
$Ca(OH)_2$									16,335	16,335							
Ca O								12,364									
Coal													13,048				

Stream:	26	27	28	29	31	32	33	34	35
K_2SO_4	442	7,972	323	7,649	7,649	7,649	37,092	7,649	
K_2CO_3									35,251
KCO_2H	2,143	38,658	1,566	37,092	37,092	37,092			
H_2O	143,240	100,629	4,076	96,553	25,607				

GAS

Stream:	7	14	15	18	19	20	21	22	30	36	37	38
O_2												
N_2			40,209		40,209	40,209		40,209				
H_2			718		718	718		718				
CO_2					5,752	5,757	5,752					
CO			1,831		14,182	14,182		14,182				
H_2O_g	31,766	25,233	15,042		6,811	6,811	?	6,811	70,946	25,607		
Flue Gas	2,283,857									995,828	995,828	2,283,857
Air				52,424								

FURMATE PROCESS
MASS FLOW/TEMPERATURE/PRESSURE

PLANT SIZE BASIS:
665,000 PPH MONTANA ROSEBUD COAL (5% H_2O)
TO MHD COMBUSTOR

100% SULFUR REMOVAL

8 May 1980 **MAIN** Fig. 3.10.4-1

Stream No:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Temp. °F	70	70	70	70	70	70	150	70	70	200	392	392	392	212	392
Press. - ATM	1	5	1	5	1+	1+	1	1+	1	30	30	30	1+	1+	30

Stream No:	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Temp. °F	70	70	1000	2450	392	212	392	200	200	200	200+	200	200	200	212
Press. - ATM	1	5	30	30	30	1	30	1	8	1	1+	1+	1+	1+	1+

Stream No.:	31	32	33	34	35	36	37	38
Temp. °F	212+	334+	334+	334	150	150	252	252
Press. - ATM	1	1+	8+	1	8+	1	1+	1+

J7170

Figure 3-38b Mass Flow and State Data for Figure 3-38a higher than the 70% sulfur removal reference case as long as no extraordinary burden is introduced for the additional evaporation required by the K_2CO_3-K_2SO_4 separation scheme. The spray drying sequences shown, taken together, will require about 73% of the available flue gas from the bottoming plant. A recompression evaporator employed as shown to concentrate the formate product solution from 32% to 64% solids will consume about 500 additional horsepower and a small amount of additional steam.

3.10.3 Seed Feed System

The seed feed system will take the potassium formate (KCO_2H), from the seed regeneration system, mix it with the proper amount of recovered potassium sulfate (K_2SO_4) and deliver it to the combustor outlet. As discussed in Subsection 3.3.2, it is proposed to inject the seed into the combustor as a liquid slurry, consisting of solid K_2SO_4 suspended in molten KCO_2H. The KCO_2H must be kept at 334°F to remain molten. For 70% sulfur removal from the combustion gases, the ratio of K_2SO_4 to KCO_2H is $\sim 2:1$. In the laboratory, molten KCO_2H was mixed with K_2SO_4 in various proportions ranging from KCO_2H alone to 25% formate by weight. As K_2SO_4 was added to the molten formate the viscosity of the mix increased. Although viscosity measurements were not made, the mixture still appeared to be pumpable with 75% K_2SO_4 and 25% KCO_2H by weight.

Figure 3-39 shows a conceptual design for injecting the seed to the combustor as a molten slurry. This scheme isolates components upstream of the feed system from the high electrical potential of the combustor. As can be seen liquid formate will be pumped to one of two mixing tanks. At the same time recovered K_2SO_4 is also fed to the mixing tank. The mixing tank not being filled will provide seed to the combustor.

The dual mixing tanks and pumps will be one means of providing electrical isolation, as only one set of equipment is in contact with the combustor at any given time. Electrical isolation can also be achieved by pumping the molten seed from the mixing tanks to the final storage tank in a pulsing flow. The air gap between pulses therefore provides the electrical isolation required. This scheme provides two means of isolating the combustor electrically. Only the final holding tank and downstream equipment should be at the combustor potential if the air gap is maintained. If the air gap fails the combustor potential would only affect equipment back to the mixing tank being used to feed the holding tank at that time.

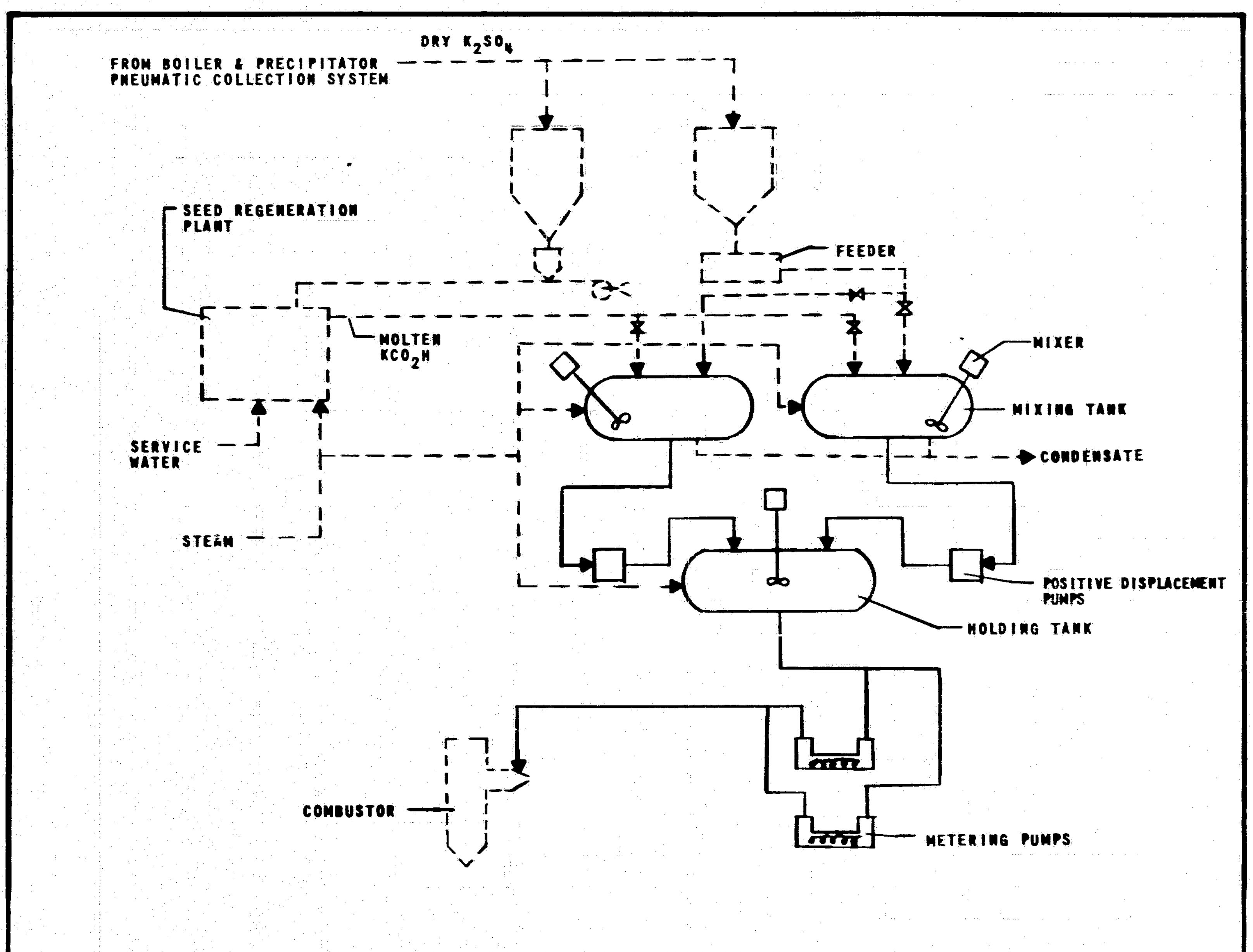

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Figure 3-39 Schematic Diagram of Seed Feed System

3.11 INVERTER SYSTEM

3.11.1 Introduction

This section describes the conceptual design of the static inverters for this nominal 950 MW_e commercial scale, entry level, coal fired MHD/Steam power plant.

In all major respects, this design follows the concepts already detailed in the ETF report.[2] Therefore, appropriate references will be made to that report. This applies, in particular, to technical expositions regarding inversion technology made in the ETF report which were considered necessary in view of the fact that, in the United States, the loading of experimental MHD channels had never (or certainly not to any meaningful extent) been made via an inverter interface with a real power system.

However, the present report suggests some innovations: use of water-cooled thyristors; a single broadband filter for ac harmonics instead of individual sharp tuned filters for the major characteristic harmonics; a static continuously variable var supply instead of switched capacitors for reactive compensation; additional inverter control for the MHD channel.

Section 2.16.1.9 of the ETF report gave a Rationale for Choice of Inversion System specifically favoring the line (naturally) commutated inverter as against a variety of forced or artificially commutated schemes. If there were justification for that choice in the case of the ETF, which is assumed to be an MHD demonstration prototype, there is even more justification in the present larger commercial scale case for choosing that system already proven in the high power, high voltage environment of high-voltage dc transmission. Apart from (roughly) compatible magnitudes of scale of components, there is the decided advantage of a considerable available base of expertise from which solutions may be found to the problems of this first-of-its-kind MHD application.

The only other general point to be made here is to again reinforce those parts of the ETF exposition which called attention to the need-to-know in a final real design, certain characteristics of the particular ac power/transmission system in which the MHD plant is to be located.

3.11.2 Inverter Bridges

The inverter components are scaled to 525 MW of nominal MHD base power. For the ETF, the inverter system was modularized to accommodate two types of channel construction (Faraday and diagonal); three modes of channel loading (segmented Faraday, three-terminal, and five-terminal diagonals); and all for two baseload MHD powers.

Here the reference plant utilizes a diagonal channel with five-terminal load circuit output. There are then only two combinations of voltages and currents corresponding to the two possible external arrangements of the total load; namely, the independent and parallel connections.

It appears now that from channel considerations alone, the parallel loading connection is preferred. This happens to coincide with the preference from the inverter system point of view. While only the parallel loading inverter configuration will be detailed here, some comments in the next section emphasize why this channel-inverter interface is advantageous compared to the independent loading interface.

The actual extraction points or consolidated frame electrodes along the channel which determine the absolute values of the voltages and currents are, of course, given and chosen from the point of view of channel efficiency and dynamics (see Section 3.1.3). These are shown in Table 3-24.

The number of bridges and internal thyristor components are indicated in Table 3-25 and are predicated on the following assumptions or constraints. To some extent, in a committed application, these would be resolved jointly with the suppliers.

The largest current rating for a single thyristor currently in use in high-voltage dc converters is 2200 A (3-phase, 6-pulse bridge rating); and the corresponding peak inverse voltage (PIV) withstand about 3000 V. The state of the art is such that very large numbers of these may be coupled in series to satisfy the required pole voltage which to date has reached 400 kV (200 kV per bridge with two bridges in series to form a 12-pulse group). A rough rule of thumb is that a string of thyristors in series (six strings for the six legs of a bridge) contains one thyristor for each kilovolt of operating voltage across the bridge, taking into account both repetitive blocking voltage needs in steady operation, transient non-repetitive PIV, and redundancy against failure of individual units.

For industrial converters (medium power at low voltage), current ratings of about 2500 A are available but the blocking voltage capability is usually something less than 3000 V, and usually only a modest number need be put in series.

It is assumed that 2500 A ratings with inherent 10% continuous overload capacity will be available at a PIV of about 3000 V.

In high-voltage dc transmissions, it has been possible to satisfy the current requirements with a single string per bridge leg, e.g., a 1000 MW, + and - 400 kV line is only 1250 A per pole. Only some few early solid state installations, when thyristors were still relatively undeveloped, required, at most, two or three strings in parallel.

TABLE 3-24

FIVE-TERMINAL PARALLEL CONNECTION

kV	kA	MW
5.4	5.3	28
9.1	5.6	51
13.6	4.8	65
19.0	3.9	74
25.9	11.9	308
		526

TABLE 3-25

FIVE-TERMINAL PARALLEL CONNECTION

Load kA	kV per Bridge of 12-p Group	No. of Groups in Parallel	No. Parallel Strings/Leg	Total No.* Thyristors	MW Per** Bridge
5.3	2.7	1	2 x 2500 A	120	14.0
5.6	4.6	1	2 x 2500 A	168	25.5
4.8	6.8	1	2 x 2500 A	216	32.5
3.9	9.5	1	2 x 2500 A	312	37.0
11.9	13.0	2	3 x 2000 A	1224	76.5
31.5		6 Groups (12 Bridges)		2040	

* Channel output voltage = 25.9 kV; voltage per 6-pulse bridge (2 such bridges in series forming 12-pulse group) = 13 kV. Required PIV = 3.5 x 13 = 45.5 kV each bridge leg. Number of series thyristors without redundancy = 45.5/3 kV PIV = 15. With redundancy, use 17. Then, 17 in series per string x 3 strings in parallel per leg x 6 legs per bridge = 306; and x 4 bridges = 1224 thyristors.

** 306 MW load from Table 3-24; by 2 groups in parallel and 2 bridges per group = 76.5 MW per bridge.

It is assumed here that up to three strings each of 2500 A can be engineered in parallel internally in a bridge without compromising the ancillary circuitry for independent voltage division among series thyristors of each string and for equal current division among strings in parallel.

It is assumed, also, that the failure rate of individual thyristors in this arrangement will remain as low as in current high-voltage dc converters. Tentatively, we use enough in series such that, upon failure of one in a string of 12 or less, or failure of two in a string of more than 12, the PIV capability of the remainder shall not be less than the required PIV for the bridge.

From Section 2.16.1.2 of the referenced ETF report, the PIV (transient surge blocking voltage) is taken as 3.5 times the rated dc voltage, and the repetitive steady operation blocking voltage as 1.75 times - both of these including a multiplier for increase of the operating voltage to allow for MHD channel power up to about 125% of baseload.

3.11.3 Converter Transformers

From the ETF report (Section 2.16.1.4.3), the MVA ratings to allow for the reactive power consumption of the inverters, including the different control modes of operation, are taken as 1.19 times the MW through-power.

The capacities for all bridges except possibly the last group in Table 3-25, are sufficiently small that three-winding single phase transformers may be considered. One bridge of a 12-pulse group would output to a wye-connected secondary, the other bridge to a delta-connected secondary, while the third or primary winding connects, of course, to the ac side. The 30° transformation shift between the two secondaries gives the 12 pulse dc to ac conversion so that the smallest normal harmonic injected into the ac side would be the 11th, followed by the 13th, then the 23rd and 25th, etc.

Alternately, each bridge of the 12-pulse group may have its own two winding transformer, one wye-wye, the other delta-wye. In this case, the transformers could be three-phase units.

Unlike the transformers in the ETF design, where taps were required on each converter winding because the bridges could be connected to any one of many working dc voltages, here the windings can have a fixed turn ratio. The secondary winding ac line-to-line voltages are calculated according to the formulae of the ETF report.

As in the ETF design and for the same reasons (Section 2.16.1.4.4), it is considered advantageous to transform to the ac grid voltage, assumed to be 345 kV, in two steps: first, to an intermediate 15 kV which is the same voltage as the bottoming plant generator bus. However, the converter transformer 15 kV bus is not connected to this, although provision may be made via a normally open bus tie breaker or switch so that an outage of, say, the main MHD 15/345 kV transformer may still allow MHD operation without the bottom plant, or of both at reduced load.

On the above basis, the converter transformer self-cooled (OA) ratings are shown in Table 3-26. For the sake of uniformity, some have slightly more capacity than actually needed by their connected bridges. In all cases, the overload capacity for channel loadings above baseload is taken by a suitable forced air (FA) rating of 120 or 125%.

These ratios of installed self-cooled MVA to nominal MHD 525 MW contrast sharply with the approximatly 1.9 ratio in the case of the ETF, i.e., 1.6 times channel power because of the fragmentation of loading circuits of the segmented Faraday channels, principally, and 1.19 times for the legitimate MVAR requirements of the inverter (1.6 x 1.19 = 1.9).

The main inverter transformer to raise the voltage to ac grid level would, of course be the same for both channel connections, say, 500/600 MVA, OA/FA, 15 kV delta/345 kV wye, grounded or not, depending on system preference. Standard + and - 10% LTC (on load tap changing) would be placed on the high side to compensate for deviations of the ac system voltage and to assist the inverter controls during off baseload operation.

The final design should evaluate three single-phase 165/200 MVA units versus two smaller three-phase units of 250/300 MVA.

Note that, since filtering of the ac harmonics and compensation of the inverter reactive power is to be done at the intermediate 22 kV bus, the main transformer(s) do not need the MVA rating of the sum of the converter transformers.

Comments on Parallel Versus Independent Connections

As previously indicated, the preferred MHD channel for the reference plant of this report is a five-terminal diagonal with parallel load connection. The corresponding inverter system configuration has therefore been detailed for this. It is nevertheless useful to give some idea of the inverter configuration which would result from a five-terminal diagonal of the same nominal 525 MW rating, but using the independent load takeoff. This is to emphasize that the chosen parallel loading scheme leads to significantly fewer number of components and to inherently greater overall simplicity.

TABLE 3-26

FIVE-TERMINAL PARALLEL CONNECTION

Load kA	MW per Bridge	No. of Groups In Parallel	3-Winding, 1-ph kV sec/15 kV	2-Winding, 3-ph kV sec/15 kV
5.3	14.0	1	1-2.3 kV, 35 MVA	2-2.3 kV, 20 MVA
5.6	25.5	1	1-3.9 kV, 60 MVA	2-3.9 kV, 30 MVA
4.8	32.5	1	1-5.8 kV, 80 MVA	2-5.8 kV, 40 MVA
3.9	37.0	1	1-8.1 kV, 90 MVA	2-8.1 kV, 45 MVA
11.9	76.5	2	Use 2-Winding	4-11.1 kV, 95 MVA
		Total Installed MVA	635	650
		Ratio: MVA/Baseload MW	1.21	1.23

Basically, this is due to the fact that about three times as many kiloamps have to be processed in the independent loading case, all at a uniformly low voltage. On the other hand, for the parallel connection, the ratio of MW to kA (i.e., the voltage of the loads) increases, with the largest block of power having also the highest voltage. In this case, it is the current which tends to remain uniformly low (relatively) in all or nearly all of the loading sections.

The first consequence of this is that the total number of individual thyristors would be about 29% more for the independent configuration. More important is that the total number of bridges and 12-pulse groups would be about twice the number in Table 3-25. While the resulting space penalty may not increase directly with the increase in quantity, due to the possibility of vertical stacking, it is expected to be significant no mattter what the physical arrangement.

Another consequence is a larger number of thyristor strings in parallel within each bridge, together with a larger number of bridge groups in parallel, as many as three in some cases. The first means more ancillary circuitry in the bridges to ensure equal current division between strings. The second involves separate external control with some form of current balancing feedback regulation. In conjunction with the controls matching inverter characteristics with those of the MHD generator, there will be instabilities due to inherent unequal division of current between parallel inverters. One will naturally move to constant extinction angle operation; the other to current regulation; total load current fluctuations may lead to sudden interchange of these modes. Some form of current sharing master control will be required.

Perhaps the largest practical disadvantage of the independent connections and so, conversely, the largest advantage of the parallel load connections, lies in the number of converter transformers required for the same MW rating. In consequence of the fact that the independent scheme will use about twice the number of bridges, it will also require about twice the number of transformers. Not only do transformers and magnetics constitute the major parts of converter costs, but also space needs escalate rapidly in the outdoor switchyard. And, of course, there will be appreciably greater transformer losses, again a consequence of the larger current processed for the same power throughput.

In summary, independent load channel-inverter configurations tend to result in less simple inverter systems, more components, greater losses, more duplication and/or complexity of controls, relatively more redundancy for a given reliability and maintenance, and a higher net cost.

3.11.4 Use of Water-Cooled Thyristor Bridges

The total bulk power and the power per bridge are here large enough to recommend serious consideration of water-cooled thyristors. This development is relatively recent, but there are now sufficient high-voltage dc experience with thyristors that the net reliability may be considered equal to the previously prevalent forced air cooled installations. The gains lie in compact bridge structures, more efficient heat removal, and increase of current capability. The cooling system supply is perhaps a little more complex than air cooling but, on the other hand, it does away with the large air plenum beneath the valve hall and a pressurized valve hall.

For the ETF, the small power modules lent themselves more to industrial type cubicle packaging, and so to forced air cooling.

By the time the commercial MHD plant is expected to be in committed form, it may be possible to evaluate realistically the possibilities with compressed SF6 gas insulated converters and metalclad buswork to achieve even more compaction.

3.11.5 Harmonic Filters

The power factor of the inverter, taking control modes into account, is about 0.84. That is, the 525 MW active power is 0.84 of the MVA; reactive power about 0.54 of the MVA, or 0.64 of the active power, i.e., 0.64 x 525 = 340 MVAR.

Of this, about half, or 170 MVAR, may be incorporated into the ac harmonic filters. The design considerations, with emphasis on the ac grid impedance versus frequency characteristic, were explained in the ETF report (Section 2.16.1.5).

The conventional provisions for ac filters to date, as adopted for the ETF, is to provide sharply tuned, high-Q filters for the first two characteristic harmonics (the 11th and 13th) and a high-pass filter for the remainder. More recently, however, high-voltage ac technologists have taken another look at some previous proposals to the effect that equally good filtering could be had with a high-pass, broadband, low-Q filter to screen all the harmonics from the 11th and up. Such filters, because of their wide resonance characteristic, do not need any tuning during operation for temperature variations of the capacitor components or for failure of capacitors. For the modest MVAR requirements of the ETF, this would probably not be a big consideration. Here, however, small departures from the tuned frequency of a high-Q filter would probably impose some burden to the ac system. Some in-service automatic tuning corrections would have to be employed on the conventional type filters. Hence, the broadband filter for all harmonics is attractive.

A high-voltage dc converter of 1800 MW, + and - 500 kV, has been designed with such a new filter and experience with it should be available in the near future.

For the MHD plant of this report, the design would be facilitated since the filter will be at the intermediate 15 kV ac bus of the converter transformers. In the just-mentioned high-voltage case, the ac voltage is 230 kV.

3.11.6 Reactive Compensation

The system considerations involved in the choice of method to supply the reactive power of the inverter not compensated by the ac filters were also covered in the ETf report (Section 2.16.1.6.2).

For the ETF, this excess amounted to 7 MVAR at 75% MHD load; 14 at full load; and 21 at 125% overload. Here, the commercial plant requires correspondingly about 85, 170 and 250 MVARs.

Until the plant location and its voltage regulation function in relation to the rest of the ac system are known (apart from the MHD/steam bottoming generator), the possibility that the over-excited field capability of the bottoming plant generator can be used to supply all the capacitive MVARs for the inverter has to be excluded. If it can be so used, there is always the question of what else on the system can supply the MVARs when the generator is out of service and the MHD channel is running, and over what transmission lines.

Again, from the system point of view, a synchronous condenser may be justified, located at this plant or nearby, particularly if it can supply other system MVAR deficiencies in addition to keeping unity power factor on the inverters.

A cheaper solution is the conventional one of switched static capacitors dedicated to the inverter requirements. The number of switching steps for the relatively large number of MVARs involved here has to be carefully considered, not simply from the point of view of keeping reasonably in step with the MHD output, but also for the effect of switching on and off on the rest of the system. As an estimate, a minimum of three switched banks of about 80 MVAR each is reasonable.

The first two solutions (generator or synchronous condenser) have the advantage of providing a continuously variable source of MVARs for the inverter, plus continuous and smoothly adjustable assistance to maintaining constant ac voltage to the inverter, which is very desirable. But the time constants of machine excitation fields are "long" compared to the rapidity of inverter firing and control action, so that ac system disturbances resulting in transient voltage reductions are corrected too late to prevent, for example, consequential commutation failures beyond the limits of the inverters' own protective control.

Switched capacitors obviously cannot give a smooth reactive power supply, nor can they make up the var deficiency when the system voltage drops either as a steady-state deviation or from a transient disturbance. In fact, the capacitors produce less MVARs when the voltage falls at the same time as the inverters require more. On the other hand, the stored energy at the instant of voltage reduction, released at the inverter junction, can "slow" down the voltage collapse on a transient basis sufficiently to allow the very rapid inverter protective circuits to advance firing angles and prevent commutation failure on the next thyristor pairs to conduct. Of course, there is a limit to this, depending on the severity and type of voltage drop and distortion.

It appears possible to combine the continuously adjustable feature of reactive power supply (capacitive vars) or reactive power absorption (inductive vars) of the rotating machine solutions, with the fast transient voltage support possible from capacitors. Such a device is known generically as a "static var source." Some particular forms (components, operating principle, etc.) are, in recent times, being used for voltage and/or reactive regulation/control in large industrial process electrical systems. They have been proposed for reactive compensation of high-voltage transmission systems as substitutes for shunt capacitors, synchronous condensers, and shunt reactors. Such a static var source is being commissioned for in-service trail on a 735 kV system (Canada), with the MVAR capability from 350 capacitive to 100 MVAR inductive.

While such a device has not been used nor yet proposed for the specific purpose of MVAR supply to a high-voltage dc rectifier or inverter station, there appears to be nothing in principle to prevent this technically. Economics are difficult to assess at this point.

Inasmuch as the MHD plant and total plant capacity is relatively large and, presumably, would be situated in connection with an ac system of reasonably large existing capacity (both generating and transmission), the possibility of a static var supply should not be discounted and is recommended as an included option in a final design. No effort can be made at this time to investigate the details, lacking knowledge of the actual system.

3.12 BALANCE OF PLANT EQUIPMENT

3.12.1 Heat Rejection and Cooling Water Systems

The heat rejection system will include a condenser, circulating water pumps, piping and, as specified in the RFP, a counterflow, mechanical draft, evaporative cooling tower. The cooling water system is a closed loop consisting of cooling water pumps, heat exchangers and interconnecting piping used for all equipment cooling requirements. Water in the closed loop is, in turn, cooled by the circulating water system.

The RFP specified that the cost of the heat rejection system be based on the 5% summer environmental conditions. These were given as a wet bulb of 77°F and 60% relative humidity. The power plant performance was specified to be based on the average day conditions, which was given as a temperature of 59°F as was used in ECAS. An economic evaluation to determine the optimum turbine design backpressure was not undertaken. This would require more detailed information concerning yearly weather conditions, plant operating hours and unit performance at various loads.

Instead, a backpressure was selected that would both be attainable with the average day wet bulb temperature of 51°F and also be consistent with plant performance values used in other studies. The backpressure selected for the basis of plant performance is 2 in. HgA. Typical equipment design values were then selected for sizing the circulating water system components. The cooling tower, condenser and circulating water pumps would then be capable of providing a backpressure of 2 in. HgA with a wet bulb temperature of 51°F. This equipment will also maintain a maximum backpressure of 5 in. HgA at the highest wet bulbs temperature expected to occur. Five inch HgA is the highest backpressure allowed by turbine manufacturers for their standard equipment.

The circulating water equipment design values are as follows. The circulating water temperature rise or range is 26.8°F. The cooling tower cold water approach to the wet bulb is 16°F. The condenser terminal temperature difference (TTD) or saturation temperature above circulating water outlet temperature is 6.1°F. Using these values and a heat load of 3.1×10^9 Btu/hr resulted in a multiple cell cooling tower with a total fan power of 2968 kW, a condenser with a surface area of $\sim$385,000 ft^2, and a circulating water flow rate of 210,000 gpm.

Since $\sim$75% of the heat load is removed by evaporative cooling, it is necessary to blowdown a portion of the circulating water flow in order to maintain acceptable levels of dissolved solids. Makeup water to account for evaporation and blowdown is provided from the North River specified in the hypothetical site description. Water from the North River is stored in a clean water holding pond and pumped to the cooling tower basin to maintain a predetermined level.

The closed-loop system will provide cooling for items such as lube oil cooling, service air compressor inter- and after-coolers, pump seal water and instrument rack cooling.

3.12.2 Waste Removal Systems

Waste collection systems are provided to collect solid and liquid wastes and transport them to the proper storage areas. Solid wastes include slag, ash, mill rejects and gypsum from the formate seed regeneration process. Liquid wastes come from the demineralizers, boiler blowdown, cooling tower blowdown and miscellaneous floor drains and cooling water.

All liquid wastes will be collected and pumped to the storm water and waste water holding pond basin. Solid wastes will be collected and trucked to the on-site solid waste storage areas. Runoff from this area will go to the storm water and waste water holding basin. The dirty water can then be treated and stored or reused as required.

Montana Rosebud coal is 8.7% ash. Approximately 80% of the ash will be removed as slag from the combustor. Of the remaining ash, 40% is assumed to be removed as slag from the radiant section of the steam generator, 30% is removed in downstream sections of the boiler, and the remainder enters the precipitator.

The various waste collection points are discussed below in more detail.

Mill Rejects - Mill rejects are collected dry at the pulverizers. The solids collected will be ~ 0.4% of the coal flow. Ten hours of pyrites storage is provided. Approximately once every 8 to 10 hours the stored pyrites will be sluiced to dewatering bins.

Combustor Slag - Slag will be removed continuously from the combustor, which operates at ~ 8.3 atm and 4700°F. This slag removal system will be unique in that it operates at a higher temperature and pressure than most present day slag tap boilers and, also, in that the combustor operates at several kilovolts above ground potential. For a previous study, two ash handling companies presented conceptual designs for this system. Both designs were a series of quench and storage tanks to lower the pressure and temperature of the slag/water slurry for sluicing to dewatering bins. The basic components of the system are shown in Figure 3-40.

Slag falling from the combustor will be cooled in the refractory lined quench tank. The desired water level and temperature in the quench tank are maintained by the overflowline pump, and heat exchanger shown. The quench tank will be maintained at 140°F to 160°F. This temperature is compatible with standard ash collection equipment and the vapor pressure at 160°F will be lower than the partial pressure of the water in the combustor, thus eliminating the possibility of water being added to the combustion gases.

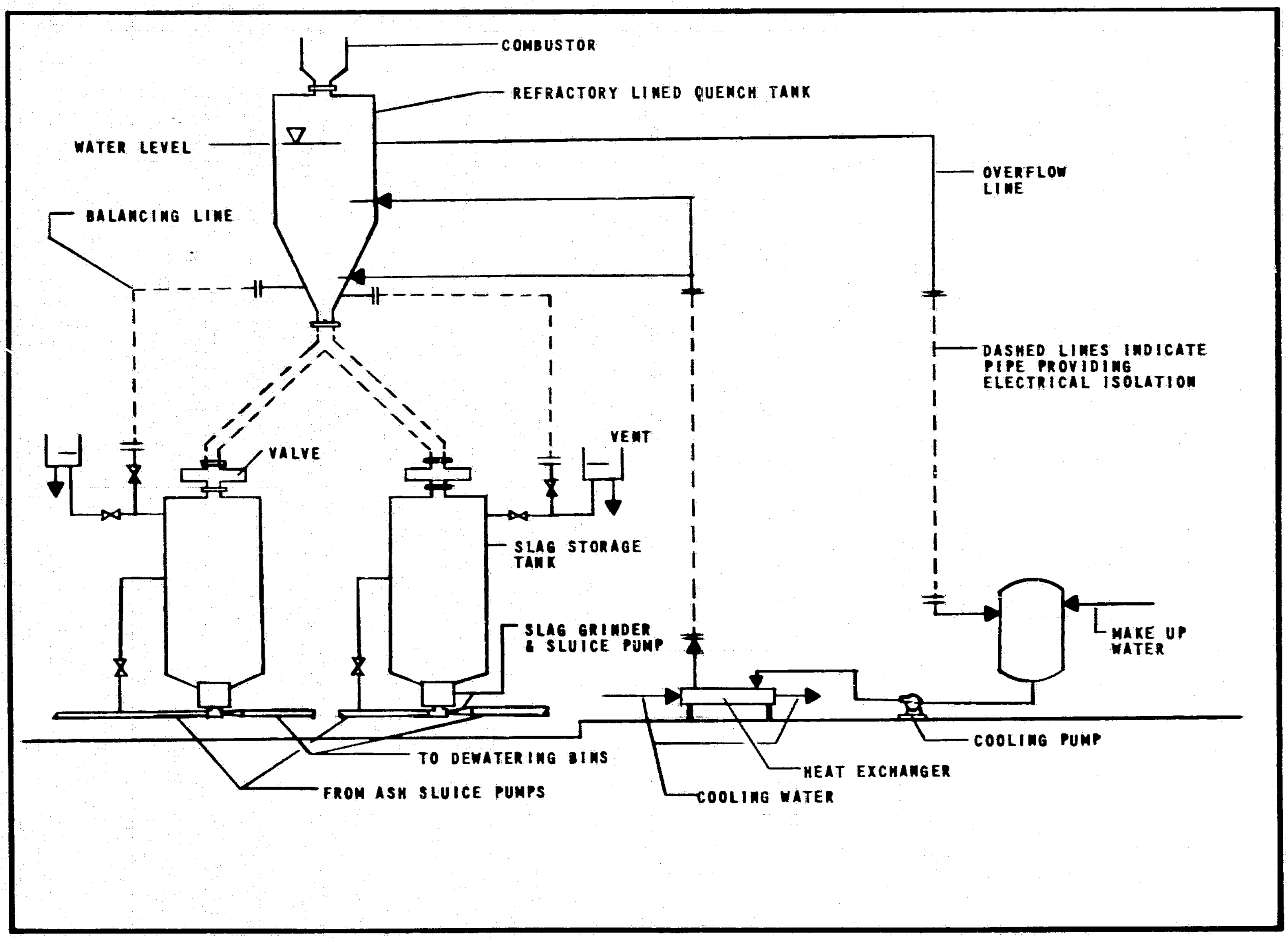

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Figure 3-40 Diagram of Combustor Slag Collection System

Slag leaves the quench tank and falls to one of the two collection tanks below. Each collection tank will have the capacity for storing 4 hr of slag. While one tank is being emptied, the other is being filled. The tanks are emptied by sluicing the slag/water mixture to dewatering bins.

Electrical isolation of the slag collection system from the combustor can be accomplished as shown in Figure 3-40. Preliminary experiments have been performed to determine the conductivity of the water/slag mixture. The water/slag conductivity was $75(10^{-6})$ mho/cm. Based on these results, using pipes of very low electrical conductivity where shown should provide adequate isolation from a safety standpoint and also minimize power losses from the channel.

Boiler Slag - Ash as molten slag will be collected from the radiant section of the boiler. The slag will fall into a wet slag tank through a refractory lined throat section hung from the boiler. A seal trough located between the boiler and slag tank allows for downward expansion of the boiler. The slag tank will have the capacity for storing 8 hr of slag. As the tank is being emptied the slag passes through a clinker grinder prior to being sluiced to dewatering bins.

Boiler and ESP Seed and Ash - Ash and seed will be collected in the boiler downstream of the slag furnace as well as below the economizer section, the N_2 heater, secondary air heater and electrostatic precipitator (ESP). Immediately downstream of the slag furnace, some of the ash and seed may fall to the ash collection system still molten. Therefore, a water-cooled screw conveyor will be used to cool and transport the seed and ash to a dry storage bin. Ash and seed collected in this storage bin and in hoppers under the remainder of the boiler, the air and N_2 heaters and the ESP will be conveyed by a pressure pneumatic system to one of two storage bins. One of these bins provides the feed to the seed regeneration system; the other bin is fed directly to the combustor without processing, as discussed in Section 3.10, Seed Processing.

Gypsum - Gypsum will be moved by conveyors to a radial stacker. The stacker will be capable of providing one week's storage immediately outside the seed regeneration plant. The gypsum will then be trucked to the final on-site waste storage location.

Dewatering Bins - The dewatering bins noted earlier are located just outside the plant island. Three dewatering bins will provide capacity for 64 hr of storage time for the slag collected at the combustor and radiant section of the boiler and for the pyrites. While one bin is being filled another is being emptied. To empty a bin, the sluicing water is drained to the dewatering bin sump. Sump pumps pump this water to the storage and settling basin. The low- and high-pressure ash water pumps take suction from the storage and settling basin and thus reuse this water for sluicing slag. After draining the dewatering bin the solids are loaded into a truck and disposed of in the on-site waste disposal area.

The solids waste storage area is located on the outer edge of the plant property. It will provide storage for the 332 x (10^6) ft^3 of solid wastes generated over the life of the plant.

3.12.3 Coal Receiving, Storage and Reclaim

This study considers Montana Rosebud coal for the design case. Montana Rosebud is received at 22.7% moisture and nominal 6 in. size. The coal handling system including unloading, storage and reclaim and delivery systems up to the pulverizers, will be designed for a coal burn rate of 817,276 lb/hr (22.7% moisture). Coal is assumed to be delivered by unit train.

The coal handling system is shown in Figure 4-1. The rail spur will bring a unit train to the loop provided around the coal handling facilities. After traveling the loop, the train will pass through a thaw shed prior to coming to the rotary dumpers. Each car is unloaded by the rotary dumper into track hoppers. Conveyors then transport the coal to the stackout building. From the stackout building the coal goes to either dead or live storage. Dead storage provides adequate coal for 90 days operation at full load. The live storage pile has a storage capacity for 2.5 days of coal burning at full load. Reclaim from the bottom of the live storage pile is accomplished with a rotary plow. Conveyors then deliver the reclaimed coal from the rotary plow to the crusher house. The 6-in. nominal coal is crushed to 3/4-in. size, and conveyed to stoage silos above the pulverizers. Seven of the other eight silos will have adequate capacity to provide 24 hr of storage. An additional conveyor from the crusher tower also permits coal to be moved from live storage to dead storage or vice versa.

Auxiliary systems such as coal sampling following the crusher and dust collection equipment are included in the scope of this sytem.

3.12.4 Feedwater, Condensate and Steam Systems

The condensate and feedwater systems include six closed feedwater heaters, one open deaerating type heater, the MHD channel and the combustor. In addition, there are two half-capacity condensate pumps, one full-size turbine driven boiler feed pump, and one 25% startup, motor driven boiler feed pump.

The condensate pumps discharge through heater No. 1 and the MHD channel. A lift pump takes suction from the channel outlet and pumps the condensate through the low pressure boiler economizer and heater No. 2 to the deaerator. One full-size turbine driven boiler feed pump takes suction from the deaerator and pumps the feedwater through heaters Nos. 4 and 5, the high-pressure boiler economizer, heaters Nos. 6 and 7, and the MHD burner to the boiler drum. The MHD diffuser has been incorporated into the radiant section water circuit of the boiler.

The MHD channel cooling is located in the feedwater circuit such that the condensate temperature is compatible with state-of-the-art channel design concepts and materials which have demonstrated successful long-term operation. A deaerator and polisher are included in the condensate cycle to minimize oxygen and corrosion products in the feedwater.

Certain features have been included in the condensate and feedwater systems to protect the MHD components from a loss of cooling water. Condensate flow is controlled by the level in the deaerator storage tank, condensate temperature out of the channel and minimum flow requirements of the pumps. The most critical of these three will determine the flow from the condensate pumps. Feedwater flow to the boiler will be regulated by a three-element feedwater flow control system. Minimum flow through the pump is assured by a recirculation line to the deaerator. A dump line to the condenser has also been included to maintain adequate cooling water flow to the combustor. A bypass line around the boiler feed pump and deaerator is used to protect the MHD components in the case of losing the boiler feed pump. In the case of a blackout, one of the condensate pumps would continue to run on the power provided by the emergency diesel generator set.

3.12.5 Miscellaneous Mechanical Systems and Equipment

A fuel oil storage and supply system will be provided for receiving, storing and forwarding the No. 2 distillate. The distillate will be used primarily for the house heating boiler, the diesel engine generator and startup of the boiler.

An auxiliary boiler will be provided for house heating steam, and to provide steam for turbine warmup, steam seals and other miscellaneous startup functions.

Water treatment and chemical feed systems will be included to provide high purity demineralized water for boiler makeup, feedwater treatment, condensate polishing, cooling tower acid treatment, cooling water chlorination, and pH adjustment of recycled wastewater.

Other systems included are as follows: fire protection, condensate makeup, including storage tank and pumps, service and instrument air compressors and dryers, nonpotable service water system and potable water system.

3.12.6 Electrical Equipment

The electrical equipment proposed for the MHD/steam power station will employ standard commercial designs utilized by the electrical utility industry. The system will be designed for safe and easy operation, redundancy of major components, and economic installation, operation and maintenance.

The design and equipment manufacture will be in accordance with applicable government standards and the following:

National Electric Manufacturers Association (NEMA)

Insulated Power Cable Engineers Association (IPCEA)

Institute of Electrical and Electronics Engineers (IEEE)

National Fire Protection Association (NFPA)

Chapter 70 the National Electric Code (NEC)

Illuminating Engineers Society (IES)

Instrument Society of America (ISA)

American National Standards Institute (ANSI)

Federal Aviation Administration (FAA)

Underwriters Laboratories (UL)

The major components of the electrical equipment have been broken down into the following catagories:

Power Distribution Equipment

Electric Motors

Emergency Power Equipment

Lighting

Communications

Cable and Raceways

Cathodic Protection and Grounding

3.12.6.1 Power Distribution Equipment

The station auxiliary power will be supplied from the low voltage windings of the station auxiliary and station startup/standby transformers at 4160 V, three-phase, 60 Hz. The 4160 V power will be supplied to four main 5 kV switchgear assemblies by nonsegregated phase bus.

4160 V Switchgear

The auxiliary system for the unit will be supplied from four switchgear buses of indoor construction, with stored energy breakers operated from the 125 Vdc battery. Each pair of buses will be fed from a secondary winding of the auxiliary transformer and startup/standby transformer, through separate circuit breakers. These four buses will be located in the turbine generator building.

Motors larger than 200 hp will be supplied from 4160 V switchgears through air circuit breakers.

Additional buses will be installed for local loads in the cooling tower, seed regeneration and coal handling areas as required.

An additional 4160 V switchgear bus will be provided for emergency shutdown power. This bus will have a feeder from the station 4160 V bus and from the emergency diesel generator.

480 V Power Centers

Station service power will be supplied from dry type transformers. These transformers will be rated 1500/2000 kVA, AA/FA, 3-phase, 60 Hz with medium voltage delta connected primary windings connected to the medium voltage switchgear by cable. The secondary winding will be 480 V wye connected and will be throat connected to the 480 V drawout switchgear. The 480 V neutral will be resistance grounded.

These transformers will be furnished as part of the station service 480 V power centers.

The 480 V auxiliary loads will be approximately equally divided among the 480 V power centers and the control centers fed from these power centers. Bus tie circuit breakers will be provided between the power centers to permit continued plant operation with one unit power center transformer out of service.

The 480 V station service power will also be supplied to baghouses, seed processing, coal handling, ash handling and cooling tower areas. The power centers will be similar to the ones described above except the size of the transformers may differ.

480 V Motor Control Centers

Motor control centers, of indoor NEMA Type 12 or outdoor NEMA Type 3S construction, as required by location, utilizing molded case circuit breakers and circuit breaker combination starters will be provided at load centers throughout the plant, to feed motors and miscellaneous loads. Starters will be provided with 120 V control transformers.

A 480 V shutdown motor control center will be provided for the unit for supply of certain auxiliary equipment considered vital to safety of personnel and equipment during and after shutdown or during emergencies. It will also be capable of holding the unit in a condition ready for restart. This MCC will be supplied from the station 480 V system with a backing supply from the emergency 4160 V bus through a dry type transformer and main breaker.

The motor control centers will consist of air circuit breakers, 100 A through 400 A frame size, combination starters size 1 through 4, reversing and nonreversing, and combination contactors size 1 through size 4.

Motors, from 1/2 through 100 hp, will be fed through combination starters, each of which will consist of a control transformer, three-phase overload devices, auxiliary alarm relay, auxiliary relays, as required and cable terminating equipment. Motor operated valves will be fed through manually operated air circuit breakers to starters mounted internal to the motor operator on the valve. Non-motor loads, 1/2 through 100 kW, that are remotely controlled by external devices will be fed through combination contactors which consist of a control transformer, three phase overload devices, auxiliary alarm relay and cable terminating equipment. All other nonmotor loads will be fed through air circuit breakers which are operated manually at the motor control center.

Low-Voltage Power Equipment

Low-voltage distribution requirements will be fed through dry type transformers to 75 kVA, 480 V 3-phase to 120/208V four wire. The 120/208 V power will be distributed through four wire distribution panels with single-, two- or three-pole breakers sized to fit the low-voltage loads.

The transformers and distribution panels will be located indoors, near the loads serviced.

3.12.6.2 Electric Motors

Except for certain special applications where corresponding special characteristics are required, e.g., crane hoist motors and application in the coal handling system, motors generally will be squirrel cage induction type designed for full voltage starting and will have lowest locked rotor current consistent with good performance and design.

Motors located outdoors, except those for coal handling equipment, will be of weather-protected Type II construction with filters except for 460 V motors built in smaller frame sizes where, dependent on economics, the manufacturer's standards justify totally enclosed fan cooled motors. Indoor motors will be drip-proof. Motors for coal handling equipment whether indoor or outdoor will be totally enclosed fan cooled. Motors located below grade in the coal handling area will be explosion proof.

Motors will have Class B powerhouse insulation. The maximum temperature rise of Class B insulated windings as measured by the resistance method will not exceed 80°C at a service factor of 1.0 and 90°C at a 1.15 service factor.

3.12.6.3 Control Power Equipment

The major control voltages will be 125 Vdc and 120 Vac, single phase, 60 Hz, for systems control, indication, monitoring and recording. Other voltages may be utilized by the solid state electronics equipment and other signal circuits. These other voltages will be transformed from one of the two major control voltages noted above.

Station Battery

A station battery, sixty cells, lead calcium type, will be installed to furnish 125 Vdc control power. This battery will be designed to provide 125 Vdc power for emergency dc motors and emergency lighting, providing these loads are not large enough to justify an independent emergency power battery. The station battery will be designed to provide continous control power for an eight hour period without requiring battery charging, while not dropping to a voltage level below 1.75 V/cell.

The battery will be located in the battery room on the ground floor of the control building. The battery room will be ventilated. An eyewash and emergency shower located just outside the battery room will be provided for personnel protection.

Battery Charger

Two solid state battery chargers will be furnished which will be supplied from separate 480 V motor control centers, one the shutdown MCC. The chargers will be designed to be capable of recharging the battery in 8 hr from a voltage level of 1.75 V/cell to full voltage while maintaining normal control requirements.

The battery chargers will be located on the ground floor of the control building near the battery room.

Vital ac System

A 120 V single phase, 60 Hz vital ac system will be furnished. This system will consist of two inverters, bypass transformers, circuit breakers and distribution panel. The distribution panel will contain two-pole breakers which supply those 120 Vac control power loads that require a continuous regulated power source. These loads include analog controls, computer power supply, control panel recorders, annunciator power supplies, emergency diesel generator monitoring and other systems as determined during detailed design.

Alarm Power

A solid state annunciator system will be furnished with annuciator systems located in the main control room and at other local control areas, where applicable. The annunciator system will be supplied by the vital ac system. Annunciator field contract voltage will be 125 Vdc transformed from the power supply.

Small Motor Control

Motors, which have power supplied from 480 V motor control centers, will have a 120 V, single phase, 60 Hz control power furnished from 480 V - 120 V control transformers which are integral parts of the motor starters.

3.12.6.4 Emergency Power Equipment

Emergency Diesel Generator

An emergency diesel generator, rated at 3000 kW, 4160 V, three phase, 60 Hz with fuel tank, starting package, control panel, main breaker and all required instruments, devices and meters for safe and reliable operation will be installed. The diesel generator will be located in a weather proof enclosure near the control building.

The 4160 V system and the 480 V main breakers will be designed with interlocks to trip nonessential loads when the emergency diesel generator is required to provide power for the safe shutdown of the station during power system voltage losses. The emergency diesel generator will be designed to have a minimum of 30% spare capacity. A synchronizing system will be furnished to permit loading of the diesel generator for weekly tests and upon return of normal power.

3.12.6.5 Lighting

The lighting design will conform to the IES minimum lighting standards for applicable areas and will conform to NFPA code for applicable hazardous areas.

Emergency Lighting

A system of emergency lighting will be installed throughout the station. Emergency lights will be incandescent type and will be 125 Vdc supplied by the station battery through the main dc panel and local 125 Vdc panels.

Freeze Protection

Freeze protection transformers, circuit breaker panelboards, thermostats, temperature sensing devices, supervisory instruments and contactors to control and supervise the freeze protection system will be furnished to provide protection for equipment subject to freezing.

3.12.6.6 Communications

Intraplant System

A transistorized solid state communication system, operated from the 120 V vital ac bus, will be provided for intraplant paging and communications. The intraplant system will use noise cancelling dynamic microphone type handsets, located throughout the station for operating and maintenance purposes, feeding into a solid state preamplifier.

Local Telephone Service

Dedicated galvanized steel conduit will be installed from the property line to the Administration Building and the Control Building to permit the installation of local company service to these areas.

Load Dispatching

The local utility will determine what type of load dispatch and other transmission communication equipment will be utilized.

3.12.6.7 Cable and Raceways

The cable and raceway systems will be divided into six dedicated subsystems. The subsystems are high-voltage (over 600 V) power; medium-voltage power (208-480 V); low-voltage power and control (120-125 V); signal (48 V and less, 0-20 mA signal), communications and lighting.

Conduit, Ducts and Trays

Whenever possible within the plant, extensive use will be made of overhead cable trays rather than conduit. Where required, trays will have covers to exclude dirt and foreign matter and to shade cables from direct sunlight. Various tray systems will be used in order to have logical grouping of cables. Where trays are used care will be taken to assure that such trays are not loaded beyond manufacturer's recomendations.

Power Wiring

Power cables will be stranded copper conductor and will be rated 5000 V and 600 V. The 600 V cables will have crosslinked polyethylene insulation suitable for 90°C conductor temperature and 130°C emergency condition.

Power cables will conform to applicable IPCEA standard.

3.12.6.8 Control Wiring

Control and indication cables will be stranded copper conductor with crosslinked polyethylene color coded conductor insulation over individual conductors and a neoprene jacket overall. Control cable will be rated 600 V. For general plant controls, No. 12 AWG will be used.

Twisted pair instrumentation cables will be used for alarm circuits, analog controls and data logger. These cables will be No. 16 AWG and be rated 600 V. Cables for low level (50 V and below) analog control and computer analog circuits, will be rated 300 V. Cables used for signal level applications will be No. 16 AWG. Low level cables will be provided with a shield to reduce "noise" pickup.

For high-temperature areas, such as around the boiler, feedwater heaters, etc., as well as fixture items and in continuous runs of fluorescent fixtures, silicone rubber insulation will be used.

Cables will conform to applicable IPCEA and ISA standards.

3.12.6.9 Cathodic Protection and Grounding

A study of the site will have to be made to determine the requirements for a Cathodic Protection System and the types of protection required.

All electric equipment or equipment with electrical parts within the station area will be bonded to structural members of the station building, which will serve as a ground grid in this area. Major members of composite steel structure such as buildings and all separate towers supporting electrical equipment, as well as electrical equipment or equipment with electrical parts, will be connected to the main copper cable grounding grid. The grid will interconnect the station ground grid with remote equipment and such ground rods or ground beds as required to achieve an adequate grounding system for the station and the switchyard. The station and switchyard ground grids will be interconnected.

The ground grid system will be designed to minimize potential volts to "remote earth" (earth point beyond which no increase in this voltage occurs) at any point on the ground grid, under maximum line-to-ground fault conditions. The resistance of the ground shall be ~ 1 ohm.

3.13 O_2 PLANTS

Technical data and cost estimates for the oxygen plant were based upon information provided by NASA and Lotopro Corp. (Lotepro Corp. under a separate study contract to NASA has developed information of O_2-plants for applications to MHD power plants.) The oxygen required is produced cryogenically in a liquid air separation plant at 80% purity. The total amount of oxygen produced at nominal load corresponds to 6957TPD of contained oxygen in the product from the plant. Three cold box units with heat exchangers and necessary valving and auxiliaries are arranged in parallel. The oxygen plant is closely integrated with the MHD/steam power plant and the air compressor for the O_2-plant has steam turbine drive which is part of the bottoming plant steam cycle. The oxygen is assumed produced at atmospheric pressure. It is mixed with air to produce oxygen enriched combustion air containing 34% oxygen by volume at nominal load. The mixture of air and oxygen is compressed by the cycle compressor and delivered to the MHD combustor for combustion of the coal.

4.0 PLANT LAYOUTS

The Plot Plan, Plant Island and Plant Island Sections and Details are shown in Figures 4-1, 4-2 and 4-3, respectively.

The Plot Plan shows the entire plant property; the total plant property is 676 acres. The two single items that account for nearly 60% of the total required area are waste disposal and the coal handling and storage facilities. Approximately 35% of the total plant area is devoted to waste disposal. About 23% of the plant area is occupied by the coal handling system.

The Plot Plan also shows the rail spur from the main track. The rail spur splits once on the plant property. One branch is used for coal delivery; the other is used to service various areas of the plant island and seed regeneration area.

The dewatering bins, cooling tower and oxygen plant are located reasonably close to the plant island. The dirty water holding ponds collect runoff from all areas of the plant, including the waste disposal area. This water is treated and can be used for ash sluicing and some types of service water. The clean water holding basin is supplied from the North River. It supplies some service water functions and makeup to the feedwater system and cooling tower.

The Plant Island is shown in Figure 4-2. The central building on the Plant Island houses the MHD components. The combustor, channel, diffuser and transition section are arranged in a straight line with flow in the horizontal direction. The steam generator centerline is arranged on the same line, with flow in the same direction. Other pieces of auxiliary equipment are located suitably around the Plant Island. The coal and seed feed systems are as close as possible to the burner to minimize response times. The main steam turbine and the steam turbines for driving the air and oxygen compressors are located in close proximity to the steam generator and share a common condenser. The stack is centrally located so as to be near both the ID fan and waste heat recovery equipment. Electrical leads from the inverter and main generator leave the plant on the same side. The control building is centrally located for convenience and ready access to all parts of the plant. The MHD building has as part of its equipment laydown area a limited access area where the magnetic field is above 200 Gauss. This space will be considered an unsafe work area when the unit is operating.

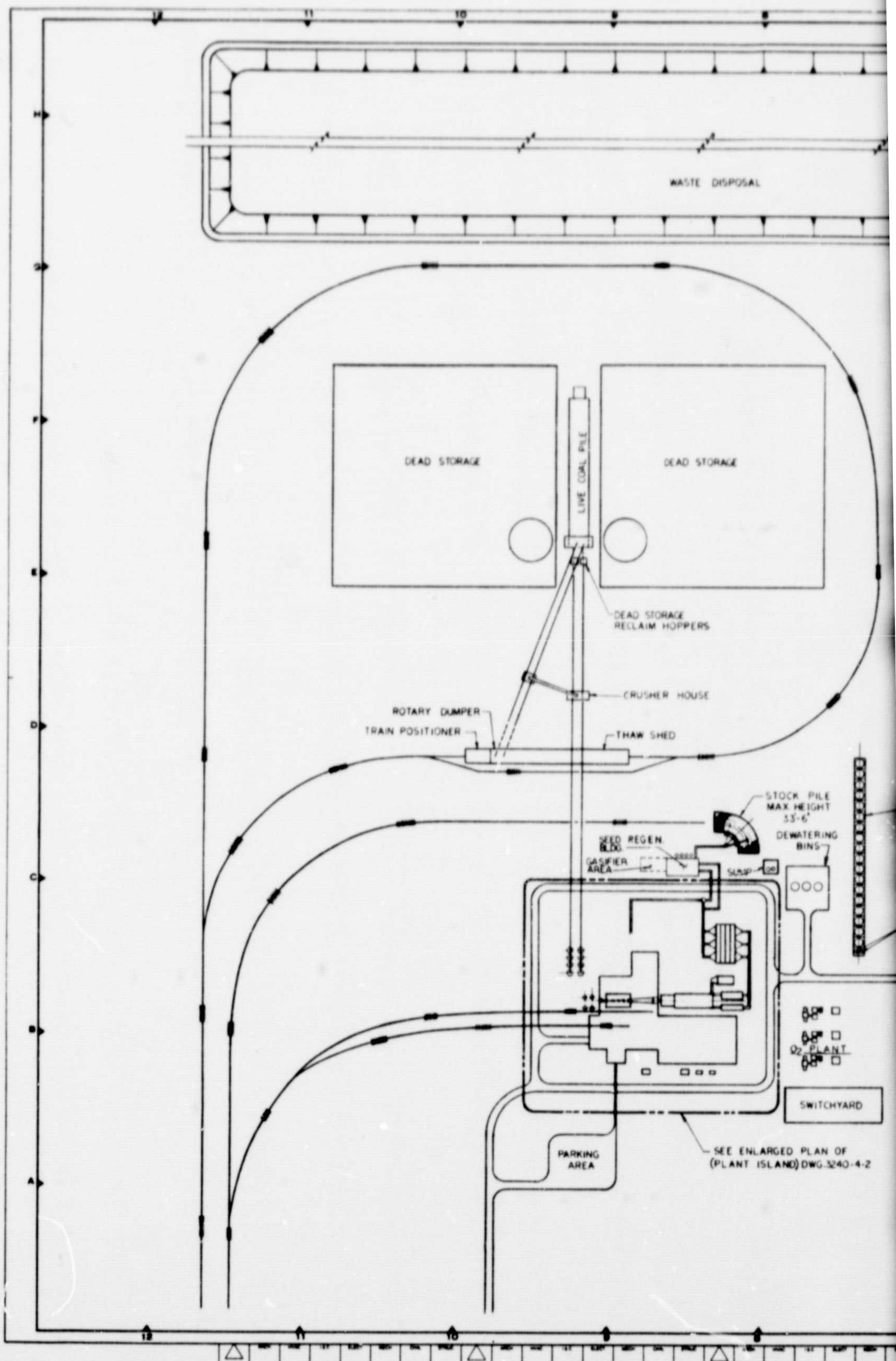

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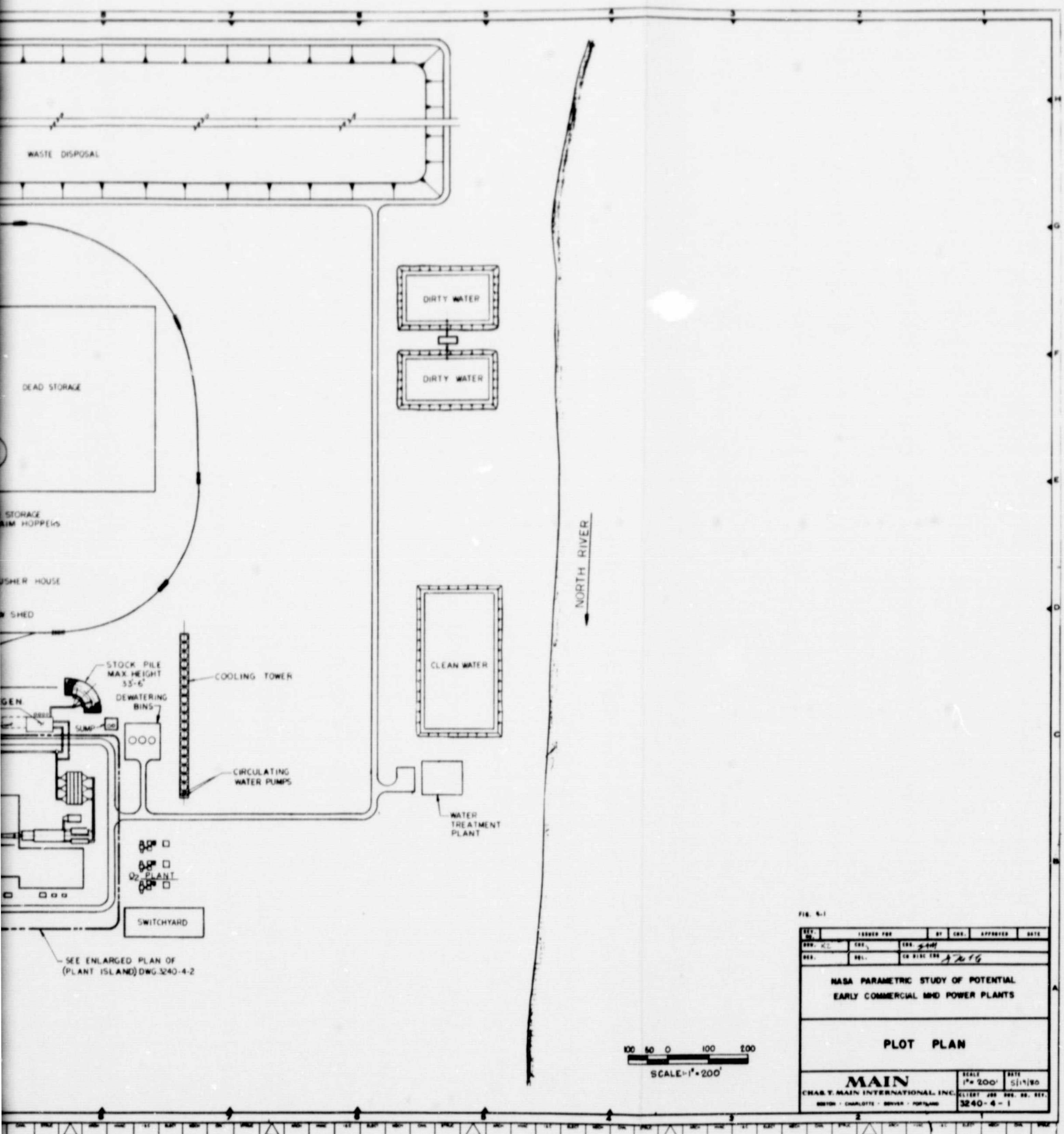
Figure 4-1 Plot Plan for Conce



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t Plan for Conceptual Early Commerical MHD Power Plant

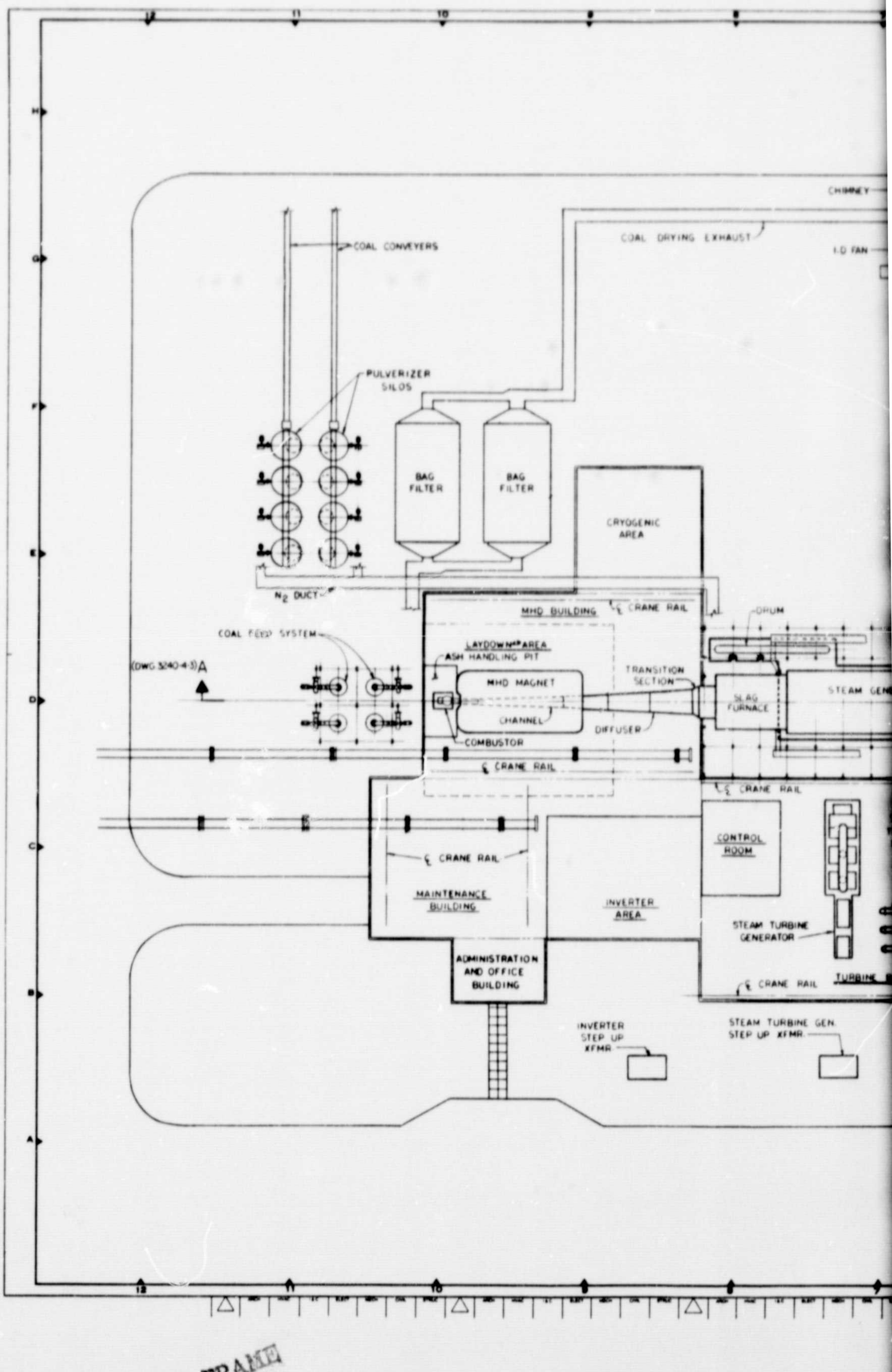

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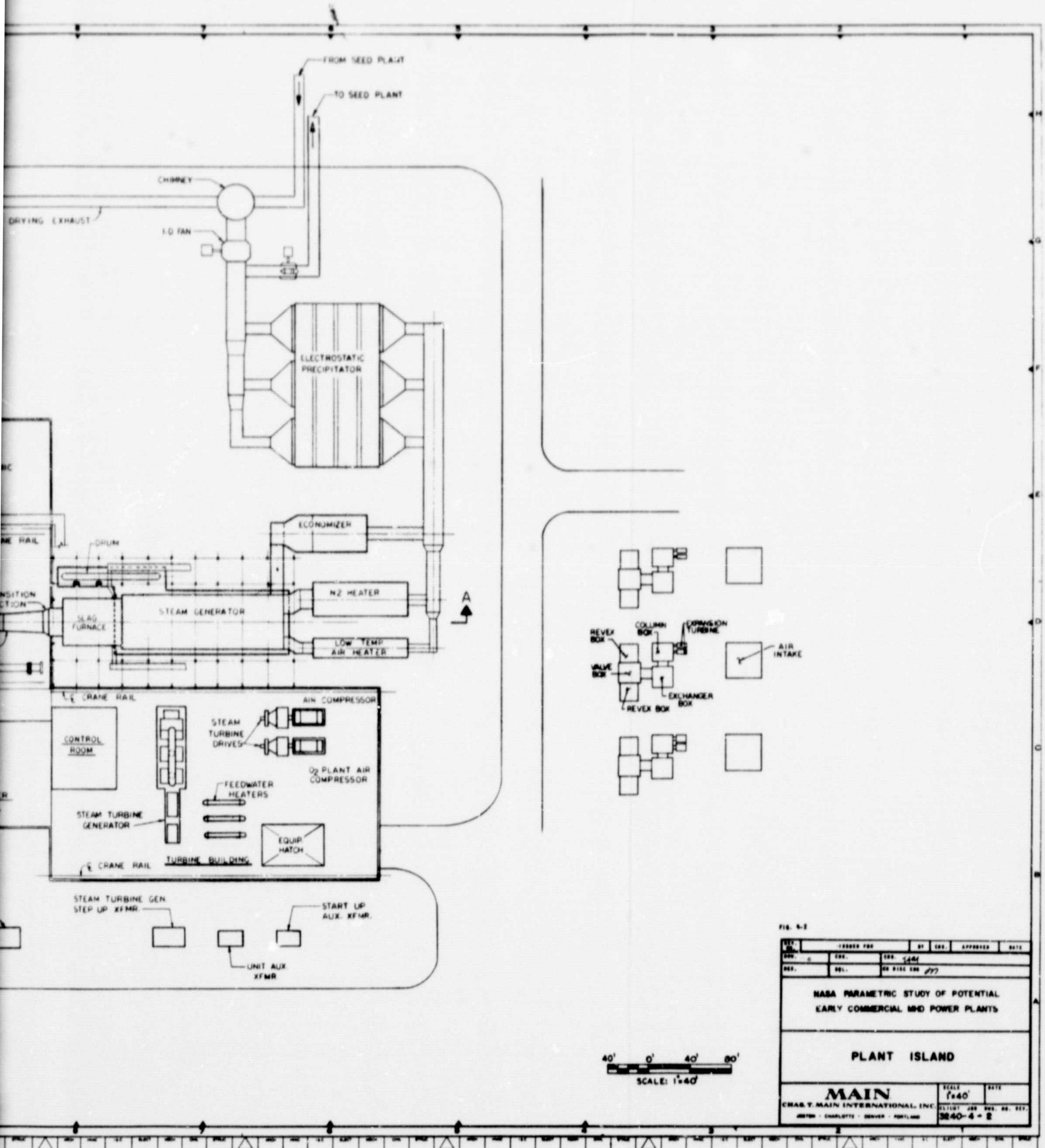
Figure 4-2 Plant Island Arrangemen
Commercial MHD Power Pl



Island Arrangement - Conceptual Early
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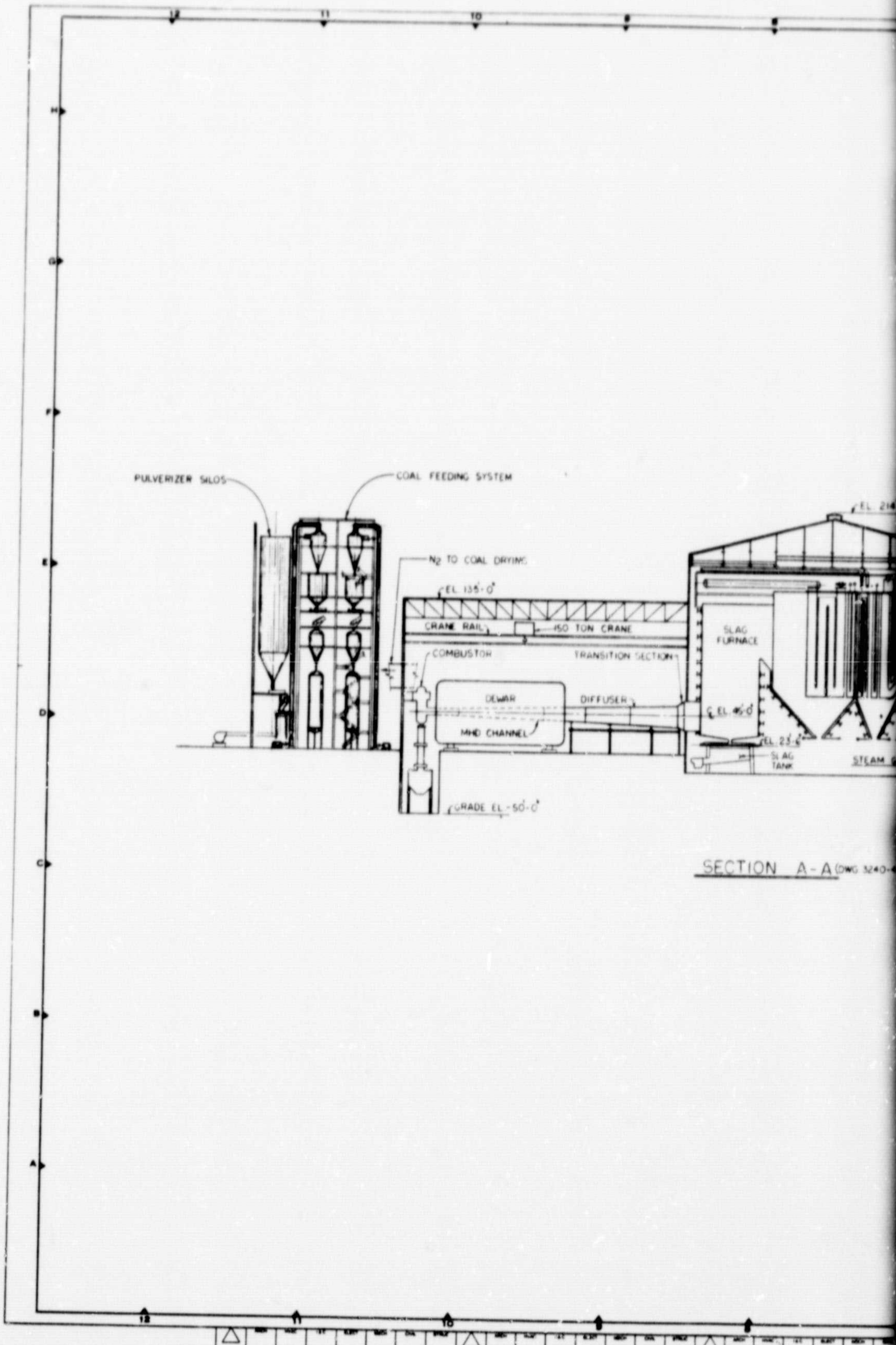

Figure 4-3 Sect

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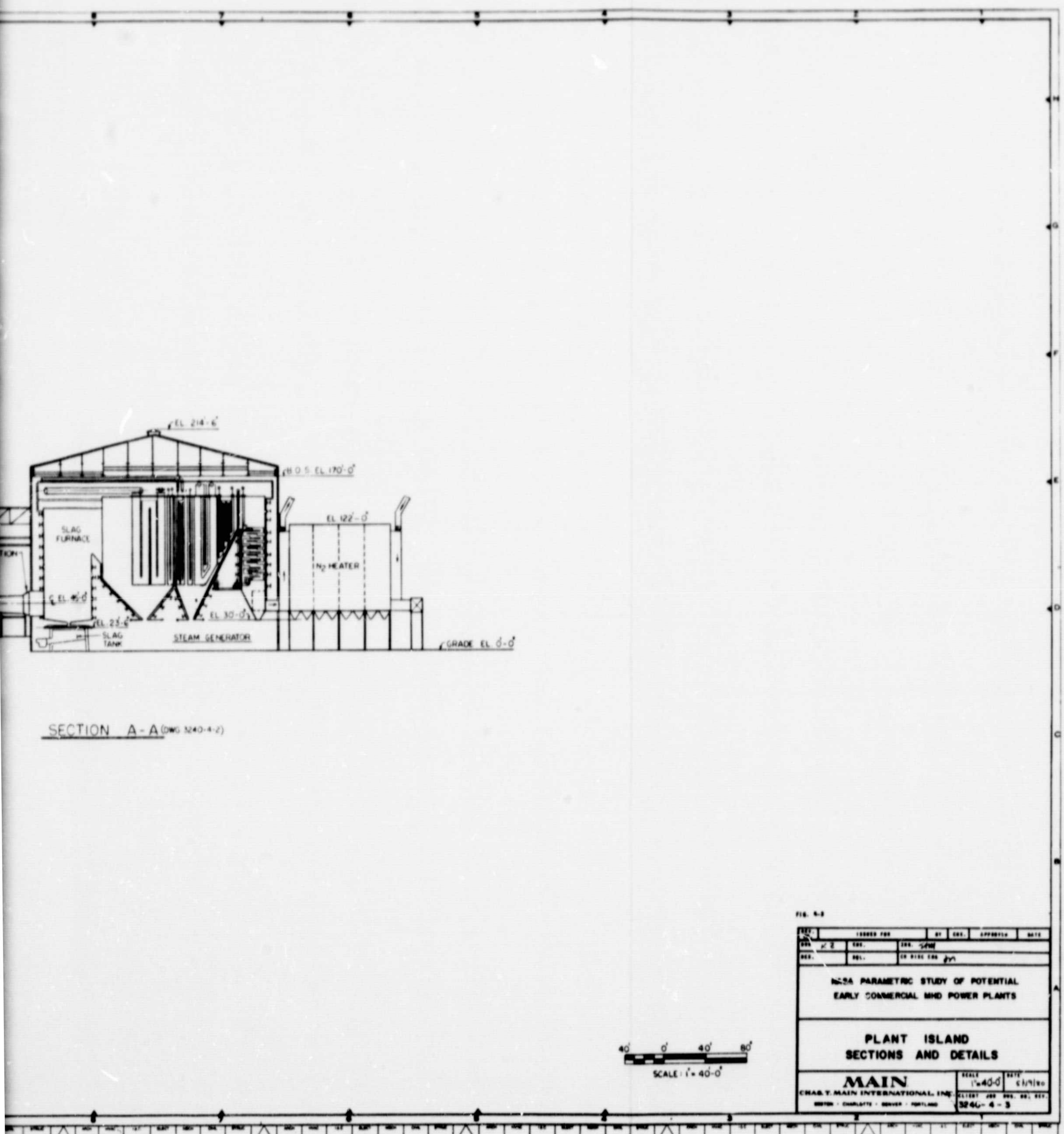

'igure 4-3   Section Through Plant Island

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Figure 4-3 shows the relative elevations of the equipment along the centerline of the MHD components. The channel centerline is 45 ft above grade. As a result, the burner slag collection equipment is in a pit. The channel centerline elevation was chosen to minimize excavation for the pit, keep the MHD components reasonably close to grade, and to provide adequate clearance below the boiler for slag and seed collection equipment.

5.0 BUILDINGS AND STRUCTURES

5.1 GENERAL

For the purpose of this study, the site and the environment are assumed to be similar to the site and environment considered in the "1000 MWe Central Power Plants Investment Cost Study" prepared by United Engineers and Constructors, Inc. and included in Wash-1230 (Volume III).

All buildings and structures will be designed to resist Zone 1 seismic forces as specified in the Uniform Building Code. All buildings and structures will be designed to meet the requirements of American National Standard ANSI A58.1 'Building Code Requirements for Minimum Design Loads in Buildings and Other Structures' and other applicable building codes. AASHRE Standard 90 - 'Energy Conservation in New Building Design' will be used as a guide in choosing materials of construction to implement conservation of energy. All buildings will be properly ventilated, adequately heated, and certain areas will be air conditioned.

5.2 FOUNDATIONS

The following soil profiles and load bearing characteristics are assumed for this study:

Soil profiles for the site show alluvial soil and rock fill to a depth of 8 ft; Brassfield limestone to a depth of 30 ft; blue weathered shale and fossiliferous Richmond limestone to a depth of 50 ft; and bedrock over a depth of 50 ft. Allowable soil bearing is 6000 psf and rock bearing characteristics are 18,000 psf and 15,000 psf for Brassfield and Richmond strata, respectively. No underground cavities exist in the limestone.

All equipment and structural loads will be supported by spread footings or mat foundations. Exterior footings and grade beams will be founded a minimum of 5 ft below plant grade to preclude frost heave.

The foundation pit of the combustor slag system, 60' x 25' in plan and 50 ft deep, is considered as a high contingency item at this stage of project development. The pit design will provide for membrane water proofing and heavy reinforced concrete pit walls capable of withstanding the high lateral pressures of the surrounding earth. Buoyancy considerations will have to be included in the design once the water table in the area is established. The pit wall adjoining the MHD magnet support will be thickened to provide foundation support in transferring one-half of the MHD magnet load to the bedrock expected at 50 ft below the plant grade.

5.3 STRUCTURES

5.3.1 Administration and Office Building

The Administration and Office Building will be an 80' x 50', three-story steel frame building with insulated metal siding and built-up roof. This building will provide space for plant supervisory personnel, including the Plant Superintendent, support engineering, first aid, purchasing, cafeteria and conference hall. The building will include locker rooms, men's and women's toilet room facilities, safety shower, eyewash, and heating, ventilating and air conditioning system.

High efficiency lighting will be used. Individual requirements will be satisfied by task lighting and maximum use of natural light. In all cases, standards of Illuminating Engineering Society will be met.

Plumbing fixtures will be latest type and facilities will be designed according to the latest OSHA rules in keeping with the requirements for handicapped persons. Rest rooms will feature ceramic tile floors and walls.

Sprinkler systems will be used throughout the building. Fire hoses or canisters will be appropriately located throughout. An electric alarm system as well as a water flow alarm will be incorporated.

The parking space provided in front of this building will facilitate easy access and necessary convenience.

5.3.2 Maintenance Building

The maintenance building will be located adjacent to the Administration and Office Building, as shown in Figure 4.2. The building will be 145 ft long, 135 ft wide, and 60 ft high. Direct road and railroad accesses will be provided to the building. The building will house the machine shop, electrical shop, instrumentation shop, welding area, tool rooms, storage areas, and maintenance offices.

The building will be enclosed with insulated metal siding and a built up roof and will include a 115 ft span bridge crane (as described in paragraph 5.4), and heating and ventilation.

5.3.3 MHD Building

The MHD building will be located in the center of the plant island surrounded by the maintenance building, cryogenic building, inversion building, etc. It will be a 230 ft long, 145 ft wide, and 120 ft high, steel frame building covered with insulated metal siding and a built up roof. A 145 ft span bridge crane located below the roof (as described in Section 5.4) will facilitate maintenance and erection of equipment. The railroad track inside the building will facilitate transporation of equipment and also ease maintenance of equipment in an outside facility when required. The building will be provided with adequate heating and proper ventilation.

5.3.4 Coal Feed Structure

A 60' x 60' by 190 ft high open-steel frame structure will support the coal feed system. The steel structure will support equipment at different levels. Platforms will be provided at various locations to facilitate operation of the system and for ease of maintenance. Adequate lighting will be provided including warning lights at the top of the structure.

5.3.5 Cryogenic Systems Building

A 105' x 105' steel frame two-story Cryogenic System Building will be located adjacent to the MHD building. The building will be covered with insulated metal siding and a built-up roof and will be provided with adequate heat and ventilation.

5.3.6 Steam Turbine-Generator Building

The 185 ft wide by 320 ft long, steel frame steam turbine-generator building will be located adjoining the inverter area. The building will house the steam turbine-generator unit, condenser, air compressor and the auxiliaries for these units.

A control room 80' x 65' wide will be located within the turbine-generator building adjacent to the MHD building at the operating floor level. The control room will include the necessary control panels and space for office storage and toilet facilities. The cable spreading area will be located directly below the control room and the electronics room below the cable spreading area. The control room will be provided with enclosures having adequate sound insulation.

The steam turbine-generator will be supported on a concrete pedestal. The reinforced concrete operating floor slab supported on structural steel framework will be conveniently located to facilitate operation and maintenance of equipment.

A bridge crane (as described in Section 5.4) located under the roof of the building, runs along the length of the building.

Stairways will be provided, running from the ground floor to the operating floor, at two locations.

Adequate entrance and egress will be provided through service and man doors.

The building will be enclosed with insulated metal siding and a built-up roof.

The building will be adequately heated, ventilated and in areas such as the control room and electronics room will be air conditioned.

5.3.7 Steam Generator Building

A 135' x 235' steel frame structure will be provided to support the boiler. Only the lower level of this structure will be enclosed with metal siding and a roof. An elevator will be provided for access to all elevations of the structure.

The economizer, N_2 heater, and the low temperature air heater will also be supported by an open steel structure.

The steam generator will be adequately lighted, including warning lights at the top of the building.

5.3.8 Water Treatment Building

A 50' x 50', one-story, steel frame water treatment building with insulated metal siding, containing an air conditioned water treatment laboratory, demineralizing and chemical facilities, toilet and space for miscellaneous storage will be provided. This building also houses the clarifier and chemical storage tanks.

5.4 CRANES AND HOISTS

Cranes and hoists will be provided in the plant at different locations to facilitate installation and operation and maintenance of equipment. These are described in the following paragraphs.

5.4.1 MHD Building Crane

A 145 ft span, 150 T capacity (150 T main hook and 25 T auxiliary hook) bridge crane with total hook travel of ~ 140 ft will be located below the roof level. It will provide for the building of the MHD generator, magnet, combustor, and diffuser components.

5.4.2 Maintenance Building Crane

A 150 ft span, 25 T capacity bridge crane with total hook travel of ~ 40 ft will be located in the maintenance building.

5.4.3 Turbine Building Crane

A 180 ft span, 90 T capacity bridge crane with a total hook travel of 40 ft will be located in the turbine building.

5.4.4 Miscellaneous Hoists and Trolleys

Miscellaneous hoists and trolleys will be provided at certain locations to service different equipment items and their components. The following are some of the equipment that will be serviced by hoists and trolleys: Pulverizer, Induced Draft Fan, and Boiler Feed Pumps.

5.5 CHIMNEY

The stack will be a reinforced concrete structure designed for a height of 250 ft. Corten steel flue liners will be inside the stack to carry gases from coal drying exhaust, exhaust from the seed plant and the exhaust from the steam generator. Sampling platforms will be provided as required. A personnel elevator and ladder system will be provided for the entire stack height. Insulation will be provided for the liners as required. Warning lights and markings will be provided in accordance with local and Federal aviation requirements.

C-3

6.0 ESTIMATED PLANT COSTS AND COST OF ELECTRICITY

6.1 CAPITAL COSTS

The code of accounts supplied in this report has been developed in accordance with the Department of Energy's directives, and closely follows standard estimating practices. The detailed project cost estimate is shown in Table 6-1. The cost elements identified for each line item are those costs for materials (divided into major components and balance of plant), costs for field installation, indirect cost, a specific contingency, and a total cost for that item. Costs are in mid-1978 dollars and are shown in thousands of dollars.

"Major Components" have been identified as those items which are engineered, designed, fabricated, shipped, and in some cases erected, by one supplier.

"Balance of Plant" items are normally designed, engineered and purchased by the engineer. All material costs include charges for delivery to the site.

The "Installation" portion of the direct cost includes wage costs for all manual labor, foremanship, and all wage related benefits and costs mandated by labor agreement. Payroll taxes, payroll premium costs and workmen's compensation insurance costs are built into the wage rate of direct labor costs. Also included is special construction equipment associated with certain civil work items to which the costs can be charged directly, and also contractor fees. Auxiliary labor for unloading, storing, sorting materials and equipment, general and final cleanup, and other miscellaneous activities directly associated with the installation of the work area are also charged to the direct account.

"Indirect Costs" for construction are those cost items which include facilities, equipment and services that are required to directly support the construction operations, but which cannot be conveniently charged by the constructor or general contractor directly to a single estimating account. For conceptual estimates, indirect construction costs are expressed as a percentage of the direct cost. Field offices and temporary facilities, transportation, safety equipment, construction tools and equipment, expendable supplies, non-manual labor, construction services and testing contracts, and insurance and bonds are all examples of indirect costs.

TABLE 6-1

PROJECT COST ESTIMATE (DOLLARS X 10^{-3})

Sheet 1 of 4

ACCOUNT NUMBER	ACCOUNT DESCRIPTION	UNIT	QUANTITY	MATERIAL		INSTALLATION COST	INDIRECT COST	CONTINGENCY	TOTAL COST
				MAJOR COMPONENT	BALANCE OF PLANT COST				
310.	LAND AND LAND RIGHTS	ACRE	673		1,010	–	–	101	1,111
311.	STRUCTURES AND IMPROVEMENTS	L.S.			19,985	15,088	7,545	4,261	46,879
311.1	Improvements to Site	L.S.	1	–	2,030	3,098	1,549	667	7,344
311.2	MHD Building	C.F.	6,317,000	–	8,592	4,926	2,463	1,598	17,579
311.3	Bottoming Plant Building	C.F.	5,301,000	–	5,050	4,340	2,170	1,156	12,716
311.4	Steam Generator Building (FDN's)	C.Y.	1,439	–	100	291	146	54	591
311.6	Maint. Serv., Warehouse and Office Buildings	C.F.	837,000	–	1,620	885	443	295	3,243
311.7	Other Buildings	C.F.	362,900	–	445	644	322	141	1,552
311.8	On-site Waste Treatment	L.S.	1	–	2,148	904	452	350	3,854
312.	BOILER PLANT EQUIPMENT			80,447	25,552	30,816	15,409	15,224	167,448
312.1	Coal Handling and Processing	TPH	408	–	13,580	4,680	2,340	2,060	22,660
312.11	Unloading and Yard Storage			–	6,055	2,008	1,004	907	9,974
312.12	Reclaim and Delivery			–	7,525	2,672	1,336	1,153	12,686
312.2	Slag and Ash Handling	TPH	35.6	–	3,997	999	500	550	6,046
312.4	Steam Generator			72,769	1,896	20,071	10,036	10,477	115,349
312.41	Steam Generator	TON	20,400	72,769	38	19,522	9,761	10,209	112,399
312.43	Instrumentation and Controls			–	1,403	374	187	196	2,160
312.44	Auxiliaries			–	455	175	88	72	790
312.5	Effluent Control			7,678	465	2,907	1,453	1,251	13,754
312.51	Precipitator and Breeching	ACFM	$1.36(10^6)$	7,678	28	2,101	1,050	1,086	11,943
312.52	Chimney			–	437	806	403	165	1,811
312.7	Other Boiler Plant Systems			–	5,614	2,159	1,080	886	9,739
312.71	Condensate and Feedwater Systems	MW	475	–	2,898	1,050	525	447	4,920
312.72	Condensate and Feedwater Treatment and Supply System			–	536	399	200	154	1,689
312.73	Secondary Air System	LS		–	1,780	710	355	285	3,130

*L.S. = Lump Sum
C.F. = Cubic Feet
C.Y. = Cubic Yard
TPH = Tons per Hour
ACFM = Actual Cubic Feet per Minute

TABLE 6-1

PROJECT COST ESTIMATE (DOLLARS X 10^{-3})

ACCOUNT NUMBER	ACCOUNT DESCRIPTION	UNIT	QUANTITY	MATERIAL		INSTALLATION COST	INDIRECT COST	CONTINGENCY	TOTAL COST
				MAJOR COMPONENT	BALANCE OF PLANT COST				
314.	TURBOGENERATOR UNITS	–		23,100	10,485	5,788	2,826	4,227	46,496
314.1	Steam Turbine Generator and Aux.	MW	475	23,100	–	1,607	804	2,551	28,062
314.2	Condenser and Auxiliaries	BTU/HR	3.1 (10^6)	–	1,691	695	348	273	3,007
314.3	Circulating Water System								
314.31	Pumps, Valves, Piping & Struc.	GPM	209,566	–	4,954	1,853	927	774	8,508
314.32	Cooling Tower	BTU/HR	3.1 (10^6)	–	1,248	618	309	218	2,393
				–	3,706	1,235	618	556	6,115
314.4	Steam Piping Systems Main, Hot & Cold Reheat, Extraction, & Aux. Steam Systems	TON	90	–	3,033	1,512	756	530	5,831
314.5	Other Turbine Plant & Mech. Equipment	L.S.	1	–	807	121	61	99	1,088
315.	ACCESSORY ELECTRICAL EQUIPMENT			–	12,715	12,286	6,143	3,115	34,259
315.1	Station and Auxiliary Transf.	EA	4	–	1,042	80	40	116	1,278
315.2	Miscellaneous Motors	EA	250	–	1,600	378	189	217	2,384
315.3	S.G. and MCC's	CUB	1,800	–	2,600	567	284	345	3,796
315.4	Conduit, Tray, Cable and Busswork	L.S.	1	–	4,362	9,295	4,648	1,831	20,136
315.5	Miscellaneous Electrical Equipment	L.S.	1	–	419	1,363	681	246	2,709
315.6	Integrated Control System	L.S.	1	–	750	489	245	148	1,632
315.7	Data Acquisition System	L.S.	1	–	1,400	57	28	149	1,634
315.8	Emergency Power Systems	L.S.	1	–	542	57	28	63	690
316.	MISC. POWER PLANT EQUIPMENT	L.S.	1	–	1,312	402	201	192	2,107

TABLE 6-1

PROJECT COST ESTIMATE (DOLLARS X 10^{-3})

Sheet 3 of 4

ACCOUNT NUMBER	ACCOUNT DESCRIPTION	UNIT	QUANTITY	MATERIAL: MAJOR COMPONENT	MATERIAL: BALANCE OF PLANT COST	INSTALLATION COST	INDIRECT COST	CONTINGENCY	TOTAL COST
317.	MHD TOPPING CYCLE			176,633	7,265	28,694	14,276	29,338	256,206
317.1	Combustion Equipment			24,289	1,826	6,931	3,466	3,759	40,271
317.11	Coal Drying	TPH	408	10,458	39	3,121	1,560	1,524	16,762
317.12	Coal Injection	TPH	333	12,808	76	3,554	1,777	1,822	20,037
317.13	Combustor	lb	81,150	1,023	–	27	14	213	1,277
317.14	Slag Coll. System	TPH	28.4	–	1,651	229	115	200	2,195
317.2	MHD Generator			7,913	–	160	81	1,631	9,785
317.21	Nozzle	lb	9,700	183	–	7	4	39	233
317.22	Channel (3000°F)	lb	145,000	6,187	–	109	55	1,270	7,621
317.23	Diffuser and Transition	lb	201,000	1,543	–	44	22	322	1,931
317.3	Magnet Subsystem	TON	5,834	51,970	–	437	219	10,526	63,152
317.31	Structure			9,470	–	95	48	1,923	11,536
317.32	Winding Assembly			23,240	–	19	9	4,654	27,922
317.33	Dewar			17,130	–	38	19	3,437	20,624
317.34	Refrigeration System			1,430	–	29	25	295	1,769
317.35	DC Power Instr. & Control			700	–	256	128	217	1,301
317.4	Inverters and Electrode Con.	MW	515	33,700	–	5,651	2,826	4,785	46,962
317.41	Inverters			29,000	–	5,000	2,500	3,656	40,150
317.42	Electric Consolidation Circ.			4,700	–	651	326	1,135	6,812
317.5	Oxidizer System	lb/hr	3.1(10^6)	7,057	599	1,006	503	917	10,082
317.51	Air Compressor and Drive			7,057	–	706	353	812	8,928
317.52	Comb. Air Piping and Ductwork			–	599	300	150	105	1,154
317.6	Seed Subsystem	lb/hr KCO_2H	25,832	12,876	400	5,436	2,718	4,220	25,650
317.61	Seed Regeneration Process			12,876	–	5,316	2,658	4,162	25,012
317.62	Seed Injection System			–	400	120	60	58	638
317.7	Oxygen Enrichment System	TPD	7,344	38,828	4,440	9,073	4,463	3,500	60,304

MAIN

TABLE 6-1

PROJECT COST ESTIMATE (DOLLARS X 10^{-3})

Sheet 4 of 4

ACCOUNT NUMBER	ACCOUNT DESCRIPTION	UNIT	QUANTITY	MATERIAL		INSTALLATION COST	INDIRECT COST	CONTINGENCY	TOTAL COST
				MAJOR COMPONENT	BALANCE OF PLANT COST				
350.	TRANSMISSION PLANT			–	4,850	838	419	611	6,718
350.1	Structures and Improvements	L.S.	1	–	163	190	95	45	493
350.2	Main Transformers	EA	2	–	2,240	115	58	241	2,654
350.3	Switchyard	L.S.	1	–	2,447	533	266	325	3,571
	SUBTOTAL – Direct Accounts			280,180	83,174	93,912	46,883	57,069	561,224
	ENGINEERING SERVICES								
	Preliminary Engineering								10,938
	Detailed Design								20,037
	Construction Management								10,948
	OTHER COSTS								11,224
	TOTAL ESTIMATED OVERNIGHT CONSTRUCTION COSTS								614,371
	CONSTRUCTION PERIOD, YEARS								5.75
	*TOTAL ESTIMATED COST (including Interest and Escalation during Construction)								675,815

*Mid-1978 dollars

MAIN

"Contingency" represents the total contingency that has been applied to each line item. As Owner commited monies for purchased material and negotiated contracts proceeds towards 100% of total project cost, necessary contingency factors may be reduced in a manner to reflect lessened possibilities of unforeseeable circumstances occurring before project completion. As project engineering nears completion, estimating may deal with more precise information and can more accurately predict material quantities and respective project costs. Items incorporated into contingency management considerations include:

Design (but not major scope) changes

Market conditions

Labor productivity

State of project definition

Unreliable and noncurrent estimating data

Unpredictable field conditions

Instabiities of material and labor markets

Uncertainties in project timing

Errors and omissions

Weather

Short term strikes, walkouts, and other labor disputes

Other unforeseeable occurences and conditions which would delay or otherwise increase material and/or installation costs.

The contingency factors used in this report reflect the above items as well as varying degrees of development and uncertainty for the MHD components. In the case of Balance of Plant (BOP) structures, improvements and well defined mechanical systems, a 10% factor is used. For the higher technology components, a factor of 20% is used. Specifically, the following accounts have 20% contingency factors.

Account	
317.14	Combustor
317.21	Nozzle
317.22	Channel
317.23	Diffuser and Transition
317.31-35	Magnet Subsystem
317.42	Electric Consolidation Circ.
317.61	Seed Regeneration Process

"Total Cost" represents the total for all material, installation, indirect and contingency costs for each account.

Professional services include project management, licensing and preliminary engineering, detailed design and engineering, construction management, procurement services, architectural design, shop inspection, expediting, and startup testing. For this project, professional services have been subdivided into preliminary engineering (2% of total direct and indirect costs), detailed design and engineering (4% of same costs), and construction management (2% of same costs).

The "Other Costs" category includes such items as the owner's field staff, legal fees and ad valorem taxes. A factor of 2% of the Direct and Indirect Sub-Total costs was assumed for this category. As directed by DOE, the costs for escalation and interest during construction have been included at the end of this capital cost estimate.

Figure 6-1 presents data showing capital costs versus plant size. This graph does not include escalation and interest during construction. The solid line represents the average prices for coal-fired steam plants as reported in Task I of this study. The dashed vertical lines indicate the variance in costs of coal-fired steam plants. The variance is the result of such items as plant location, site conditions, type of labor force available and environmental regulations. For example, a remote location can increase capital costs by 7 to 8% and flue gas desulfurization equipment can increase capital costs by 15 to 20%. Also shown on Figure 6-1 are plant capital costs that were developed in a 1979 EPRI study (Technical Assessment Guide PS-1201-SR). The coal-fired stream plants in the EPRI study were designed to meet the New Source Performance Standards for Electric Utilities (NSPS). A separate capital cost was developed for each of six regions of the country. The costs were reported in end-of-year 1978 dollars. These numbers reported by EPRI were converted to mid-1978 dollars and averaged to arrive at the data shown on Figure 6-1. As can be seen, they are somewhat higher than the costs reported in Task I for coal-fired steam plants. The capital cost of the MHD plant developed in Task II is also shown on Figure 6-1.

6.2 COST OF ELECTRICITY

The levelized cost of electricity (COE) has been calculated in accordance with the procedure specified by DOE. The economic parameters which are the basis for calculating the COE are shown on Table 6-2. Escalation and interest cost factors are given in Table 6-3. Items 1 through 3 and 5 through 14 of Table 6-2 were specified by DOE. Item 4, the construction time, was developed by the contractor. The labor rate, Item 11, was specified by DOE to be $14.20/hour. This was assumed to include base pay and fringe benefits only. Therefore, an additional 45% was added to the specified labor rate to account for the construction contractor's cost adders.

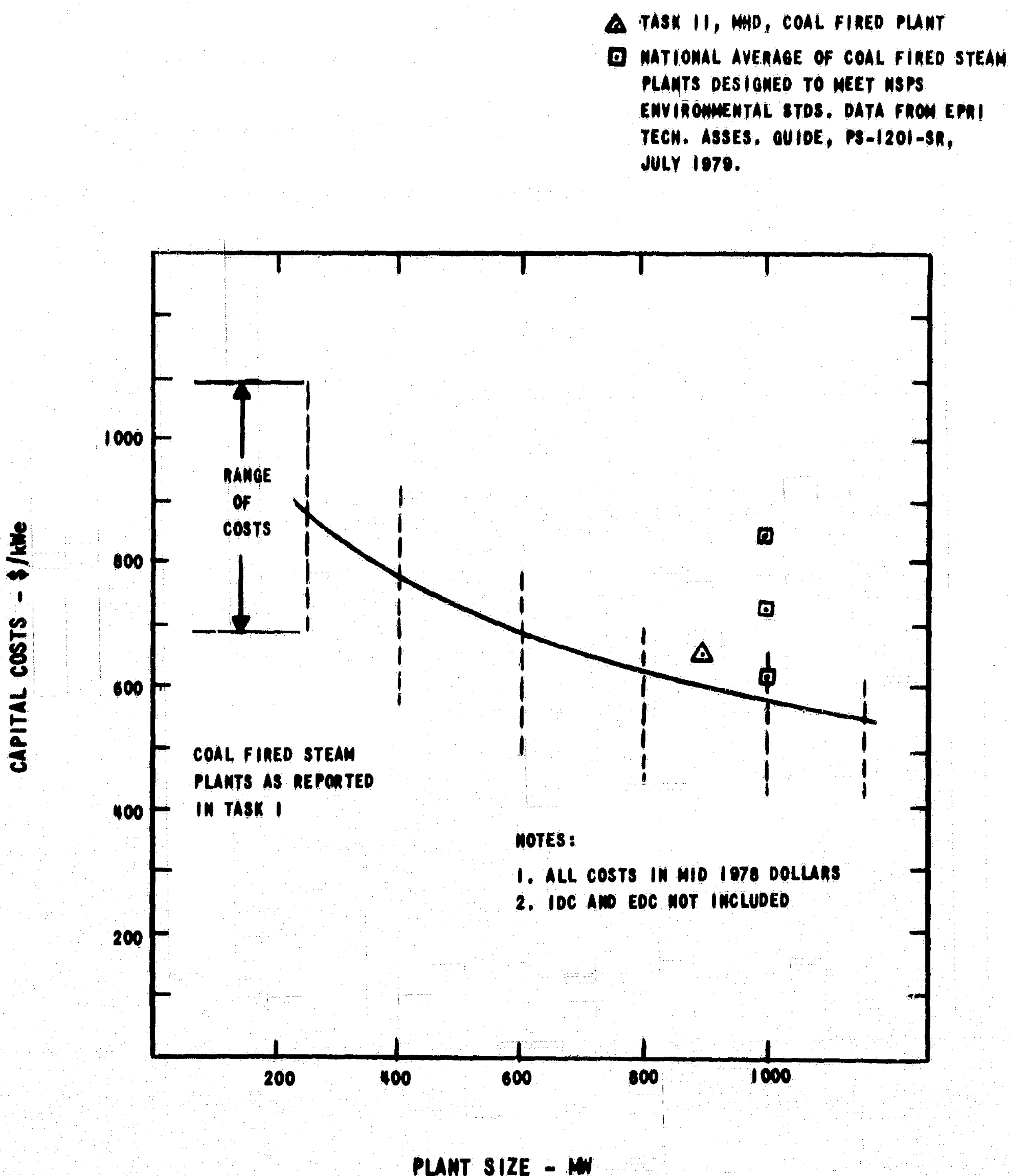

Figure 6-1 Capital Costs vs Plant Size

TABLE 6-2

ECONOMIC PARAMETERS

1.	Plant Life	30 years
2.	Plant Site	Middletown, USA
3.	Capacity Factor	65%
4.	Construction Time	5.75 years
5.	Fixed Charge Rate	18%
6.	Escalation During Construction	6.5%/year
7.	Interest During Construction	10%/year
8.	Percent Expenditure vs Time	Specified "s" Curve (See Table 6-3)
9.	Economic Base Year	Mid 1978
10.	Fuel Cost (Coal Fuel Cost Range	105¢/MBtu 105 to 150¢/MBtu
11.	Labor Rate (1) Labor Rate Range	\$14.20/hour \$14.20 to \$17.04/hour
12.	Plant Performance for COE	Full-Load Heat Rate
13.	Fuel and O&M Levelizing Factor	2.004 (for real fuel esc. rate = 0)
14.	Real Fuel Escalation Rate (2)	0 to 3%/year

(1) 45% will be added to account for construction contractors cost adders.

(2) Fuel price escalates at the general inflation rate up to the time of plant startup. From this time on, the real fuel escalation rate will also be considered.

TABLE 6-3

ESCALATION AND INTEREST COST FACTORS

[Escalation + Interest = Total. Annual rates: escalation, 6.5 percent; interest 10 percent]

Time from Start of design to Powerplant Completion, T, yr	Escalation	Interest on Obligated Funds	Total
	Cost Factor Cf		
0	1.000	1.000	1.000
0.5	1.018	1.022	1.040
1.0	1.037	1.044	1.081
1.5	1.056	1.069	1.125
2.0	1.076	1.094	1.170
2.5	1.096	1.122	1.218
3.0	1.116	1.151	1.267
3.5	1.137	1.182	1.319
4.0	1.158	1.214	1.372
4.5	1.179	1.249	1.428
5.0	1.202	1.285	1.487
5.5	1.224	1.324	1.548
6.0	1.247	1.365	1.612
6.5	1.270	1.409	1.679
7.0	1.294	1.454	1.748
7.5	1.319	1.503	1.822
8.0	1.344	1.554	1.898
8.5	1.369	1.609	1.978
9.0	1.395	1.666	2.061
9.5	1.422	1.726	2.148
10.0	1.449	1.790	2.239

This chart is based on the "s" shaped cash flow curve used in ECAS. See Fig. 2.3-1 of NASA TM X-73515. "Evaluation of Phase 2 Conceptual Designs and Implementation Assessment Resulting from the Energy Conversion Alternatives Study (ECAS)," April 1977.

The basic components of the COE are capital costs and production costs. The capital costs have been discussed in Section 6.1 and presented in Table 6-1 for the base labor rate of $14.20/hour. The production costs consist of fuel costs and O&M costs. Fuel costs are developed from the plant efficiency discussed in Section 2.2. O&M costs have been developed for this plant. They include the costs for personnel, consumables, waste disposal and major maintenance items. All of the O&M costs for the oxygen plant have been lumped into one number as recommended by Lotepro. The yearly O&M costs in mid-1978 dollars are tabulated and discussed below.

	Mid-1978
Personnel	$ 3,456,560
Waste Disposal	336,675
Fuel Oil ($.50/gal.)	114,760
Lime ($63.90/ton)	1,566,542
Seed Makeup ($102/ton)	1,588,286
Channel Maintenance	3,522,308
Oxygen Plant	460,806
Total	$11,054,937

The personnel costs are the result of developing a staffing plan to operate the plant. This includes administrative, operations and maintenance people. Waste disposal costs account for transporting ash and gypsum from the plant island to the 30-year on-site waste storage area. These costs include the initial costs, replacement costs and operating costs of the loader, trucks and bulldozer for handling the wastes. Fuel oil will be used for heating the facilities and for plant startup. Lime costs are for the seed regeneration plant. Seed makeup is to make up for the 6.6% of the total seed flow that is assumed to be lost. Channel maintenance cost is estimated to equal the cost of the initial channel after 10,000 hours of full load operation has been accumulated on the channel. It is noted that channel maintenance can occur at shorter time intervals than 10,000 hours of continuous operation. Finally, Lotepro has suggested a yearly O&M cost equal to 1% of the total plant cost. The result is a yearly cost of $11,054,937 in mid-1978 dollars.

Therefore, the basic components of the COE are as follows:

CAP = $614,371,000	Total capital (labor rate = $20.59/hr) cost at the end of construction expressed in mid-1978 dollars - without escalation and interest during construction (EDC & IDC)
O&M = $11,054,937	Yearly operation and maintenance cost expressed in mid-1978 dollars
η = 43.9%	Power plant efficiency

For the above values, a fuel cost of $1.05/$10^6$ Btu and a real fuel escalation equal to zero, the levelized COE is 42.99 mills/kWhr. This can be broken down as follows:

COE CAP = 22.51 mills/kWhr

COE O&M = 4.10 mills/kWhr

COE Fuel = 16.38 mills/kWhr

Figure 6-2 shows the levelized COE versus plant size for the coal-fired steam plants considered in Figure 6-1. Again, the solid line represents the average COE for coal-fired plants and the vertical dashed lines show the variance in COE.

Also shown is the COE for the 1000 MW plants studied in the 1979 EPRI Study. The corresponding capital costs are shown on Figure 6-1. As can be seen, the levelized COE for the Task II MHD plant is less than all costs reported by EPRI and below the mid-range of the costs of coal-fired plants as reported in Task I.

As specified by DOE, the effects on the COE resulting from varying the labor rate, fuel cost and real fuel escalation have also been investigated. Three values of labor rate and fuel cost and four values of real fuel escalation have been considered. For each labor rate, the total capital cost at the end of construction in mid-1978 dollars is as follows:

Labor Rate $/hr	CAP* $
20.59	614,371,000
22.65	631,628,000
24.71	648,803,000

*without EDC and IDC

Table 6-4 presents levelized COE for the parametric variations.

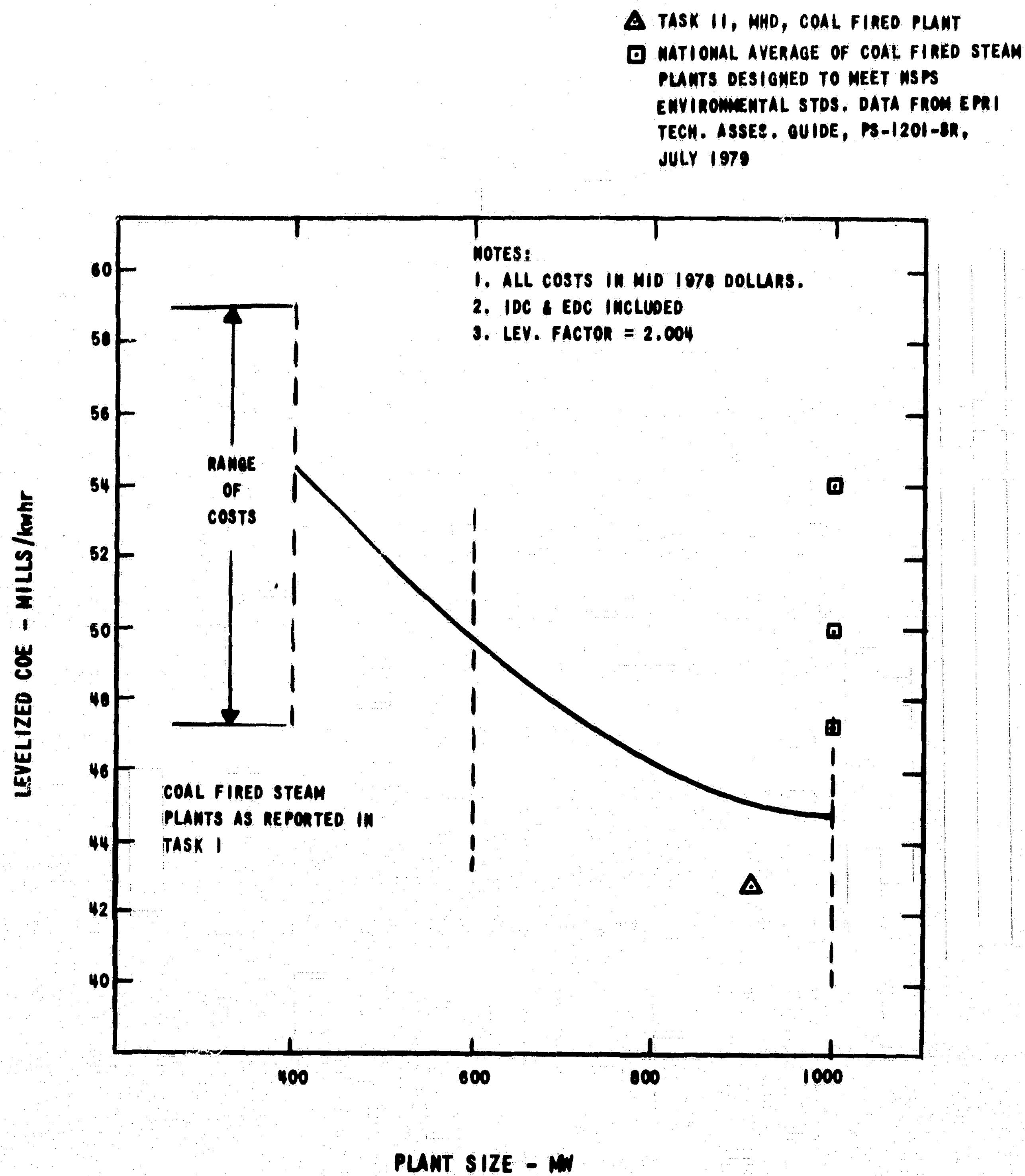

Figure 6-2 Levelized COE vs Plant Size

TABLE 6-4

LEVELIZED COE FOR VARIOUS PARAMETERS

Real Fuel Esca.	0	0.01	0.02	0.03
Levelizing Factor	2.004	2.292	2.636	3.049
	Levelized COE = mills/kWhr			
<u>Fuel = 105¢/10^6 Btu</u>				
Labor Rate $/hr				
20.59(14.20)	42.99	45.94	49.45	53.68
22.65(15.62)	43.62	46.57	50.08	54.31
24.71(17.04)	44.25	47.20	50.71	54.94
<u>Fuel = 125¢/10^6 Btu</u>				
Labor Rate $/hr				
20.59(14.20)	46.11	49.51	53.56	58.42
22.65(15.62)	46.74	50.14	54.19	59.05
24.71(17.04)	47.37	50.77	54.82	59.68
<u>Fuel = 150¢/10^6 Btu</u>				
Labor Rate $/hr				
20.59(14.20)	50.01	53.97	58.69	64.36
22.05(15.62)	50.64	54.60	59.32	64.99
24.71(17.04)	51.27	55.23	59.95	65.62

7.0 RELIABILITY/AVAILABILITY ANALYSIS

7.1 INTRODUCTION

Some reliability/availability analyses were conducted of the early MHD power plant developed in Task II as part of the conceptual design effort. These analyses considered the use of selected redundant MHD system flow train components and the cycle compressor. Components were analyzed on an individual basis. In addition, the use of a dual MHD power train arrangement consisting of two full capacity parallel flow trains (combustor, nozzle, channel, magnet and diffuser) was also analyzed.

Table 7-1 lists the components considered in the analysis. The table shows the availability, mean time between failures (MTBF), mean time to repair (MTTR), and the failure rate for each component. The mean time between failures (MTBF), and the mean time to repair (MTTR) hours were used to derive the availabilities.

Availability is defined as:

$$A = \frac{\text{Mean Time between Failures (Hours)}}{\text{Mean Time between Failures (Hours) plus Mean Time to Repair (Hours)}}$$

$$A = \frac{\text{MTBF (Hours)}}{\text{MTBF (Hours) + MTTR (Hours)}}$$

It should be noted that the failure rate in the table is the number of failures in 10^6 hr. The failure rate is defined as the reciprocal of the mean time between failures (in hours) multiplied x 10^6.

$$\text{Failure Rate} = \frac{1}{\text{MTBF (Hours)}} \times 10^6 \text{ hr.}$$

The unit size and cost data developed in the Task II conceptual design effort were used in the availability analysis.

Table 7-2 lists the material and the installed costs for the equipment considered. The economic evaluation was made by comparing the estimated component and installed cost with the worth factor times the percent improvement in availability utilizing spare or redundant components. The worth factor is defined as the equipment capital investment that can be expended for each percent change in availability per kW_e installed capacity. As such it indicates the justifiable investment to gain 1% of improved availability. For this study, a factor of $\$12/kW_e/1\%$

TABLE 7-1

COMPONENT AVAILABILITY DATA

	MTBF (Hours)	MTTR (Hours) (1)	Availability	Failure Rate Per 10^6 hour
Compressor	5,000	50	0.99010	200
Combustor	15,000	100*	0.99338	66.67
MHD Generator	5,000	50* (2)	0.99010	200
Magnet	260,000	700	0.99731	3.85
Nozzle	25,000	50*	0.99800	40
Diffuser	20,000	75*	0.99626	50
			0.96562	

Notes: (1) Data from Gilbert Commonwealth Analysis and 1975 EEI data, except where modified by Avco and marked by an asterisk(*).

(2) Assumes spare channel is available.

TABLE 7-2

MHD COMPONENT COSTS

	Material Cost ($)	Installed Cost ($)
Combustor	1,023,000	1,277,000
Nozzle	183,000	233,000
Channel	6,187,000	7,621,000
Diffuser	1,543,000	1,931,000
Magnet	51,970,000	63,152,000
Air Compressor and Driver	7,057,000	8,928,000

improvement in availability was used.[1] Figure 7-1 shows the expendable dollars versus worth factor for the nominal 950,000 kW early commercial MHD power plant. For this plant the curve shows that an expenditure of $11,400,000 can be justified to gain 1% improvement in availability for a worth factor of $12/kW_e$.

7.2 COMPONENT AVAILABILITY

7.2.1 Channel Availability

The effects on channel availability for channel mean time between failures from 1000 to 10,000 hr and for mean times to repair of 50, 100 and 150 hr are shown in Figure 7-2.

In this study, a base channel life or mean time between failure of 5000 hr or more was assumed based on extrapolation of results from duration testing of experimental MHD channels.

Furthermore, it was also assumed that a spare channel is available and can be put into operation in an estimated 50 hr. The following assumptions and sequence of events were used to determine the channel replacement time.

Assumptions:

A. Mature Plant, Experienced Crew

B. MHD Components Designed for Fast Turnaround

C. Replacement Channel Assembled, Checked out and Completely Ready for Installation

D. Channel Cooling Water Supplied by Low Pressure and Low Temperature Condensate Loop

Sequence of Events:

		Hours
1.	De-energize Magnet (channel cool-down and isolation accomplished simultaneously)	3.5
2.	Install Scaffold	2
3.	Disconnect Channel	
	a. Structural-Mechanical - 2 b. Hydraulic - 4 Concurrent c. Electrical - 4	4
4.	Remove Channel from Magnet Bore	4
5.	Install New Channel in Magnet Bore	4

(1) As defined in EPRI Report NP-493-76-662.

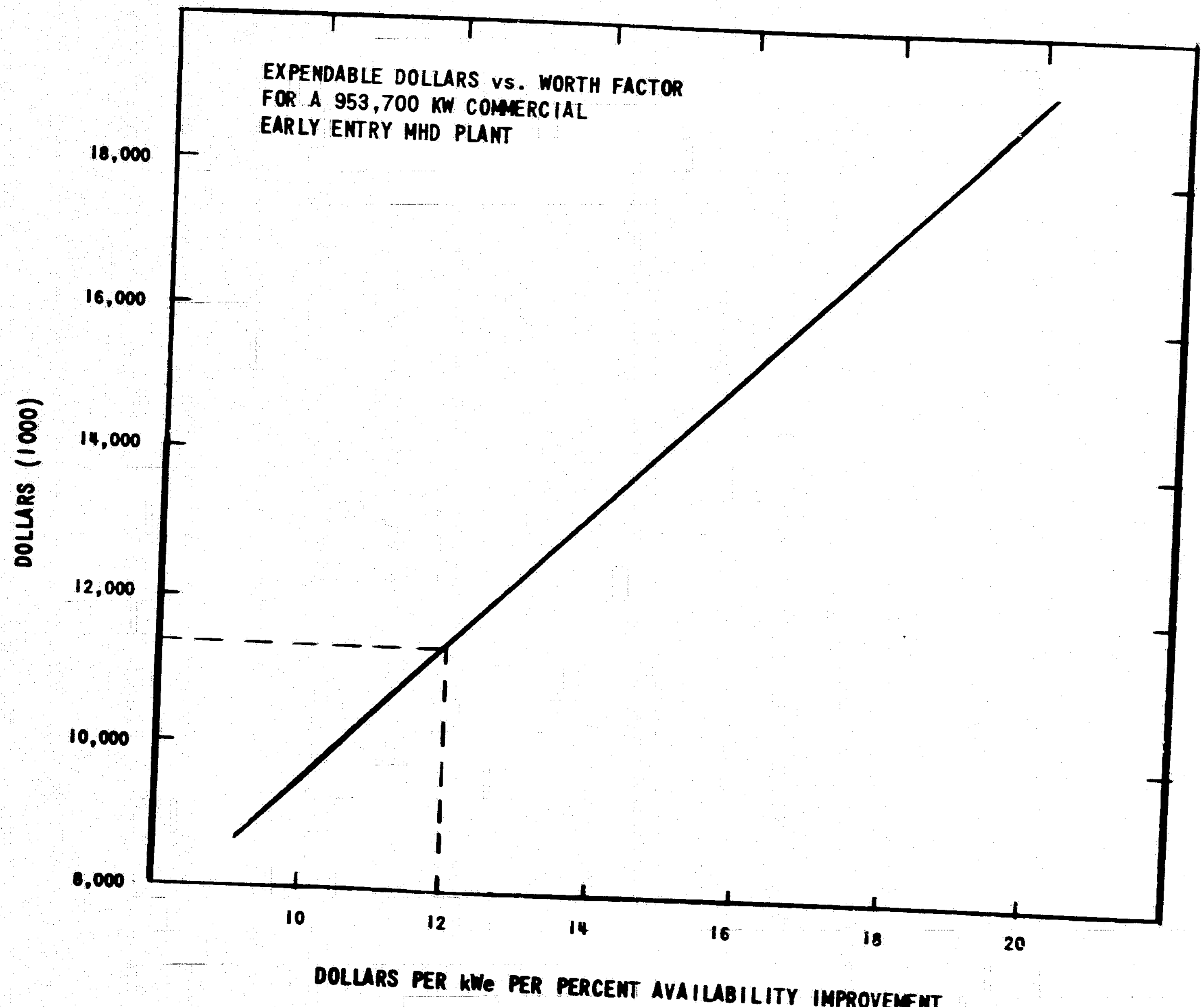

Figure 7-1 Permissible Expenditure vs Worth Factor

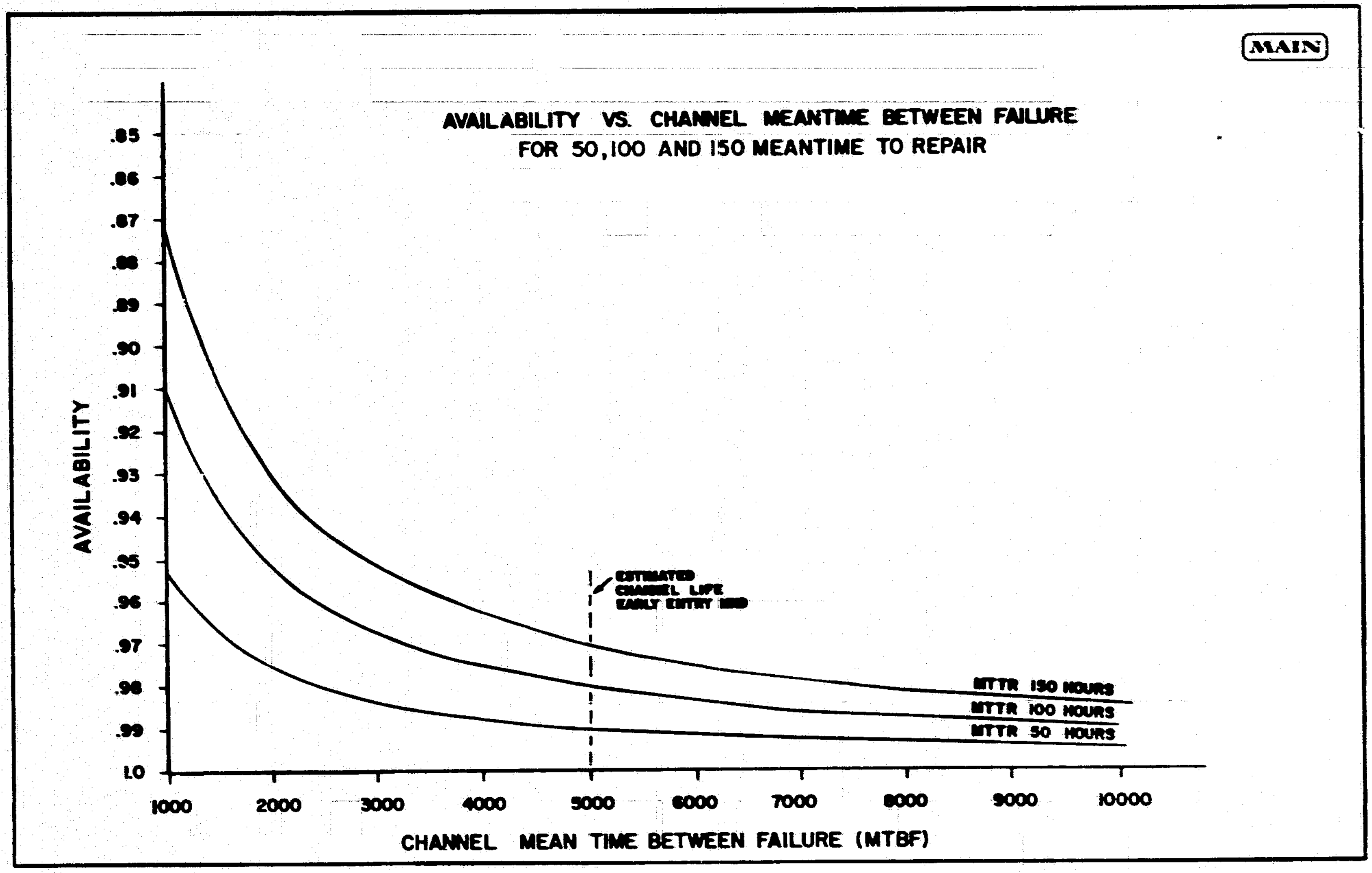

Figure 7-2 Channel Availability vs Channel Mean Times Between Failure as a Function of Channel Mean Time to Repair

6.	Channel Alignment and Hookup		
	a. Alignment, Mechanical and Structure - 4		
	b. Hydraulic - 4	50% Overlap	6
	c. Electrical - 4		
7.	Electrical and Hydraulic Checks		2
8.	Remove Scaffolds		2
9.	Re-energize Magnet		3.5
		Total Time	31.0

It is mentioned that additional events will occur in parallel to the above listed sequence of events. For example, the diffuser is considered isolated, cooled down, disconnected and removed in parallel with steps 1, 2 and 3, and it is put back in place, reconnected and checked out in parallel with steps 6 and 7.

The above sequence of events results in a total time of 31 hr. However, a longer total replacement time of 50 hr was used as the basics for the availability analysis to account for contingencies and unforeseen circumstances. This longer replacement time may be considered conservative.

The effects on channel availability of extending the channel duration from 5000 hr to 10,000 hr and of increasing the replacement time or mean time to repair (MTTR) from 50 hr to 100 hr and 150 hr, respectively, are shown in Table 7-3.

The significance is that by doubling the channel duration time from 5000 hr to 10,000 hr, availability is increased by only one-half of 1% for the 50-hr mean time to repair case. It appears, therefore, marginal to spend large amounts of money to improve the channel duration beyond the 5000-hr range until actual operating experience has been achieved and replacement time (MTTR) is minimized. It is noted that an increase of channel duration from 2000 hr as assumed in our ETF design effort to 5000 hr will improve the availability with 1.99% for the same assumed MTTR of 50 hr. The important and significant improvements in availability resulting from reducing the mean time to repair (MTTR) are clearly indicated by the curves in Figure 7-2.

The effects of channel life on unit availability for 50- and 150-hr mean times to repair are shown in Figure 7-3. The availability of a conventional fossil-fired power plant for units 800 MW and larger was used as a base in this analysis. The historical unit availability for this size unit is 72.5%.* This value was assumed to be the unit availability baseline value

*Unit availability from the EEI Report on equipment availability 10-year period 1968-1977 issues July 1979, pgs. 20 and 21.

TABLE 7-3

CHANNEL LIFE (MTBF) VERSUS REPAIR TIME (MTTR)

Channel Life (MTBF) Hours	Availability 50 Hr MTTR	% Change	Availability 100 Hr MTTF	% Change	Availability 150 Hr MTTR	% Change
5,000	0.9901		0.9804		0.9709	
10,000	0.9950	0.49%	0.9901	0.97%	0.9852	1.4%

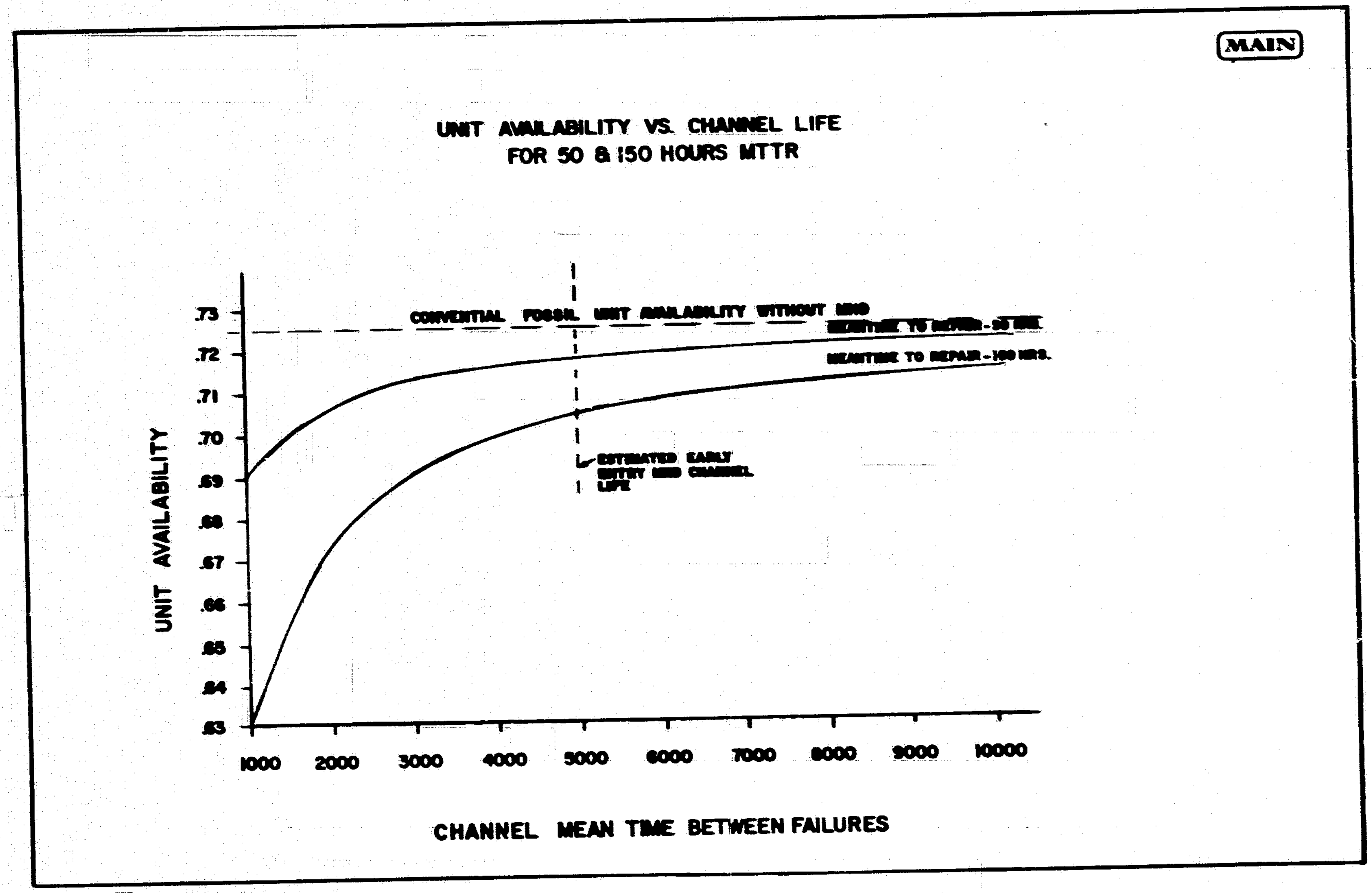

Figure 7-3 Unit Availability vs Channel Mean Time Between Failure as a Function of Channel Mean Time to Repair

exclusive of the channel. In addition, a higher base unit availability of 85% was also assumed. Table 7-4 summarizes comparative results from the availability analysis for the two assumed base unit availabilities (exclusive of the channel) of 72.5% and 85%, respectively, and for assumed channel lifetimes between failures (MTBF) of 5000 hours and 10,000 hours and replacement times of 50 hours and 150 hours, respectively.

The analyses indicate that the unit availability will improve with about 1/2% by increasing the channel lifetime from 5000 hours to 10,000 hours for an assumed replacement time (MTTR) of 50 hours. However, an increase of the replacement time to 150 hours for the longer assumed channel lifetime of 10,000 hours decreases the unit availability with about 1/2% compared to the shorter channel lifetime of 5000 hours along with the shorter assumed channel replacement time of 50 hours. These analyses show that a relative short channel replacement time is of prime importance for improvement of channel and thus overall unit availabilities. The significant improvement in channel availability for a shorter channel replacement time can also be seen by comparing the two curves of channel availability in Figure 7-3 for mean times to repair (MTTR) of 50 and 150 hours, respectively.

The above analysis was based on 5000 and 10,000 hr mean time between failure channels and mean times to repair of 50,000 and 150 hr. The mean time to repair hours assumed one spare channel. The justification for a spare channel is based on the following.

A 5000 hr MHD channel without a spare is assumed to require a unit outage of 168 hr to repair the channel and return the unit to service. Therefore, the channel availability would be:

$$A = \frac{5000}{5000 + 168} = \frac{5000}{5168} = 0.96749$$

As previously mentioned a spare channel can be replaced and the unit placed back in operation in an estimated 50 hr.

The availability for a 50 hr MTTR is:

$$A = \frac{5000}{5000 + 50} = \frac{5000}{5050} = 0.9901$$

The improvement in availability by providing the spare channel is:

$$\frac{0.9901 - 0.96749}{0.96749} \times 100 = 2.34\%$$

TABLE 7-4

UNIT AVAILABILITY VS. CHANNEL LIFE (MTBF) AND REPAIR TIME (MTTR)

Channel Mean Time Between Failures MTBF	Channel Mean Time To Repair MTTR	Channel Availability	Unit Avail. Excluding Channel A_o	Unit Avail. Including Channel A_1	Difference in Unit Availability $D = \frac{A_1 - A_o}{A_o} 100$
5,000 hrs	50 hrs	99.01%	72.5%	71.8%	- 0.99%
"	"	"	85.0	84.2	- "
"	150	97.09	72.5	70.4	- 2.91
"	"	"	85.0	82.5	- "
10,000 hrs	50 hrs	99.50%	72.5%	72.1%	- 0.50%
"	"	"	85.0	84.6	- "
"	150	98.52	72.5	71.4	- 1.48
"	"	"	85.0	83.7	- "

The worth factor based on $12/KWe/percent improvement in availability is $11,400,000. Therefore, for a 2.34% availability improvement a capital expenditure of $26,779,000 could be justified. The spare channel cost is $6,187,000. The spare channel is obviously cost effective and should be purchased. From the analysis, one could conclude that a second spare channel might also be cost effective; however, this would only be true if the spare channel fails before the first channel is repaired or during the first 168 hours of operation on the new channel. If it should fail after 168 hr of operation, the original channel would have been repaired and be ready for service. No credit is taken for repair of the failed channel during the downtime. The assumption is that repair work on the failed channel would not commence until the unit is back on-line.

7.2.2 Availability with Two Parallel Power Trains

This analysis was based on the use of two identical MHD power trains arranged in parallel. The two parallel MHD power trains consist of the combustor, the nozzle, the MHD channel, magnet, and diffuser. As shown in Appendix D, the reliability of a single power train is 0.97528. The calculation of the reliability of two identical power trains assumes that each train is rated for 100% power and that one train is in operation and the redundant power train is on hot standby and can be placed in service in one hour or less. The reliability of two parallel trains is 0.99939 resulting in improvement of 2.47% over the availability of a single power train. The worth factor indicates that an expenditure of $28,267,000 can be justified for this improvement. However, the installed cost of a complete second power train is $74,214,000 exclusive of costs, for additional equipment required, such as ducting and valving for upstream and downstream connections and for flow control and isolation of the two power tains. In summary, two parallel full capacity power trains cannot be economically justified due primarily to the cost of the superconducting magnet. Also, the cost of the consolidation circuitry and inverter equipment for the channel output were not included in this analysis. Any additional costs associated with this equipment would increase the total cost further and makes a parallel channel configuration even less attractive or cost effective.

7.2.3 Air Compressor and Driver

This analysis considers the use of one and two full-size air compressors with drivers. The availability of the one air compressor without a standby is 0.9901. About 1% improvement in availability can be provided by the use of two full size compressors operating in parallel if the second compressor can be brought on-line in a very short time, in the order of less than one hour.

One method of achieving this is by having both compressors on-line running at reduced capacity.

The 1% improvement in availability would indicate that an additional expenditure of $11,400,000 could be justified. The installed cost of a spare compressor is estimated to be $8,928,000. Therefore, from a cost standpoint, a spare compressor could be justified. Additional detailed studies would be required to determine the overall effects on cost of electricity. This should include resulting effects from reduced compressor efficiency expected from operating the compressors at derated conditions or the time that would be required to bring a standby compressor on-line.

7.2.4 Nozzle

For the nozzle a mean time to repair of 50 hr was estimated, assuming no spare nozzle was available. An estimate was made that a spare nozzle could be installed in 30 hr. The availability with the use of a spare nozzle increased from 0.99800 to 0.99880 or 0.08%. The present worth factor indicates that an expenditure of $915,000 could be justified for this nozzle. The nozzle cost is $183,000 and $233,000 installed. On this basis, the use of a spare nozzle could be justified.

7.2.5 Diffuser

For the diffuser a mean time to repair of 75 hr was estimated without a spare diffuser. An estimate was made that a spare diffuser could be installed in 35 hr. The availability increased from 0.99626 to 0.99825 or an improvement of 0.2%. This indicates that an expenditure of $2,288,800 could be justified. The diffuser cost is estimated to be $1,543,000 or $1,931,000 installed. This indicates that the use of a spare diffuser is justified.

8.0 NATURAL RESOURCE REQUIREMENTS AND ENVIRONMENTAL INTRUSION

Tables 8-1 and 8-2 summarize the environmental intrusion and natural resource requirements. The data is presented in two ways. The first column gives the total quanity used or produced. The second column gives unit values that are convenient for making comparisons to other power generating facilities.

Table 8-1 lists the quantities of ash and gypsum to be disposed of and the heat rejected from the cooling tower, flue gases and by equipment heat losses. Also shown are the SO_x, NO_x and particulate emissions, which are in accordance with the New Stationary Sources Performance Standards for electric utilities. SO_x emissions of 0.57 lb/10^6 Btu corresponds to 70% removal of the sulfur in the coal.

Table 8-2 shows the use of coal, potassium sulfate, lime, water and land. The seed makeup is 6.6% of the total seed flow, 5.4% is assumed lost in the boiler and MHD components, 1% in the seed regeneration process and 0.2% with stack gases. The cooling tower water usage rate assumes that 75% of the cooling is done by evaporation. This is typical of mechanical draft cooling towers.

The land usage is divided into two categories. The first is the area required for storing the ash and gypsum generated over the life of the plant. The second area shown includes all of the other plant facilities. Of this area the plant island is $\sim$ 5%, coal handling and storage is 35%, waste water and clean water holding ponds are 4.8% and cooling towers, oxygen plant, transmission plant and seed facilities account for 1.8%. The remaining portion of the plant facilities area is accounted for primarily by on-site roads and the site boundary property

The estimated usage of critical components is shown on Table 8-3.

TABLE 8-1

ENVIRONMENTAL INTRUSION

Plant Net Output 953.73 MW

Wastes	lb/hr	lb/kWhr
Ash	71,103	0.075
Gypsum	33,044	0.035
Heat Rejected	**Btu/hr**	**Btu/kWhr**
Cooling Tower	$3\ (10^9)$	3,145
Chimney & Losses	$7.5\ (10^8)$	784
Emissions	**lb/hr**	**$lb/10^6$ Btu**
SO_x	4,155	0.57
NO_x	3,645	0.5
Particulate	218	0.03

TABLE 8-2

NATURAL RESOURCE REQUIREMENTS

Plant Net Output 953.73 MW

	lb/hr	lb/kWhr
Coal (22.7% Moisture)	817,276	0.857
K_2SO_4 - Seed Makeup	5,397	0.00566
Unslaked Lime	8,611	0.00903
Water-Cooling Tower	GPM	gal/kWhr
Evaporation	5,681	0.268
Blowdown	1,781	0.112
Land	Acres	Acres/100 MW_e
Waste Disposal	234	24.6
Plant Facilities	442	46.1
Total	676	70.9

TABLE 8-3

ESTIMATED USAGE OF CRITICAL ELEMENTS
(1000 lbs)

	Cr	Ni	Mo	Mn	Nb	Ti	Cu	Al	Mg	Pt*
MHD COMPONENTS										
Combustor and Nozzle	4.9	4.7					24.2			
Channel							68.7			6.28
Diffuser	8.3	3.7								
Magnet	1194	677			58	46	1240	2293	104	
STEAM GENERATOR	431	145	28	52						

*1000 oz

9.0 SUMMARY AND CONCLUSIONS

The performance analysis has shown that a net plant efficiency of 43.9% can be attained by a nominal 950 MW_e early commercial or first generation MHD power plant, designed for combustion of coal with oxygen enriched air, preheated to 1200°F in a metallic tubular recuperative heat exchanger which is part of the bottoming plant heat recovery system. The optimum degree of oxygen enrichment for the power plant design conditions is 34% by volume in the oxidizer. The oxygen required is produced at 80% purity by volume in a cryogenic air separation plant. This oxygen plant is closely integrated with the power plant and produces oxygen with a power consumption of 190 kWhr/ton of contained oxygen in the product.

Overall performance and cost data for the 950 MW_e early commercial MHD power plant are listed in the first column of the Power Plant Comparison Summary in Table 9-1. The second column lists data for the mature MHD power plant of advanced design considered in ECAS. This plant uses a directly fired high-temperature air preheater. The ECAS cost data for this mature MHD power plant have been converted from mid-1975 to mid-1978 dollars by applying an annual escalation factor of 6.5%. The data listed in the third and last column are for a modified ECAS conventional reference steam power plant with wet lime scrubber and 175°F stack temperature.[16] This conventional reference steam power plant is designed to meet NSPS similar to the early commercial MHD power plant design. The mature MHD power plant in ECAS was designed for the less stringent EPA emission standards existing at the time ECAS was conducted.

Although the early commercial MHD power plant does not offer the same high efficiency and low cost as the mature MHD power plant defined by ECAS, the performance and estimated costs are still considered attractive compared to conventional power plants.

Parametric sensitivity analysis conducted showed that the variations in plant performance and estimated costs for a variation in preheat temperature are relatively small. A variation in the preheat temperature of ± 100°F results in about ± 1/4 percentage point variation in the net plant efficiency, and ± 0.1-0.2 mills/kWhr or ± 0.25-0.50% in estimated COE.

TABLE 9-1

POWER PLANT COMPARISON SUMMARY

	MHD/STEAM PLANT		CONVENTIONAL STEAM PLANT
	Early Commercial 34% Oxygen 1200°F Preheat NSPS 1979	Mature-ECAS Direct Fired HTAH 2500°F Preheat PS 1976	Modified ECAS Reference Wet Lime Scrubber, 175°F Stack NSPS 1979
Overall Eff. - %	43.9	48.3	34.3
Capital Cost - $/kW	712	576	675
COE (Lev.)-Mills/kWhr			
Capital	22.51	18.20	21.3
Fuel @ 105¢/MBtu	16.38	14.87	20.9
O & M	4.10	3.50	6.4
Total	42.99	36.57	48.6

The overall net plant efficiency at part load with an electrical output of about 70% of nominal or 680 MW_e was calculated to be 41.8% or 2.1 percentage points lower than that at nominal load. This shows that a relatively high efficiency also can be maintained at part load operation, which is important for practical utility application. The efficiency of a conventional steam plant at 70% load might typically be about 0.5-1.0 percentage point lower than at full load. Complete part load analyses were beyond the scope of this design effort, and it is pointed out that further analysis is required to optimize plant and equipment design for all expected utility operating conditions, as well as to establish the important load following capability and controls aspects of the MHD plant.

The plant efficiency was optimized both at nominal and part load operation by optimization of net MHD power generation, or MHD power output minus the compressor power required for oxygen production and for compression of the oxygen enriched combustion air to the peak cycle pressure. At nominal load the gross MHD power production was 525 MW_e or 55.3% of the net electrical output from the plant. The net MHD power produced after deducting the total compressor power was 355.4 MW_e or 16.7% of the fuel heat input to the MHD combustor.

The channel performance calculations conducted in this Task 2 conceptual design activity were more detailed than the simplified comparative channel calculations conducted in the initial parametric analysis of Task 1. The channel calculations in Task 2 employed a more sophisticated treatment of the boundary losses including slagging effects. This forms a better basis for projecting the channel performance and operating characteristics than the initial routine channel performance calculations.

Important projected channel performance data for the early commercial channel design of this study (CSPEC) are summarized in Table 9-2 and compared with calculated design data for the CDIF 1B MHD Flow Train and test data obtained from experimental operation with the Avco Mark VI generator channel.

The values of the critical design parameters for the CSPEC channel, electrical fields, current density, power density and Hall parameter are considered reasonable projections for early commercial use. The increase in enthalpy extraction and isentropic efficiencies for the much larger early commercial channel are expected because of the inherent MHD scaling effects. Low pressure and low temperature boiler feed water is used as channel coolant for the "moderate technology" CSPEC channel. This is in accordance with present experience in experimental MHD channel operation.

TABLE 9–2

COMPARATIVE MHD CHANNEL PERFORMANCE DATA

		TEST FACILITIES		EARLY COMMERCIAL PLANT
		EXP. DATA	DESIGN DATA	CSPEC
		AVCO MK–VI	CDIF # 1B	34% O_2 1200°F PREHEAT
THERMAL INPUT	MW_{th}	15	50	2140
PRESSURE RATIO		2.9 – 3.5	3.5	8.3
INLET TEMP. (STAG.)	°K	2900	2860	2881
MAX. MAGNETIC FIELD	TESLA	2.8	6	6
MASS FLOW RATE	kg/s	2.5	10	472
GAS VELOCITY	MACH NO.	~ 1.2	~ 0.8	~ 0.8
POWER OUTPUT	MW	0.2 – 0.6	3.4	525
MAX. TRANSV. CURRENT	$amps/cm^2$	0.8 – 1.5	1.0	0.8
MAX. AXIAL FIELD (E_x)	kV/m	1.0 – 3.0	2.2	1.8
MAX. TRANSV. FIELD (E_y)	kV/m	1.0 – 3.0	3.9	4.0
HALL PARAMETER	$\omega\tau$	1.5 – 2.5	2.8	3.9
POWER DENSITY (AVG)	MW/m^3	5 – 15	~10	6.0
ENTHALPY EXTRACTION	%	1.5 – 4.0	7	24.5
ISENTROPIC EFFICIENCY	%		44	74.0
DIFFUSER EFFICIENCY	%		45	60

H9333–1

Subcritical steam conditions of 2400 psig/1000°F/1000°F were selected for the bottoming steam cycle to avoid any additional operational problems which might be introduced by the use of supercritical steam conditions. The resulting steam cycle (Rankine) efficiency is 41.8% with the use of seven feedwater heaters. The MHD combustor is cooled by high-pressure and high-temperature feedwater and the diffuser cooling is incorporated as part of the evaporative steam generator circuit. The later possible use of supercritical steam conditions and of high-pressure and high temperature feedwater cooling of the channel is estimated to raise the steam (Rankine) cycle efficiency to 43% or slightly higher which would increase the net plant efficiency to the 45% level.

Previous conceptual design studies such as ECAS have shown that significant improvements in plant performance can be obtained for more advanced MHD power plant designs employing directly fired high-temperature air preheaters and/or chemical regeneration of the MHD generator exhaust gas. The latter advanced concept is applicable to MHD power systems using either oxygen enriched combustion air or high temperature preheated air. It is also pointed out that potential improvements in net plant efficiency of the particular reference power plant configuration studied here can directly be attained by improved performance of the MHD generator. This is shown by the two curves in Figure 9-1. The lower efficiency curve is based on the use of LP boiler feed as channel coolant and subcritical (2400 psig/1000°F/1000°F) bottoming plant steam conditions, as used in this conceptual design study. The calculated CSPEC plant efficiency of 43.9% is plotted on this curve for the calculated performance of the MHD generator of 74.5% machine efficiency (isentropic eff.). The upper curve is the estimated corresponding plant performance based on the use of HP boiler feedwater as channel coolant and supercritical (3500 psi/1000°F/1000°F) steam conditions. (It is mentioned that the conventional steam plant data in Table 9-1 is for a supercritical unit).

Significant developments for improvement of the MHD generator performance would be:

- Ability to handle higher power densities and electrical stresses along with the use of higher magnetic fields.
- Ability to improve diffuser efficiency.
- Ability to use a higher channel wall temperature.

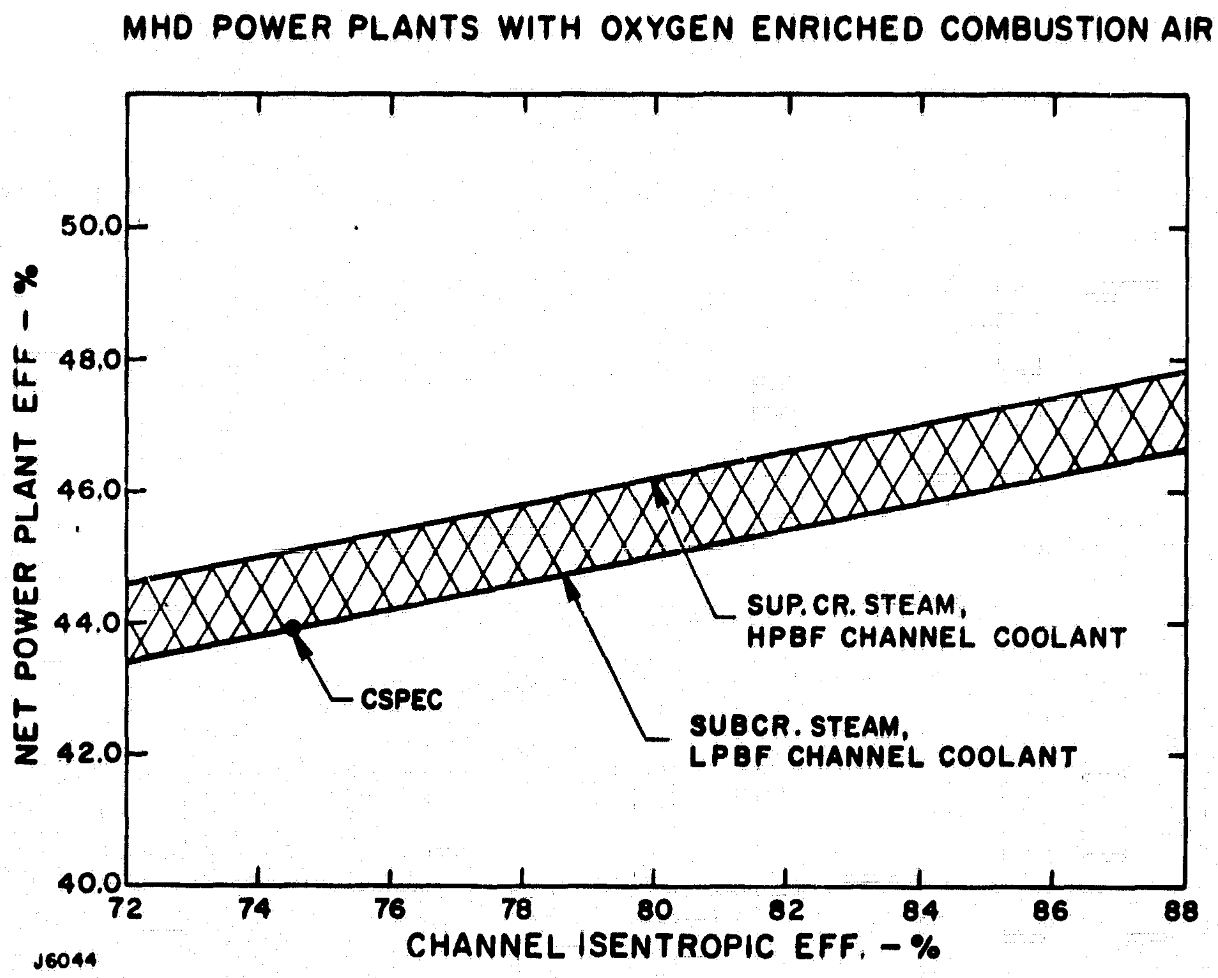

Figure 9-1 Net Plant Efficiency vs Channel Isentropic Efficiency

Also, improvements of the oxygen plant would directly improve the power plant performance and its costs. The performance and cost data of the oxygen plant in this study were based upon information provided by NASA and developed by LOTEPRO in a separate study of oxygen plants for MHD power plant applications.

The cost distribution by categories in percent of plant direct costs for the early commercial MHD power plant is summarized in Table 9-3. The most costly equipment item is the steam generator with oxidant preheater. The second most costly is the superconducting magnet. The magnet cost is slightly higher than the cost of the oxygen plant.

In simple terms the cost of the superconducting magnet can be expressed as a function of the product between the magnet bore volume, V, and the magnetic field, B or Cost $\approx (VB^2)^n$ where n is an exponent whose value can change with magnet size. It is clear that the magnet is a very important cost item and that particular attention and effort in its design must be devoted to cost effectiveness. Efficient utilization of the magnet bore volume is one important design consideration which was emphasized. This is an area which requires close coordination between the channel and magnet designers and further development and design work. The magnet bore utilization factor arrived at in this conceptual design was ~ 0.5 (channel gas volume/ magnet warm bore volume). A primary magnet design objective otherwise was to minimize the magnet construction cost by minimizing field construction and installation work. For this, a modular magnet design concept was adopted similar to that utilized in our ETF conceptual design.(2)

Sulfur removal is achieved by regeneration and recycling of recovered seed. The formate process was selected for regeneration of seed because of its relatively low energy requirements and high efficiency and also because its basic viability has been demonstrated in industrial use. The basic plant performance and cost data were based on 70% removal of the sulfur contained in the coal type used (Montana Rosebud) which satisfies NSPS requirements. One hundred percent sulfur removal was considered as a design alternate to minimize potential corrosion problems related to sulfur in the gas. Complete sulfur removal appears practicable. The estimated reduction in plant performance resulting from this would be slight and in the order of 1/4 percentage point. The size of the seed processing plant would have to be increased by roughly 40%. The additional cost for this appears tolerable. An important new and additional design feature in seed processing was introduced in this conceptual design study. It is based on the discovered differences in the solubilities of alkali carbonates and sulfates. This makes it possible to separate recovered potassium and also any sodium carbonates from potassium sulfate <u>before</u> conversion of

TABLE 9-3

COST DISTRIBUTION FOR EARLY COMMERCIAL MHD/STEAM BASE LOAD POWER PLANT

950 MW_e nominal plant capacity with use of oxygen enriched combustion air.
All estimated cost percentages are % of direct costs and refer to constant dollar -mid-1978.
Construction time period - 5 3/4 years.

			% of Direct Costs
1.	Land		0.2
2.	Structures and Improvements		8.4
3.	Boiler Plant		29.8
	Coal and Ash Handling	5.1	
	Steam Generator with Oxidant Heater	20.5	
	Effluent Control and Other	4.2	
4.	Steam Turbine Generator		8.3
5.	Accessory Electric Equipment		6.0
6.	Miscellaneous Power Plant Equipment		0.4
7.	MHD Topping Cycle		45.7
	Combustion Equipment	7.1	
	MHD Generator	1.8	
	Magnet Subsystem	11.3	
	Inverters	8.4	
	Oxidizer Supply Subsystem	1.8	
	Oxygen Plant	10.7	
	Seed Subsystem	4.6	
8.	Transmission Plant		1.2
	Subtotal Direct Costs		100.0
	Engineering Services and Other Costs		9.5
	Overnight Construction Cost		109.5
	Interest and Escalation		11.0
	Total Construction Cost with IDC & EDC		120.5
	Specific Plant Cost with IDC & EDC	Dollars per KW	712

potassium sulfate to potassium formate. With 100% sulfur removal only part of the potassium seed would combine with all of the sulfur in the gas and the remaining potassium and sodium (which has less affinity to sulfur than potassium) in the gas are expected to form carbonates and be recovered as such. Sodium carbonate can again be separated from potassium carbonate, by for instance, crystallization. In this way buildup of sodium in the system can be avoided.

Ash impurities other than sodium are recognized as potential problems in any seed regeneration process. Further efforts and development work are required to finalize the design and to select the optimum process for regeneration of seed.

NO_x emission control is accomplished by using initial fuel rich MHD combustion conditions with an oxidizer/fuel equivalence ratio of 0.9 of stoichiometric. The fuel rich MHD generator exhaust is then cooled in the primary radiant chamber of the bottoming heat recovery steam generator from about 3700°F to 2900°F in 2 sec, and afterburning with final oxidation of the gas is subsequently performed in the secondary chamber of the steam generator. The substoichiometric MHD combustion conditions of 0.9 together with the 2 sec residence time of the hot exhaust gas in the primary radiant boiler chamber result in an expected reduction of the NO_x concentration in the exhaust gas to 300-350 ppm or less.(2) This expected NO_x concentration in the gas corresponds to half or less of the NO_x emission limit stipulated by NSPS (0.5 lbs NO_x/MBtu fuel input). It is mentioned that combustion with oxygen enriched air containing 34 vol% O_2 reduces the amount of combustion gases produced to about 2/3 of that using air only and the amount of stack gas emitted is reduced accordingly.

The ESP for removal of condensed seed and remaining flyash from the stack gas was designed for an efficiency of 99.83%. This removal efficiency reduces the amount of particulate emitted with stack gas to about 50% of the particulate emission limit stipulated by NSPS (0.03 lbs/MBtu fuel input).

Some reliability/availability analyses were conducted considering the use of selected redundant MHD power system components. This included the consideration of a dual MHD power train (combustor, nozzle, channel, magnet, diffuser) each of 100% (fuel load) capacity arranged in parallel. These analyses indicate that a spare channel definitely is cost effective. Also, the importance of providing for a relative rapid replacement of the channel (MTTR) for improvement of channel availability is clearly pointed out. A channel replacement time (MTTR) of 50 hr appears practical. This along with a channel mean operating time between failures (MTBF) of 5000 hr results in a channel availability (A = MTBF/MTBF + MTTR) of 99%. A dual MHD power train with each train rated at full capacity is not considered to be cost effective mainly because of the relatively large cost associated with the additional superconducting magnet. It is clear that high plant availabilities are particularly important as capital and fuel costs rise. However, since availability studies rely heavily on past operating experience, results from such analyses of MHD power systems must be tempered by the fact that operational lifetime and availability of MHD components are not well known at this time.

Plant reliability in addition to energy efficiency, costs and pollution control are determining factors for electric utility utilization and acceptance of commercial MHD power generation. This conceptual design study has provided valuable information for an assessment of these important factors for an early "moderate technology" MHD base load power plant design of nominal 950 MW_e capacity utilizing oxygen enriched combustion air.

10.0 REFERENCES

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APPENDIX A

COAL AND ASH ANALYSES OF SELECTED COALS

	Montana (Rosebud)	Illinois (No. 6)
Proximate Analysis, Coal as Received, Percent		
Moisture	22.7	8.9
Volatile Matter	29.4	38.0
Fixed Carbon	39.2	41.7
Ash	8.7	11.4
Ultimate Analysis, Percent		
Hydrogen	6.0	5.4
Carbon	52.1	62.4
Nitrogen	0.79	1.2
Oxygen	31.5	16.3
Sulfur	0.85	3.3
Heating Value, Wet, Btu/lb	8920	11265
Heating Value, Dry, Btu/lb	11539	12370
Coal Rank	Subbit B	HVCB
Ash Analysis, Percent		
SiO_2	37.6	41.4 ± 5.4
Al_2O_3	17.3	19.3 ± 6.8
Fe_2O_3	5.1	22.3 ± 6.8
T_1O_2	0.7	0.9
P_2O_5	0.4	0.12
CaO	11.0	5.4 ± 3.3
MgO	4.0	1.7 ± 1.3
Na_2O	3.1	0.6 ± 0.2
K_2O	0.5	2.1 ± 0.4
SO_3	17.5	7.5 ± 0.6
Initial Deformation Temp °F	2190 ± 230	1960 ± 70
Softening Temp °F	2230 ± 240	2030 ± 70
Fluid Temp °F	2280 ± 240	2260 ± 200

APPENDIX B

SUMMARY OF AUXILIARY POWER REQUIREMENTS (KW)

Superconducting Magnet	
Cryogenic System	1,100
Coal Handling & Proc.	
Feeders, Conveyors, etc.	1,330
Pulverizers & Blowers	4,825
Nitrogen Blowers	1,483
Coal Feeding	
Petrocarb System Comp.	2,135
Steam Generator	
Boiler Circ. Pumps	4,290
Condensate Pumps	1,098
ID Fans & Sec. Air Blower	3,370
Electrostatic Precipitator	1,400
Seed Regeneration System	
Seed Regeneration Plant	8,075 (1)
Seed Feed System	25
Balance of Plant	
Circ. & Cooling Water Pumps	4,706
Cooling Tower Fans	2,970
Ash Handling System	446
Miscellaneous	202
Station Services	
HVAC, Lighting, Control, Power, etc.	1,110
TOTAL	38,565

(1) Includes power recovered from expansion of reactor offgas.

APPENDIX C

MAJOR EQUIPMENT LIST

The following is a list of major pieces of plant equipment. The numbering system corresponds to the account numbers specified for the NASA code of accounts.

MAJOR EQUIPMENT LIST

Account Number	Item	Number Required	Description	Notes
311.8	On/Site Wast Treatment			
	Waste Water Chemical Feed		Caustic & acid storage and feed systems	
312	Boiler Plant Equipment			
312.1	Coal Handling and Processing Area			
	Includes all converyors, feeders, scales, stack out equipment, metal detectors, rail car unloading equipment, reclaim and unloading hoppers, dust handling system and coal storage silos required.			
312.2	Slag and Ash Handling			
	Includes all collecting hoppers, ash sluice pumps, eductors, piping, pneumatic conveying equipment, dewatering bins and dewatering in sump pumps.			
312.4	Steam Generator Sections			
312.41	Steam Generator and Oxidizer Preheater	1		Balanced draft, controlled circulation, 2400 psig/1005F/1000F: 4,713391 lb/hr main steam; 2,775, 956 lb/hr reheat steam; 147 ft high x 233 ft deep x 54 ft wide plus economizer section, 124 ft high x 50 ft deep x 35 ft wide 1200F oxidizer preheater
312.44	Auxiliaries			
	Warmup Oil Guns	6		Firing No. 2 oil at 283 x 10^6 Btu/hr each
	Air Nozzles	6		139,333 lb/hr of 600°F burnout air each
	Sootblowers	188		27 ft travel full retract in seed recovery/convective section and rear pass
		132		18 ft travel full retract in economizer section
	ID Fan	1		683,000 acfm; ΔP = 21 in. H_2O
312.5	Effluent Control			
312.51	Precipitator and Breeching	1		C-E Walther; designed for 1.36 x 10^6 acfm at 250°F; 99.82% eff., gas velocity 3.26 ft/sec
312.52	Chimney	1	21 ft ID, 250 ft tall	
312.7	Other Boiler Plant Systems			
312.71	Condensate and Feedwater Systems			
	Condensate Pumps	2	3600 gpm @ 525 ft TDH	
	Boiler Feed Pump	1	11,000 gpm	
	HP & LP FW Heaters	6		
	Deaerator			
	BFP Turbine	1	Multistage turbine, 18,000 HP, Steam @ 176 psig - 760°F	
312.72	Water Treatment and Supply System			
	FW Treatment - Hydrazine, Morpholine, H_2SO_4, Organic Phosphate	1		Skid mounted systems including storage tanks, mixers and metering pumps
	Makeup Deminerilizer	1	125 gpm capacity per train	Skid mounted two train system
	Condensate Storage Tank	1	200,000 gallon	
	Pumps			
	River Water Supply	2	3500 gpm @ 30 ft TDH	
	Service Water	2	450 gpm @ 17? ft TDH	

MAJOR EQUIPMENT LIST

Account Number	Item	Number Required	Description	Notes
312.73	Secondary Air System			
	Low Temperature Air Heater	1		Tubular heater, 836,000 lb/hr air to 600 F for burnout; 91 ft high x 105deep x 32 ft wide
	Sootblowers	168		16 ft travel full retract in LTAH
	Secondary Air Fans	2	169,658 acfm @ 96 in. H_2O each	
	Air Ductwork, Fans to Air Heater and Heater Bypass	200 ft		
314	Turbogenerator Units			
314.1	Steam Turbine Generator & Auxiliary	1	475 MW, steam cond, 2400 psig, 1000°F/1000°F, 3600 rpm, tandem-compound multiflow, condensing	
314.2	Condenser and Auxiliaries		Two pass, 385,000 ft^2, 38 ft tubes	
314.3	Circulating Water System			
314.31	Pumps, Valves and Piping			
	Pumps	2	104,800 gpm @ 65 ft TDH	
	Piping	3200 ft	91 in. ID	
	Valves	7	60 in.	
	Valves	18	24 in.	
314.32	Cooling Tower	1	Mechanical draft, multicells	
315	Accessory Electric Equipment			
315.1	Station and Auxiliary Transformers			
	Startup, Standby Transformer	2	OA/FOA/FOA, 24/32/40 MVA, 345 kV to 4.16 kV, 3 winding, 15% impedence, 3 ø	
	Unit Auxiliary Transformer	2	OA/FOA/FOA, 24/32/40 MVA, 15 kV to 4.16 kV, 3 winding, 15% impedence, 3 ø	
315.2	Miscellaneous Motors		480 and 4160 V, 3 phase motors with bearing thermocouples, six stator winding RTDs, two grounding points, oversized conduit boxes, space heaters, bearings as required for service. Mounting, speed, enclosure and service factor to be determined later.	
	SC Magnet Helium Compressor	1	1475 HP	
	Circulating Water Pump	2	3000 HP	
	Cooling Tower Fan	18	220 HP	
	Boiler Induced Draft Fan	2	1800 HP	
	Startup Boiler Feed-Pump		3000 HP	
	Coal Pulverizer	8	500 HP	
	Pulverizer Blowers	8	350 HP	
	Secondary Air Blower	2	700 HP	
	Nitrogen Blowers	2	1250 HP	
	Seed Regen. Flue Gas Blowers	2	1000 HP	
	Condensate Pumps	2	800 HP	
	HP Ash Pumps	2	300 HP	
	Seed Regen. Gasifier Air Compressor	1	4250 HP	
	Isolated Phase Bus Duct	1 set	Inverter to step-up transformer 15 kV, 22 kA	
	Isolated Phase Bus Duct	1 set	STG to step-up transformer and auxiliary transformers 15 kV, 20 kA	

MAJOR EQUIPMENT LIST

Account Number	Item	Number Required	Description	Notes
315.3	<u>Switchgear and Motor Control Centers</u>			
	Switchgear Assembly	11	5000 V metal clad, indoor, 3000 main bus, 350 MVA 3000 incoming ACB, 1200 A 250 MVA ACB's, as required, 1 cubicle for instruments. Switchgear will include 1 set of 1600 A tie bus between assemblies.	
	Power Centers	11	Metal clad 600 V switchgear with 4000 A incoming ACB, 800 A to 3000 A feeder ACB's, throat connection to dry type 4.16 kV to 480 V Delta-Wye transformer, 750/1000 kVA or 1500/2000 kVA as required, with grounding resistor. Power center will contain instruments for protection and indications.	
	480 V Metal Clad Motor Control Center	11	Indoor, with 100 A and 225 A frame circuit breakers, combination motor starters - FVNR sizes 1-4, FVR sizes 1 and 2, and space for future expansion. Buses will be sized to fit loads.	
315.4	<u>Conduit, Tray, Cable and Buswork</u>			
	Ladder Type Cable Tray	Lot	4-in. and 6-in. deep, 6 to 24-in. wide, aluminum. To be utilized for 125 Vdc and 120 Vac control, 480 V power, 120/208 V power, 4.16 kV power and lighting cables. Tray includes elbows, fittings, covers, cover clamps, and accessory hardware.	
	Solid Type Cable Tray	Lot	4-in. deep, 6 to 24-in. wide, aluminum. To be utilized for signal cables (0-10 MV, 4-20 mA), thermocouple and communications cables. Tray to include covers (complete), elbows, fittings, clamps, and accessory hardware.	
	Conduit and Fittings	Lot	1/2 in. - 1 in. EMT (lighting); 3/4 in. - 4 in. rigid steel; 3/4 in. - 4 in. aluminum; 1 1/2 in. - 4 in. fiber or Korduct	
	Isolated Phase Bus	1 Set	Metalclad, self cooled for steam-turbine-generator leads. Bus to be 2500 A, 15 kV with neutral grounding equipment, PT's and support structures. Bus will have a 1000 A tap to the unit auxiliary transformer including supports, elbows, and connecting hardware.	
315.5	<u>Miscellaneous Electrical Equipment</u>			
	Grounding Equipment	Lot	Including ground rods, rod extensions, clamps, Thermoweld molds, Thermoweld cartridges, soft drawn copper ground cable (bare or insulated, dependent on conditions). Ground pads and miscellaneous hardware.	
	Lighting for Indoor Areas	Lot	Fixtures to be mercury vapor, fluorescent or incandescent, dependent on areas; illuminated and environment. MV and fluorescent fixtures to include ballasts. Mounting brackets, lamps and switches to be included.	
	Outdoor Lighting Equipment	Lot	Including poles, brackets, fixtures, ballasts, foundations and photoelectric control.	
	Uninterruptibe Power Supply	1	Inverter system 125 V to 120 V 1ø a-c, including transfer switches to bypass transformer and distribution panel.	
	Lighting & Control Transformers	Lot	Dry type 9 kVA - 7 kVA, 480 V, 3 wire to 120/208 V, 4 wire.	
	Lighting and Control Distribution Panels	Lot	Wall mount, main lugs, single, double or three pole circuit breakers.	

MAJOR EQUIPMENT LIST

Account Number	Item	Number Required	Description	Notes
315.6	Integrated Control System			
	Balance of Plant Analog and Digital Control Systems	1 Lot		Required to complete an integrated control system for plant control
	Control Room Control Panels	1 Lot		Complete with annunciators, indicators, recorders, control inserts, control switch, indicating lights required. To control and monitor plant operation from the remote control room.
	Hardware Cabinets	1 Lot		For analog control systems and digital logic system. To be located in the Electronics Room.
	Primary Sensing Elements and Signal Generating Devices	1 Lot		Necessary to provide input signals to control systems for balance of plant.
	Final Control Drive Devices	1 Lot		To control plant variables.
315.7	Data Acquisition System			
	Central Processing Unit (Main Frame)	1 Lot		Complete with software programs.
	Input/Output Cabinets	1 Lot		Containing required terminations, multiplexers, analog to digital converters, signal conditioners, amplifiers and buffers.
	Output Printers	4 each		For periodic logs, digital trends, alarm printouts and post trip or incident reviews.
	Analog Trend Recorders	1 Lot		
	Interconnecting Cables	1 Lot		Between major equipment components.
	Operator's Console	1 each		Mounted on a desk, complete with all required pushbuttons, selector switch, indicating lights, address switches, reduced size CRT for operator messages and other items necessary for output devices.
	Programmer's Console	1 each		With input/output printer. Tape reader and punch and necessary other controls and devices to provide a suitable interface for the programmer.
	Large Screen Display CRT	1 each		To display alarms and operational graphic displays.
	Primary Sensing Elements and Signal Generating Devices	1 Lot		To provide input intelligence.
315.8	Emergency Power Systems			
	60 Cell Station Battery	1	2080 amp-hour, lead-calcium, mounted on racks with portable test devices	
	Battery Charger	2	480 V to 125 Vdc	
	Diesel Generator	1	3 MW, 4.16 kV with control panel, starting equipment, day tank, exhaust stack and muffler	
316	Miscellaneous Power Plant Equipment			
	Fuel Oil Handling Equipment			Transfer from train to storage tank
	Fuel Oil Storage Tank		185,000 gallon capacity	
	Fire Protection System			
	Machine Shop and Maintenance Shop Equipment			
	Instrument and Service Air Comp.	2	900 acfm @ 125 psi each	
	Sump Pumps			
	Heating System Boiler	1		
	Fuel Oil Pumps	2	130 gpm each	
	Cooling Water Pumps	2	5500 gpm each	

MAJOR EQUIPMENT LIST

Account Number	Item	Number Required	Description	Notes
317	MHD Topping Cycle			
317.1	Combustion Equipment			
317.11	Coal Drying System			
	Bulk Material Valves	8		S-ECO 8 in. valves
	Airlocks	8		102,000 lb/hr coal
	Gravimetric Feeders	8		" "
	Mills	8		C-E Raymond RP 1003 (1 spare)
	Cyclones	8		61,000 acfm gas at 200 F plus 83,125 lb/hr coal each
	Fans	8		61,000 acfm gas at 200 F plus 12,500 lb/hr coal each
	Prepared Coal Storage Bins	4		15 ft dia., 21 ft high with sloping bottom; each holds 166,250 lbs coal
	Bin Activators	4		Vibrascrew 8 in. Bin Activators
	Scalping Screens	4		C-E Tyler Hummer
	Screw Feeders	4		Vibrascrew 15 in. dia. Heavy Duty Feeders
	Baghouses	2		C-E Air Preheater Model 8-9-264
	N_2 Preheater	1		Tubular heater 1,547,000 lb/hr N_2 to 600 F; 92 ft high x 111 ft deep x 33 ft wide
	Sootblowers	168		17 ft travel full retract in N_2 preheater
	N_2 Fans	2	181,780 acfm @ 30 in. H_2O each	
	N_2 Ductwork - Fan to N_2 Heater	325 ft	9.3 ft W x 14 ft H	
	N_2 Ductwork - N_2 Heater to Pulverizer Area	610 ft	11.2 ft W x 16.8 ft H	
	N_2 Ductwork to Pulverizers	200 ft	7.9 ft W x 11.8 ft H	
317.12	Coal Injection System			
	Petrocarb System	4		166,250 lb/hr coal to combustor at 8.5 atm pressure
	Inert Gas Pressurization System	4		8,500 scfm N_2 each at 200 psig to Petrocarb System (Ingersoll Rand reciprocating compressors plus ancillary equipment with 2500 HP motors).
317.13	Combustor	1		Single stage, water cooled
317.14	Slag Collection System			
	Quench Tank	1	Refractory lined steel tank to quench molten slag	
	Tank	2	5100 ft^3 for 4 hr storage time	
	Heat Exchanger	2	64 (10^6) Btu/hr	
	Pump	2	3000 gpm @ 120 ft	Provide cooling water to quench tank
317.2	MHD Generator System			
317.21	Inlet Nozzle	1		Subsonic, water cooled, slagging walls
317.22	Channel	1		Diagonal, water cooled, slagging walls
317.23	Diffuser and Transition Section	1		Water cooled, slagging walls
317.3	Magnet System	1		Nb-Ti Superconductor Windings, Dewar, Cryosystem, Controls
317.4	Inverters and Electrode Control System			
317.41	Inverters			Solid state, Line commutated
317.42	Electrode Consolidation			Solid State

MAJOR EQUIPMENT LIST

Account Number	Item	Number Required	Description	Notes
317.5	Oxidizer System			
317.51	Air Compressor and Drive			
	Air Compressor	1	Axial Comp., non-intercooled, 3,086,781 lb/hr capacity, 8.8 pressure ratio	
	Air Compressor Turbine	1	Multistage turbine, throttle condition - 2400 psig/1000°F	
	Inlet Filters and Silencer		3-stage filtration	
317.52	Combustion Air Piping and Ductwork			
	Compressor Discharge to Boiler	185 ft	55 in. ID pipe from ASTM A-387-76 Gr. 22 plate material	
	Boiler to Combustor	525 ft	60 in. ID pipe from ASTM A-240 Type 304 plate material	
317.6	Seed System			
317.61	Seed Regeneration Process			
	Air Compressor System	1	9000 scfm 30:1 ratio (Ingersoll Rand Mod. C90M5 centrifugal and Ingersoll Rand type HSE reciprocal)	
	Coal Gasifier System	1	100 TPD to produce 10,000 pph CO, 30 atm (Texaco pressurized gasifier plus waste heat recovery)	
	Reactor	2	1800 cu ft, 30 atm, stirred 3-stage, jacketed type 316 SS (Bethlehem Equipment Corporation, 9 ft ID x 36 ft high)	
	Gypsum Filter	1	27,000 lb/hr, 3 ft ø x 3 ft long atmospheric, type 316 SS rotary drum filter (Bird-Young vacuum filter by Bird Machine Company)	
	Spray Dryer	2	225,000 scfm, parallel flow, 20 ft ø x 35 ft high, type 316 SS (Swenson type by Whiting Mfg. Corporation)	
	Flue Gas Blowers	2	375,805 acfm @ 13 in. H_2O	
317.62	Seed Injection System			
	Tank	2	2280 ft^3 mixing tank with heating coils	
	Tank	1	3325 ft^3 holding tank with heating coils	
	Mixers		For above tanks	
	Feeder		Feed K_2SO_4 to mixing tanks	
	Pumps	2	70 gpm @ 35 psi - feed from mixing to holding tank	
317.7	Oxygen Enrichment System	1		Integrated oxygen production plant
350	Transmission Plant			
350.1	Structures and Improvements			
	Substation Structural Steel System	1	Four circuit ring bus, 345 kV	
	Foundation System	1	Four circuit ring bus, 345 kV	Includes 3 transformers and 4 OCB's
	Control House	1	345 kV substation	Includes control and relaying for 3 transformers and 1 commercial feeder

MAJOR EQUIPMENT LIST

Account Number	Item	Number Required	Description	Notes
350.2	Main Transformers			
	Main Turbine Generator Step-Up Transformers	1	500 MVA, 15 kV to 345 kV, 3 Ø, FOA, 11.5% impedence	
	Main MHD Inverter Transformer	1	550 MVA, FOA, MVA, 15 kV to 345 kV, 3Ø, 12% impedence	
	Startup Transformer & Const. Power Transformer	1	12/16/20 MVA, 115/4.16 kV	
	Inverter Step-Up Transformers	2	20/25 MVA, OA/FA, 3 phase 2.3/15 kV	
	Inverter Step-Up Transformers	2	30/37 MVA, OA/FA, 3 phase 3.9/15 kV	
	Inverter Step-Up Transformers	2	40/50 MVA, OA/FA, 3 phase 5.8/15 kV	
	Inverter Step-Up Transformers	2	45/55 MVA, OA/FA, 3 phase 8.1/15 kV	
	Inverter Step-Up Transformers	4	95/120 MVA, OA/FA, 3 phase 11.1/15 kV	
350.3	Substation			
	Main Circuit Breakers	4	345 kV, 1200 A, 10,000 MVA	
	Inverter Circuit Breakers	12	15 kV, 3000 A	
	Disconnect Switch	12	345 kV, 1200 A, manually operated	
	Cable and Conduit System	1	345 kV switchyard	
	Grounding and Bus System	1	345 kV switchyard	
	Relay and Control System	1	Four OCB ring bus system	

APPENDIX D

CALCULATIONS ON AVAILABILITY ANALYSIS

MHD Channel

No Spare Channel

MTBF = 5,000 hr

MTTR = 168 hr

$$A = \frac{5000}{5000 + 168} = \frac{5000}{5168} = 0.96749$$

One Spare Channel

MTBF = 5,000 hr

MTTR = 50 hr

Failure Rate = $200/10^6$ hr

$$A = \frac{5000}{5000 + 50} = \frac{5000}{5050} = 0.9901$$

$$\text{Increase in Availability} = \frac{0.9901 - 0.96749}{0.96749} \times 100 = 2.34\%$$

$6,187,000 Channel Cost

Worth Factor = $11,400,000/%

Therefore a spare channel is cost effective.

Two Spare Channels

$$A = 1 - (1 - 0.96749)^2 = 0.99894$$

$$\text{Increase in Availability} = \frac{0.99894 - 0.9901}{0.9901} \times 100 = 0.89\%$$

This indicates that there would be an improvement in availability with two spare channels but only if the second channel fails in less than 168 hr, or before repair of the first failed channel. The assumption is that the spare channel would not be repaired until after the unit is returned to service.

Parallel Power Trains

Two parallel MHD power trains consisting of combustor, nozzle channel, magnet and diffuser.

Component	Availability	Cost Installed ($)
Combustor	0.99338	1,277,000
Channel	0.99010	7,621,000
Nozzle	0.99800	233,000
Diffuser	0.99626	1,931,000
Magnet	0.99731	63,152,000
Power Train Availability	0.97528	74,214,000

Availability with two complete power trains in parallel:

$$A = 1 - (1 - 0.97528)^2 = 1 - (0.02472)^2 = 1 - 6.1108 \times 10^{-4}$$

$$= 0.99939$$

Availability improvement

$$= \frac{0.99939 - 0.97528}{0.97528} \times 100 = 2.47\%$$

Capital expenditure for a 2.47% improvement in availability

$$= \$11,444,000 \times 2.47 = \$28,267,000$$

To justify a $74,214,000 expenditure, an availability improvement of 6.48% would be required.

Combustor Availability

One Single Combustor Availability = 0.99338

Two Combustors in Parallel

$$A = 1 - (1 - 0.99338)^2 = 0.99996$$

$$\% \text{ Improvement} = \frac{0.99996 - 0.99338}{0.99338} \times 100 = 0.66\%$$

Allowable Expenditures = $11,400,000 x 0.66 = $7,524,000

Installed cost of combustor = $1,277,000

This preliminary calculation indicates that a parallel combustor arrangement would be cost effective. However, a more detailed analysis, which was beyond the scope of this study, should be conducted to include other costs which would be incurred by implementing this concept. These would include the costs for additional ducting and valves in the combustor reactant supply and high temperature gas discharge systems, cooling water system and a dual slag collection system. The analysis must also include the costs of additional instrumentation and controls, and increased foundation and structural requirements. Also, the mode of operation such as hot standby or continuous partial shared load or other possible schemes and the effect of the selected mode of operation on overall unit efficiency must be considered.

Nozzle

MTTR = 50 hr — $233,000 installed

MTBF = 25,000 hr — $183,000 equipment

No Spare

$$A = \frac{25,000}{25,050} = 0.99800$$

With One Spare MTTR = 30 hr

$$A = \frac{25,000}{25,030} = 0.99880$$

$$\text{Improvement} = \frac{0.99880 - 0.99800}{0.99800} \times 100 = 0.08\%$$

Allowable Expenditure = $11,400,000 x 0.08 = $912,000

Diffuser

MTTR = 75 hrs — $1,931,000 installed

MTBF = 20,000 hr — $1,543,000 equipment

No Spare

$$A = \frac{20,000}{20,075} = 0.99626$$

With One Spare MTTR = 35 hr

$$A = \frac{20,000}{20,035} = 0.99825$$

$$\text{Improvement} = \frac{0.99825 - 0.99626}{0.99626} \times 100 = 0.2\%$$

Allowable Expenditure = \$11,400,000 x 0.2 = \$2,280,800

Cycle Compressor

Single Compressor

Availability = 0.9901

Two Compressors in Parallel

$$A = 1 - (1 - 0.9901)^2 = 0.999902$$

$$\%\ \text{Improvement} = \frac{0.999902 - 0.9901}{0.9901} \times 100 = 0.99\%\ (\text{say } 1\%)$$

Allowable expenditure for 1% improvement in availability is \$11,400,000

Installed cost of cycle compressor and driver = \$8,928,000

Section 7.2.3 addresses additional costs which must be considered in determining the overall cost effectiveness of a parallel cycle compressor arrangement.

APPENDIX E

NEW STATIONARY SOURCES PERFORMANCE STANDARDS FOR ELECTRIC STEAM GENERATING UNITS

JUNE 1979

Emission Limits/10^6 Btu Heat Input

SO_2

1.2 lbs maximum

90% reduction if > 0.60 lb/MBtu

70% reduction if < 0.60 lb/MBtu

NO_x

0.60 lbs for bituminous coal

0.50 lbs for subbituminous coal

Particulates

0.03 lbs