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Parametric Study of Potential Early Commerical MHD Power Plants Task III—Parameter Variation of Plant Size

Finn A. Hals
Avco Everett Research Laboratory, Inc.

September 1981

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
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1.0 INTRODUCTION

1.1 SCOPE

This report is the final document reporting information developed in a third task, Task III, 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, 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. The results of Task II are contained in Reference 2.

Task III reported on in this document consisted of parametric performance and cost analyses of two plants of the same basic configuration as the plant studied in Task II but smaller in size. The two power plant sizes investigated in Task III correspond to nominal plant capacities of 200 MW_e and 500 MW_e, respectively. The smallest plant size of 200 MW_e corresponds to the size presently specified for the Engineering Test Facility (ETF). In addition to providing cost estimates for each of the two downsized plants in Task III consistent with the cost analyses used in Task II, a capital cost estimate for a "first of its kind" power plant was developed for the smallest plant size of 200 MW_e. This latter estimate served to identify the impact of applying learning curve factors to cost estimates of new technology items. Also, a detailed breakdown of the operating and maintenance cost of the larger Task II plant was a separate work subtask item of Task III.

Task III was conducted by the same contract team that conducted the two previous program Tasks I and II. 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 in this program are outlined in Table I-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 "moderate technology" entry level power plant 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.

Task III - Parametric Variations of Plant Size, was to use the conceptual design of Task II as a starting point to analyze the cost and performance of power plants of the same basic configuration as the Task II plant but smaller in size. The size range of interest is from the 200 MW_e of the Energineering Test Facility (ETF) up to the nominal 1000 MW_e of the Task II plant. The information provided by the Task III study permits an assessment of the competitiveness with steam plants of such first generation MHD power plants over the range of 200 to 1000 MW_e and contribute to establishing minimum MHD plant sizes for economical operation.

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
2. Plant Integration and Performance	2. Coal Processing	2. Plant Costs and COE
3. MHD Equipment MHD Combustor and Nozzle MHD Generator Including Electrode Consolidation Circuitry and Diffuser Superconducting Magnet	3. Gas Cleaning	3. Inversion
4. O_2 Plant		4. Seed Processing
		5. BOP Equipment

2.0 OVERALL POWER SYSTEM DESIGN AND PERFORMANCE - 500 MW_e and 200 MW_e PLANTS

2.1 OVERALL POWER PLANT CONFIGURATION AND DESIGN PARAMETERS

The basic plant configurations for the two power plants analyzed in Task III of nominal 200 MW_e and 500 MW_e capacity, respectively, are the same and identical to that of the larger plant with close to 950 MW_e output studied in Task II (CSPEC). The selected overall design parameters for the two Task III Plants are listed in Table 2-1.

The main common plant design feature is the use of oxygen enrichment of the combustion air and preheating of this oxygen enriched combustion air to 1200°F in a metallic, recuperative type, tubular heat exchanger which is part of the bottoming plant heat recovery system.

Various degrees of oxygen enrichment of the combustion air ranging from 30-36% oxygen content by volume were considered in optimization analysis of each plant.

The MHD generator design assumptions such as channel type, peak magnetic field, gas seed concentration, subsonic operation, channel cooling by low pressure and low temperature boiler feedwater, diffuser recovery factor and exit pressure were all similar to those assumed in CSPEC. Also, the channel critical electrical and gasdynamic operating parameters were limited to the same reasonable values as before.

The bottoming steam plant design conditions were assumed to be the same as in CSPEC with subcritical steam conditions of 2400 psig/1000°F/1000°F. These steam conditions were found to be in line with steam conditions for conventional commercial units both for the 500 MW_e and 200 MW_e plant sizes. The steam turbine ac generator for the smaller plant size of 200 MW_e has a power output of roughly 130 MW_e and for the larger 500 MW_e plant about 270 MW_e.

For completeness a brief description of other overall plant design characteristics are included here. Subbituminous coal is dried to 5% moisture content before firing in the MHD coal combustor. Nitrogen supplied from the oxygen plant is heated by flue gas and used for drying of the coal. The dried coal is burned under fuel rich conditions in the MHD combustor for NO_x-emission

TABLE 2-1

OVERALL DESIGN PARAMETERS FOR TASK III

1. Plant Size - MW_e (Nominal)	200 and 500
2. Fuel Type	Mont. Subbit.
3. MHD Combustion:	
Oxidizer O_2 content - % Vol.	30-36
Fuel Moist. as fired - %	5
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
Channel Gas Velocity	Subsonic
Diffuser Rec. Factor	0.6
Diffuser Exit Pressure - atm	1.0
Channel Coolant	LPBF Water
5. Bottoming Plant:	
Main Steam	2400 psia/1000^{o}F
Reheat Steam	1000^{o}F
Final MHD Combustor Gas Ox/Fuel Eq. Ratio	1.05
Oxidizer Preheat Temperature - ^{o}F	1200 F
Condenser Press - HgA	2 in.
6. Seed Regeneration Process	Formate

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 afterburning. 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. 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 for 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 as before.

All plants were designed to comply with EPA New Source Performance Standards for Electric Utility Steam Generating Units, NSPS 1979.

2.2 PERFORMANCE ANALYSIS

The plant performance analysis has established plant performance at nominal full load. The performance analysis followed in principle the approach used in previous program tasks and is outlined in Section 2.0 and Reference 1 and 2.

It is mentioned that the net plant efficiency has been optimized by a simultaneous optimization of net MHD power generation (MHD generator power minus cycle compressor power and oxygen plant compressor power) and of waste heat recovery and utilization in the steam bottoming plant (steam plant efficiency and degree of heat recovery). The latter is particularly important for the smaller 200 MW_e sized plant because the relative heat losses from the MHD components increases with decreasing size and effective recovery of these heat losses become more problematic. In addition, MHD generator optimization is based on a compromise between performance (high net MHD power output) and cost (in particular of the magnet but also of the O_2-plant and other equipment).

MHD generator channel performance was calculated for both the 500 MW_e and the 200 MW_e plant sizes using the AERL MHD4 computer code.

For each combination of generator length, oxygen enrichment and power plant size, a set of preliminary channel calculations were carried out to determine the magnetic field distribution that would yield optimum MHD power output while satisfying a prescribed set of design constraints.

A detailed description of the MHD channel performance calculations is presented in subsection 3.1.1. The channel performance calculations results in a final selection of 34% oxygen by volume of the oxidizer for the 500 MW_e plant and 32% for the 200 MW_e plant, and channel lengths of 18 m and 12 m, respectively.

A flow diagram with heat and mass balances and state point conditions for nominal load is shown in Figures 2-1 and 2-2 for the 500 MW_e and 200 MW_e plant sizes, respectively.

The net plant output from the larger plant is 504.1 MW_e corresponding to a net plant efficiency of 42.9% (coal pile to busbar). The smaller plant has a net plant output of 215.8 MW_e and a net plant efficiency of 41%. The Rankine cycle efficiency of the bottoming plant with steam conditions of 2400 psig/1000°F/1000°F is 41.6% for the larger 500 MW_e plant and slightly less or 41.4% for the smaller 200 MW_e plant. The total feedwater temperture rise in the feedwater heater train (LP and HP) is 321.0°F for the 500 MW_e plant which employs a total of six heaters and 320°F for the 200 MW_e plant which employs four heaters.

In both plants low-pressure and low-temperature feedwater is used for channel cooling, and high-pressure and high-temperature feedwater is used for cooling of the MHD combustor. Cooling of the diffuser is incorporated as part of the evaporative circuit of the steam cycle. Smaller amounts of heat are recovered from the seed regeneration process. This includes combustion of very 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 3.2 MW_e for the 500 MW_e plant and 1.4 MW_e for the 200 MW_e plant.

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) operation is 3996 and 1618 tons/day (TPD) of contained oxygen for the 500 MW_e and 200 MW_e plant, respectively. The specific compressor

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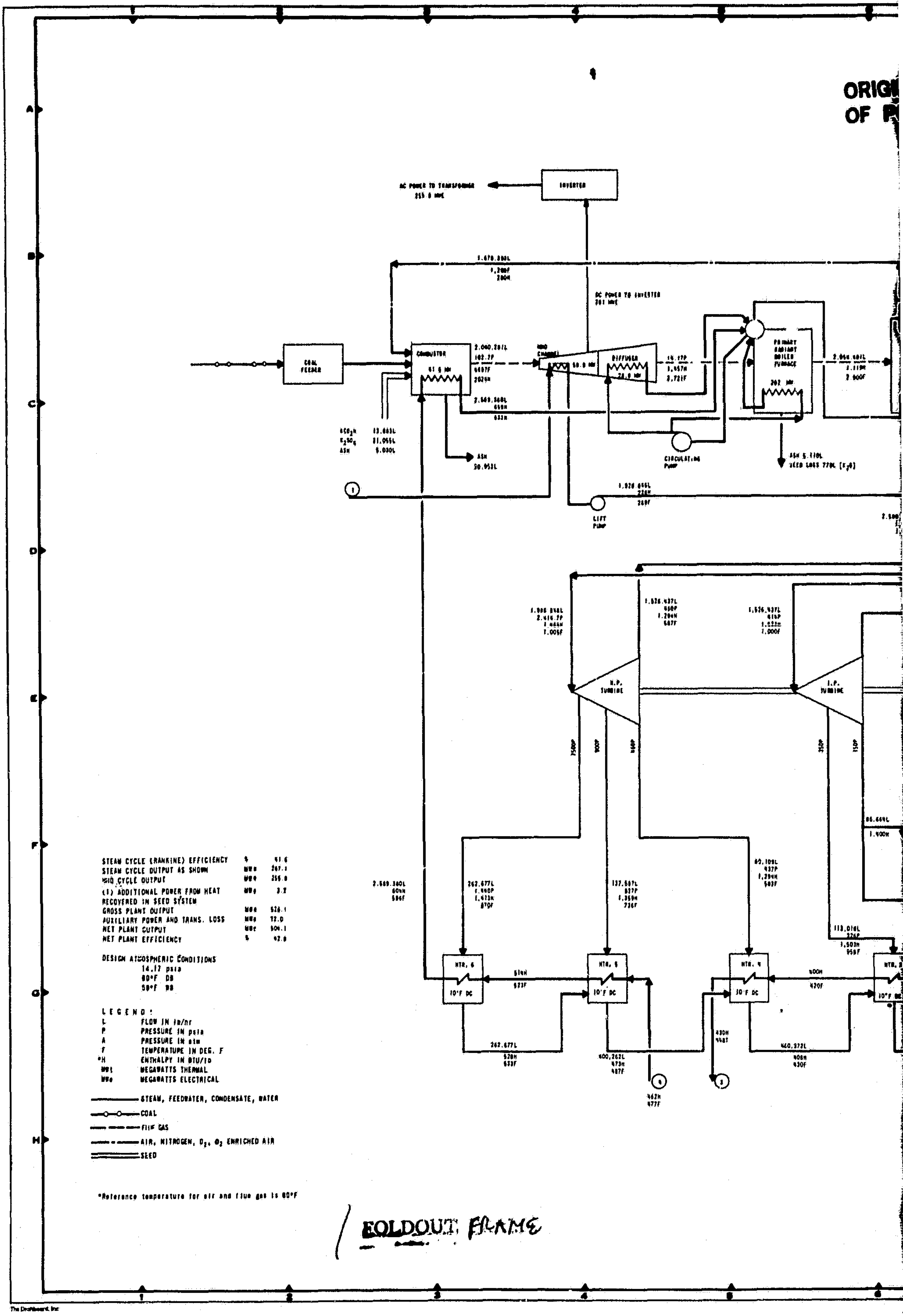

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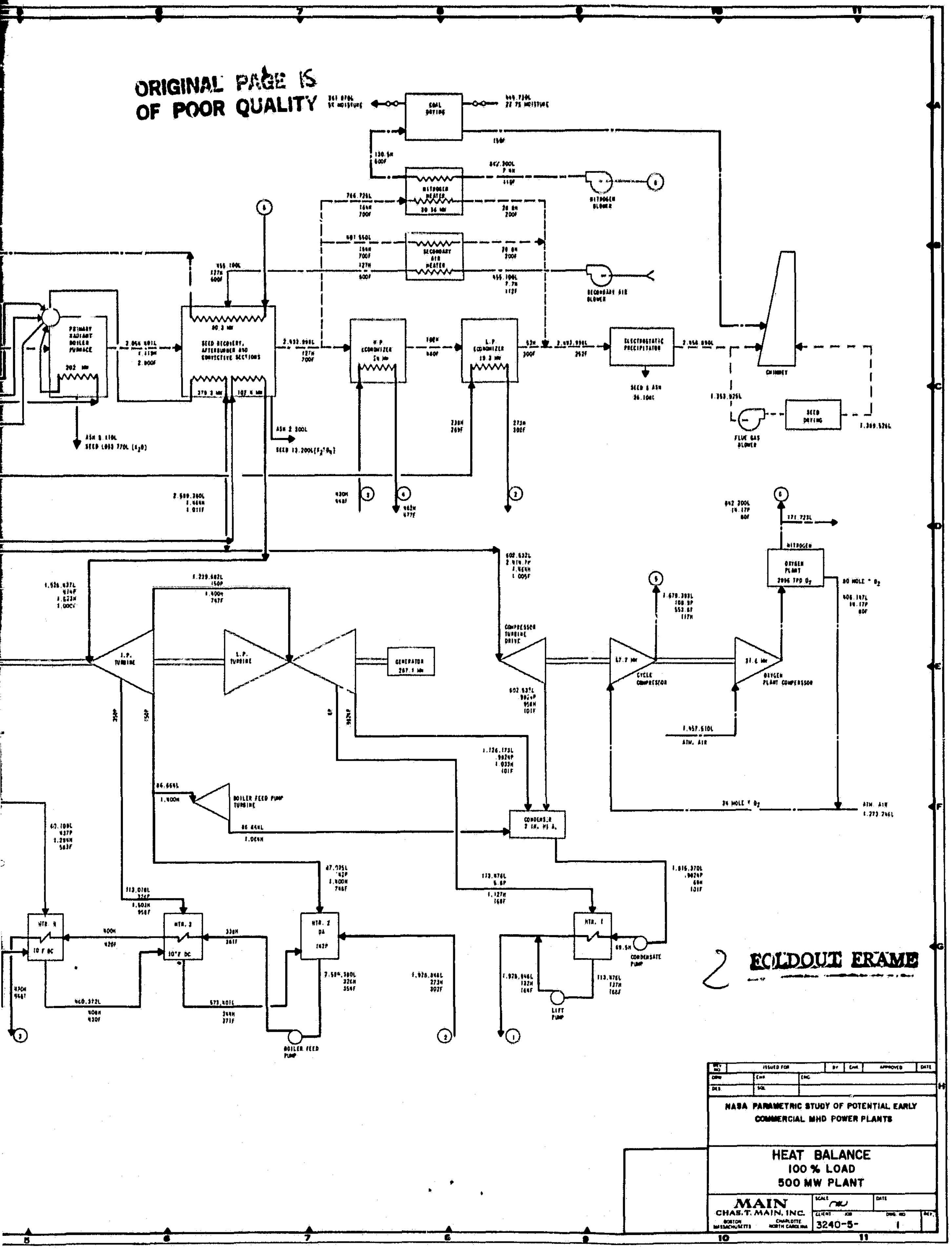
Figure 2-1 Heat Balance



Heat Balance for 500 MW_e Plant

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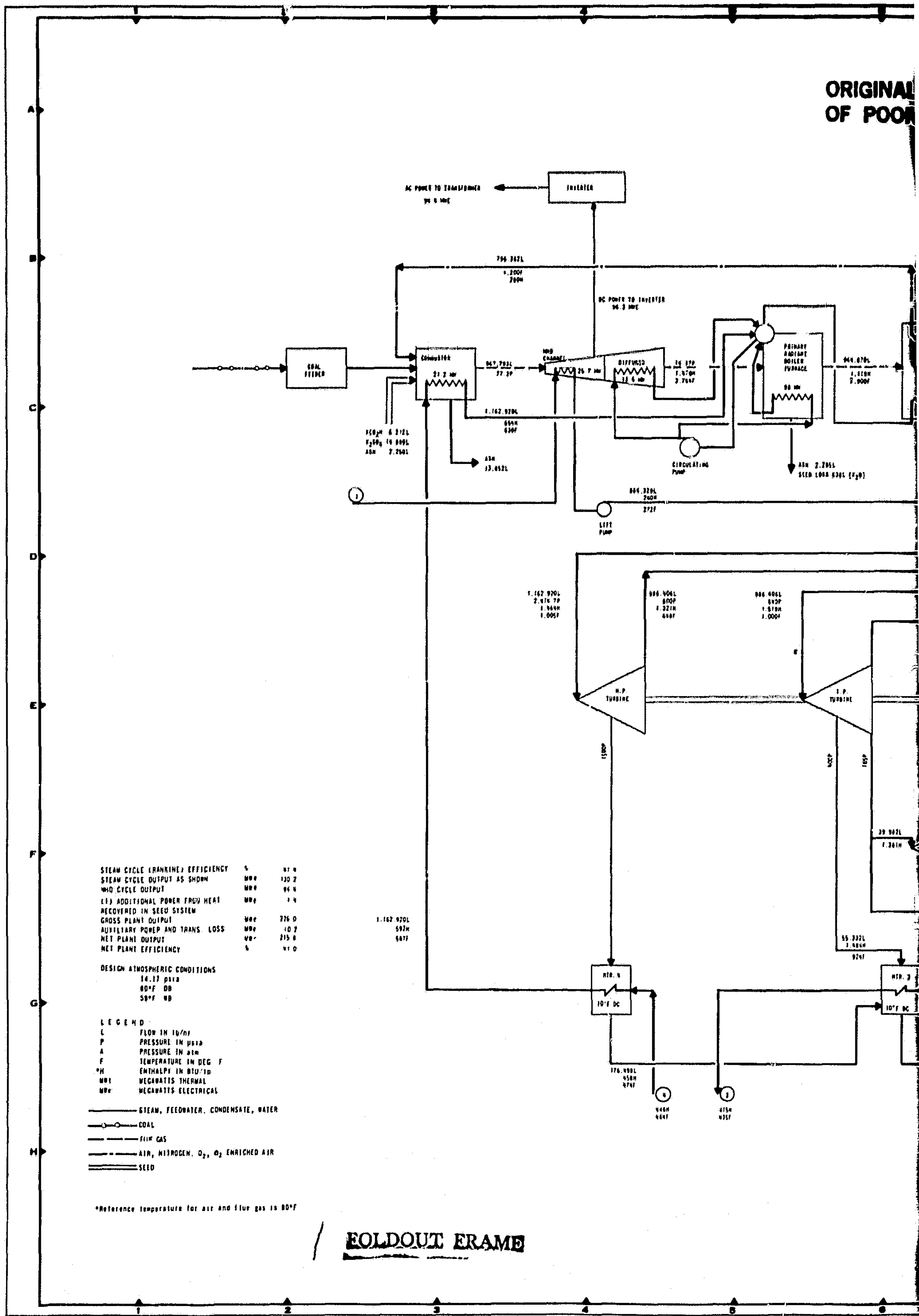

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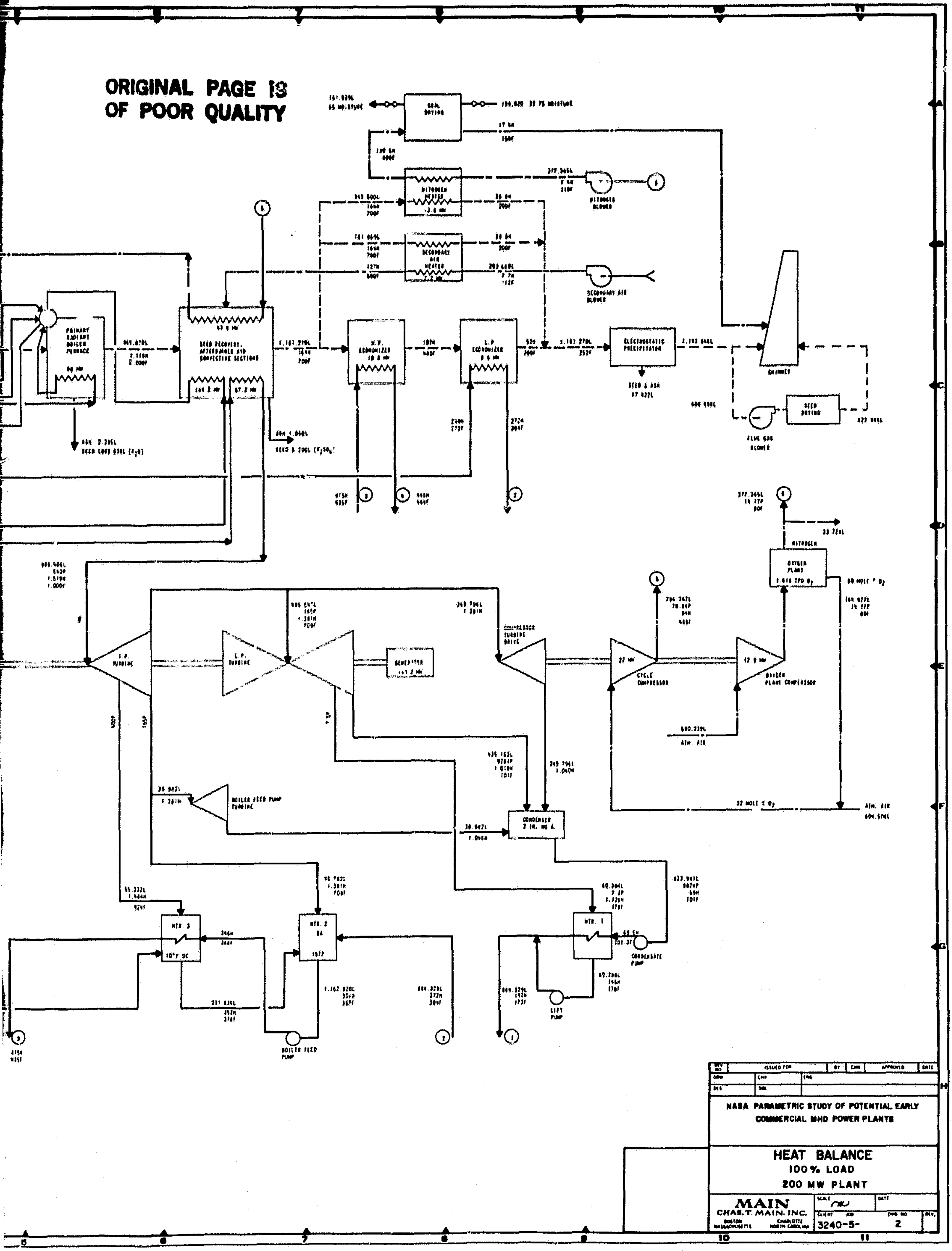
Figure 2-2 Heat Balance fo



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Heat Balance for 200 MW_e Plant

power required for manufacturing of oxygen is 190 kWhr/ton of contained oxygen or 31.6 MW_e and 12.9 MW_e for the two plants, respectively, at nominal plant 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. It is noted that low-pressure steam is used for the turbine which drives the cycle compressor and oxgyen plant compressor in the 200 MW_e plant as opposed to high-pressure steam in the larger 500 MW_e plant (as in the larger Task II plant), because of the relatively small size of the turbine for compressor drive in the smaller 200 MW_e plant.

The resulting overall energy balances for the two plants of nominal load conditions are listed in Table 2-2. Corresponding data for the larger Task II (CSPEC) plant are also included in this table for comparison.

Table 2-3 lists heat balances with inputs and outputs for the MHD - steam power systems for the 500 MW_e and 200 MW_e plants.

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TABLE 2-2

OVERALL ENERGY BALANCE AT NOMINAL LOAD

	950 MW_e (CSPEC) Nominal Load	500 MW_e Nominal	200 MW_e Nominal
Fuel Input - MW			
MHD Combustor	2135.0	1162.0	520.0
Gasifier for Seed Regeneration	29.0	16.0	7.0
Total	2164.0	1178.0	527.0
Gross Power Outputs - MW			
MHD Power	525.0	261.0	96.3
Steam Power*	647.3	359.6	166.5
Total	1172.3	620.6	262.8
Auxiliary and Losses - MW			
Cycle Compressor	111.5	57.7	22.0
O_2 Plant Compressor	58.1	31.6	12.9
Auxiliaries	38.6	19.5	9.1
Inverter and Transformer	15.1	7.7	3.0
Total	223.3	116.5	47.0
Net Plant Output - MW	949.0	504.1	215.8
Net Plant Efficiency - %	43.9	42.9	41.0

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

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TABLE 2-3

HEAT BALANCE FOR MHD-STEAM POWER SYSTEM

	500 MW_e 34% O_2	200 MW_e 32% O_2
Heat Inputs (MW)		
Coal to MHD Burner (HHV)	1162.0	520.0
Coal Drying	27.9	12.5
Primary Oxidizer	138.0	63.4
Secondary Air	16.9	7.6
Seed Chemistry	10.6	4.7
Heat Input from Auxiliaries	5.8	2.6
Total	1361.2	612.8
Heat Outputs (MW)		
MHD Power	261.0	96.3
MHD Heat Losses		
Burner	41.6	21.2
Channel	59.9	25.7
Diffuser	28.8	13.5
I.T. Oxidizer Heater	80.3	43.4
L.T. Secondary Air Heater	15.9	7.2
Coal Drying	27.9	12.5
Stack Loss	107.8	48.2
Heat Losses	11.0	6.0
Steam Generator	683.7	319.4
Economizer (HP + LP)	43.3	19.4
Total	1361.2	612.8

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3.0 SUBSYSTEMS/COMPONENTS DESIGNS - 500 MW_e and 200 MW_e PLANTS

3.1 MHD CHANNEL

3.1.1 MHD Channel Calculations and Performance

MHD Channel calculations and performance analyses were conducted for the 500 MW_e and 200 MW_e plant sizes. The AERL MHD4 computer program was used to perform the generator calculations. A procedure, which will be briefly described below, is used to determine the operating conditions of the MHD generator. This process ensures that a set of electrical constraints is satisfied while maximizing the performance of the MHD topping cycle. The procedure to determine the generator operating condition was carried out for each combination of oxygen enrichment level, generator length, and power plant size studied in the present task.

Based on the channel performance calculations together with overall plant performance and optimization analyses, a channel design was selected for each plant size. Table 3-1 summarizes the selected MHD generator design characteristics for the 500 MW_e and the 200 MW_e plant sizes. Design data for the Task II (CSPEC) MHD generator are also included in the table for comparison. The streamwise distributions of the magnetic field and major electrical parameters for these generators are shown in Figures 3-1 through 3-3.

3.1.1.1 Channel Working Fluid

The thermochemical an electrical properties of the working fluid for the MHD generator were calculated. These calculations were done identically as in Task II, which also provides a common basis for plant size scaling assessments. Hence, as in Task II, the negative ion CO_2^- was excluded and Itikawa's water cross section was used in the calculation of electrical conductivity.[2]

The combustion gas is produced by burning subbituminous Montana Rosebud coal, dried to 5% moisture, in oxygen enriched air. The oxidizer/fuel equivalence ratio is 0.90 and the seed concentration is one percent potassium by mass of the total combustion gas. The Mollier diagram for the MHD working fluid at various oxygen enrichment levels are shown in Figures 3-4 through 3-8. The pressures on the Mollier charts are in NEMA atms (one NEMA atms equals 0.96392 standard atms). Also, the zero for enthalpy is that of the free elements at 0^oK.

TABLE 3-1

SUMMARY OF SUBSONIC CHANNEL PERFORMANCE DATA FOR DIFFERENT PLANT SIZES

Plant Sizes	950 MW_e CSPEC	500 MW_e	200 MW_e
Oxidizer O_2 Content (% O_2)	34.0	34.0	32.0
Burner Pressure - atm	8.3	7.52	5.45
Mass Flow - kg/sec	472.0	256.90	120.7
Burner Temperature - °K	2881.0	2865.4	2796.3
Elec. Load Parameter, K	0.786	0.766	0.743
Inlet Mach Number	0.89	0.89	0.89
Diffuser Recovery Factor - Cp	0.6	0.6	0.6
$\mathbb{P}_{MHD}$ (MW_e)	524.9	261.02	96.289
*$\mathbb{P}_{Net}$ (MW_e)	354.6	171.45	61.326
η_{ee} (%)	24.50	22.62	18.546
η_{is} (%)	74.00	70.66	66.369
η_{MHD} (%)	16.62	14.86	11.81
Maximum E_y (kV/m)	4.01	4.01	3.97
Maximum E_x (kV/m)	1.77	1.81	2.00
Maximum J_y (A/cm^2)	0.82	0.88	0.83
Maximum Hall Parameter β	3.93	4.00	3.98
V_{Hall} (kV)	28.13	25.78	20.72
(L/D) averaged	12.59	14.22	13.29
Length (m)	21.5	18.0	12.0
$q_{Wall\ Loss}$ (MW)	96.00	59.89	25.68

* $\mathbb{P}_{Net}$ = MHD Power - Cycle Compressor Power - O_2 Plant Compressor Power

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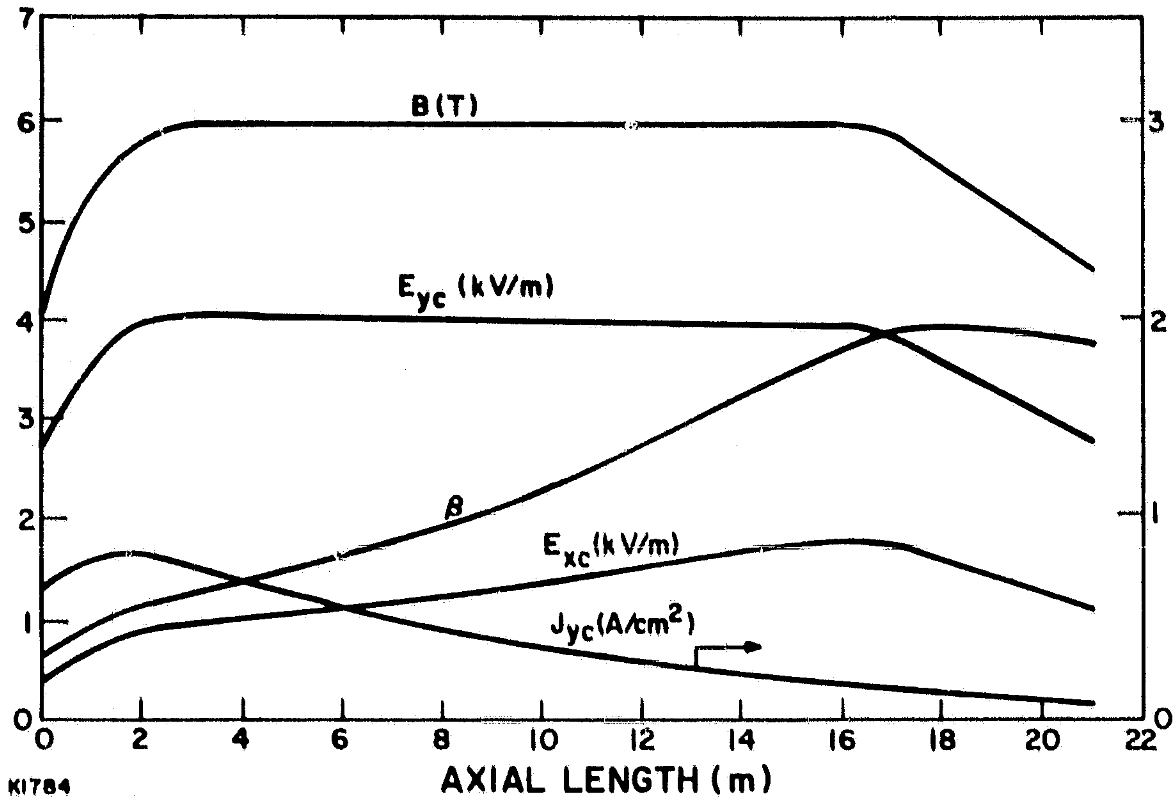

Figure 3-1 Axial Variations of Magnetic Field and Major Electrical Parameters in the Flow Core for the CSPEC MHD Generator of Task II

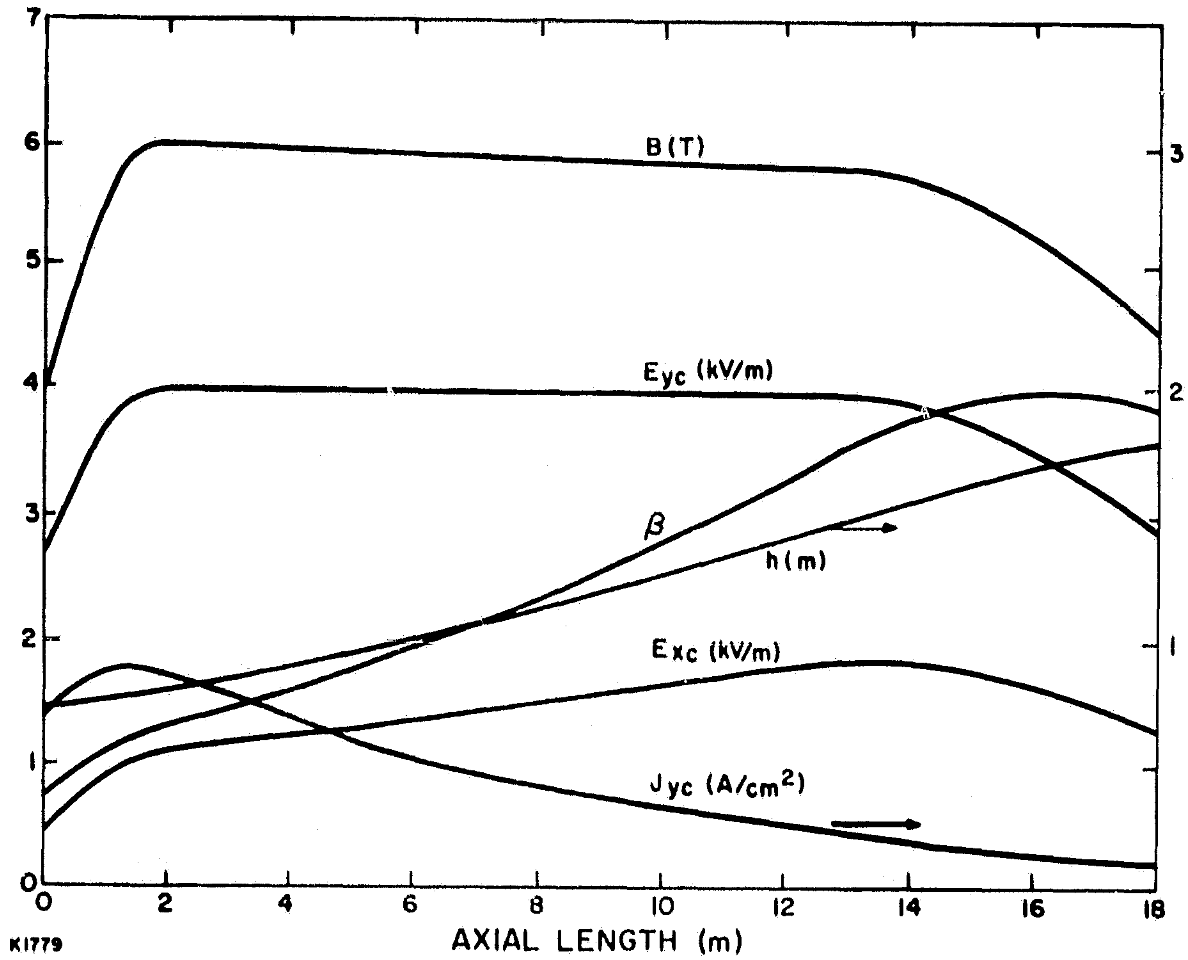

Figure 3-2 Axial Variations of Magnetic Field, Channel Height and Major Electrical Parameters of Channel Design Selected for the 500 MW_e Plant

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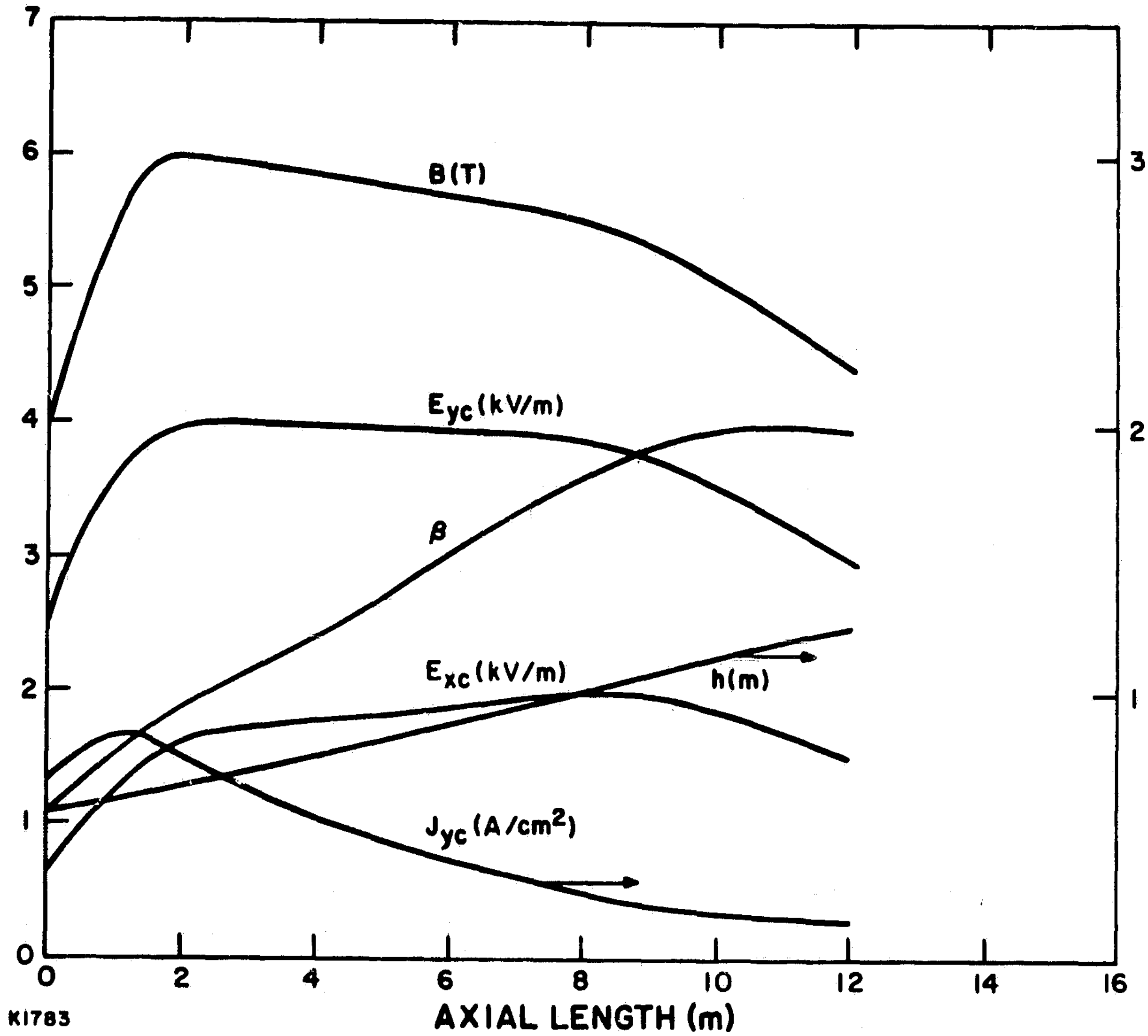

Figure 3-3 Axial Variations of Magnetic Field, Channel Height and Major Electrical Parameters of Channel Design for the 200 MW_e Plant

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MONTANA ROSEBUD COAL-DRIED TO 5% MOISTURE CONTENT, 1% K BY MASS
30% O2 CONTENT, 0.9 OXIDIZER/FUEL EQUIVALENCE RATIO

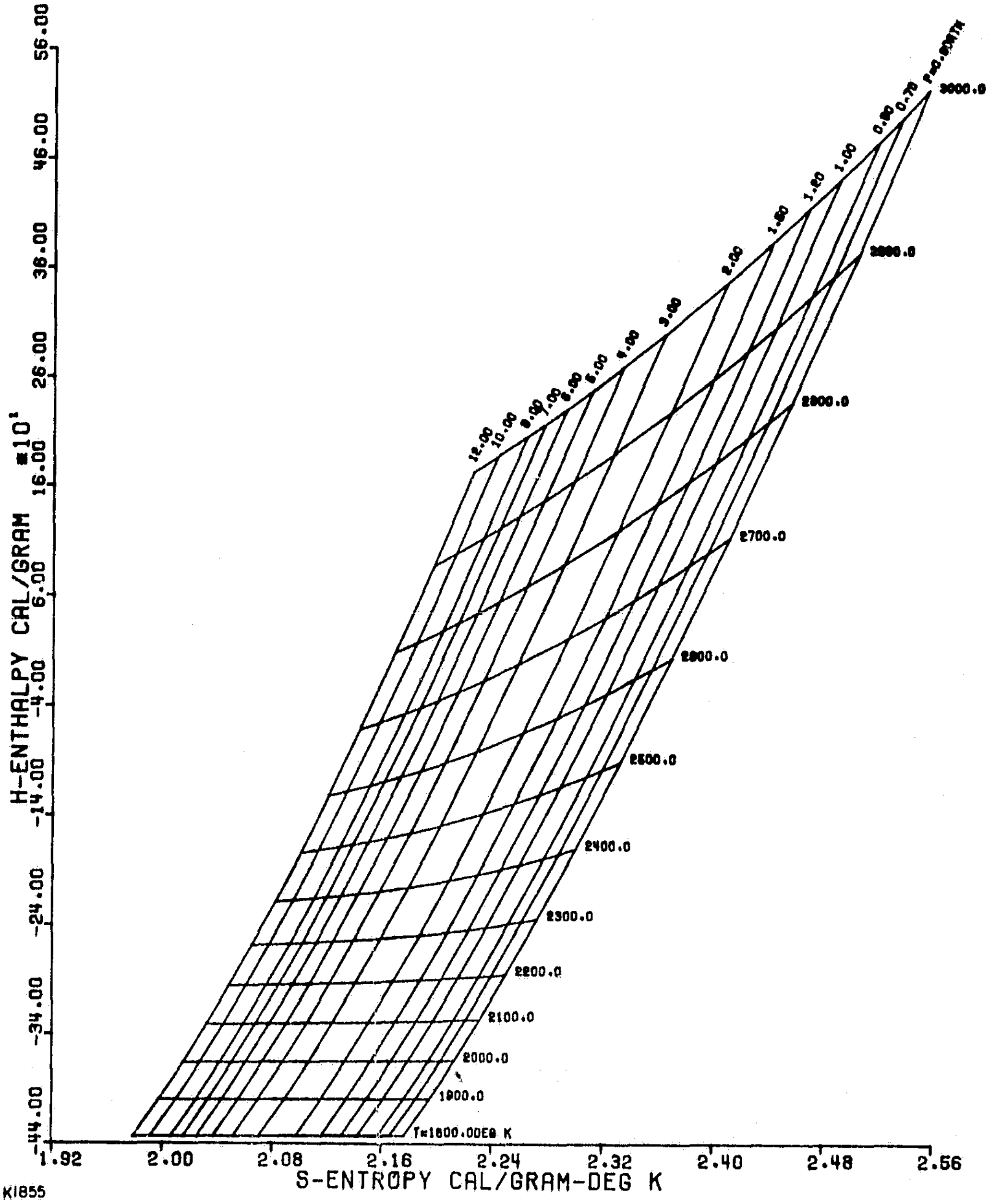

Figure 3-4 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

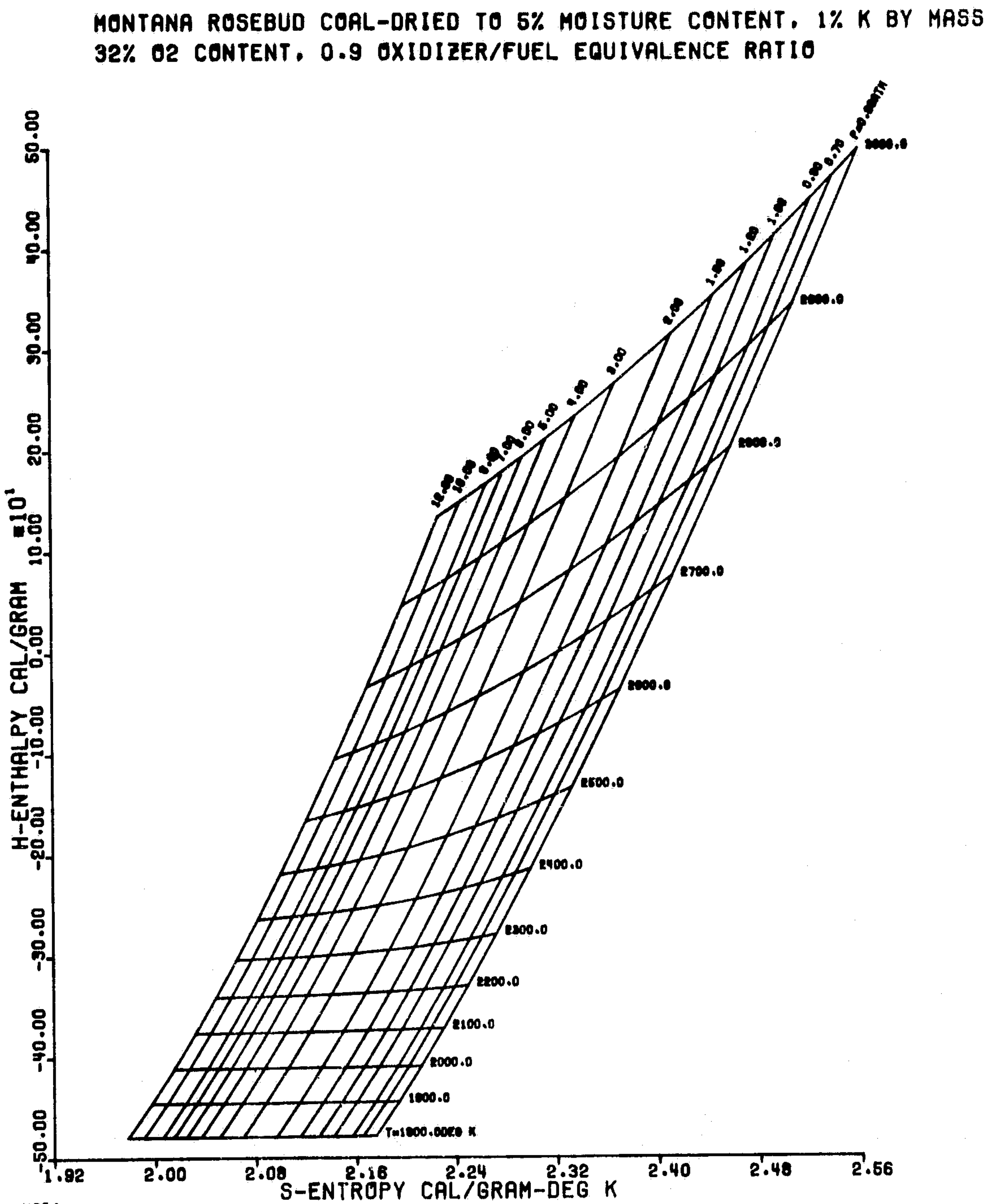

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Figure 3-5 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

MONTANA ROSEBUD COAL-DRIED TO 5% MOISTURE CONTENT, 1% K BY MASS
34% O2 BY VOLUME, 0.9 OXIDIZER/FUEL EQUIVALENCE RATIO

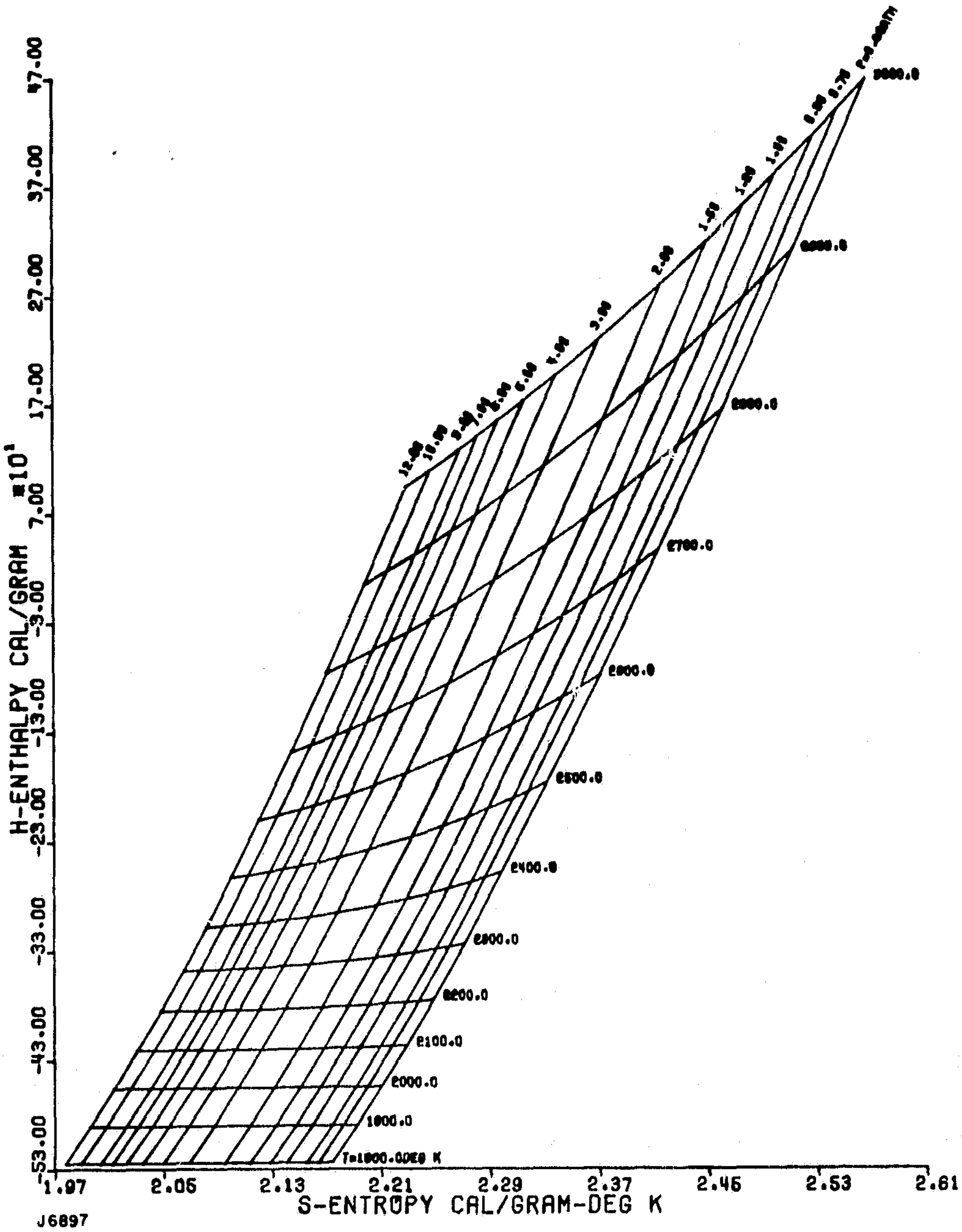

Figure 3-6 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

MONTANA ROSEBUD COAL-DRIED TO 5% MOISTURE CONTENT, 1% K BY MASS
35% O2 CONTENT, 0.9 OXIDIZER/FUEL EQUIVALENCE RATIO

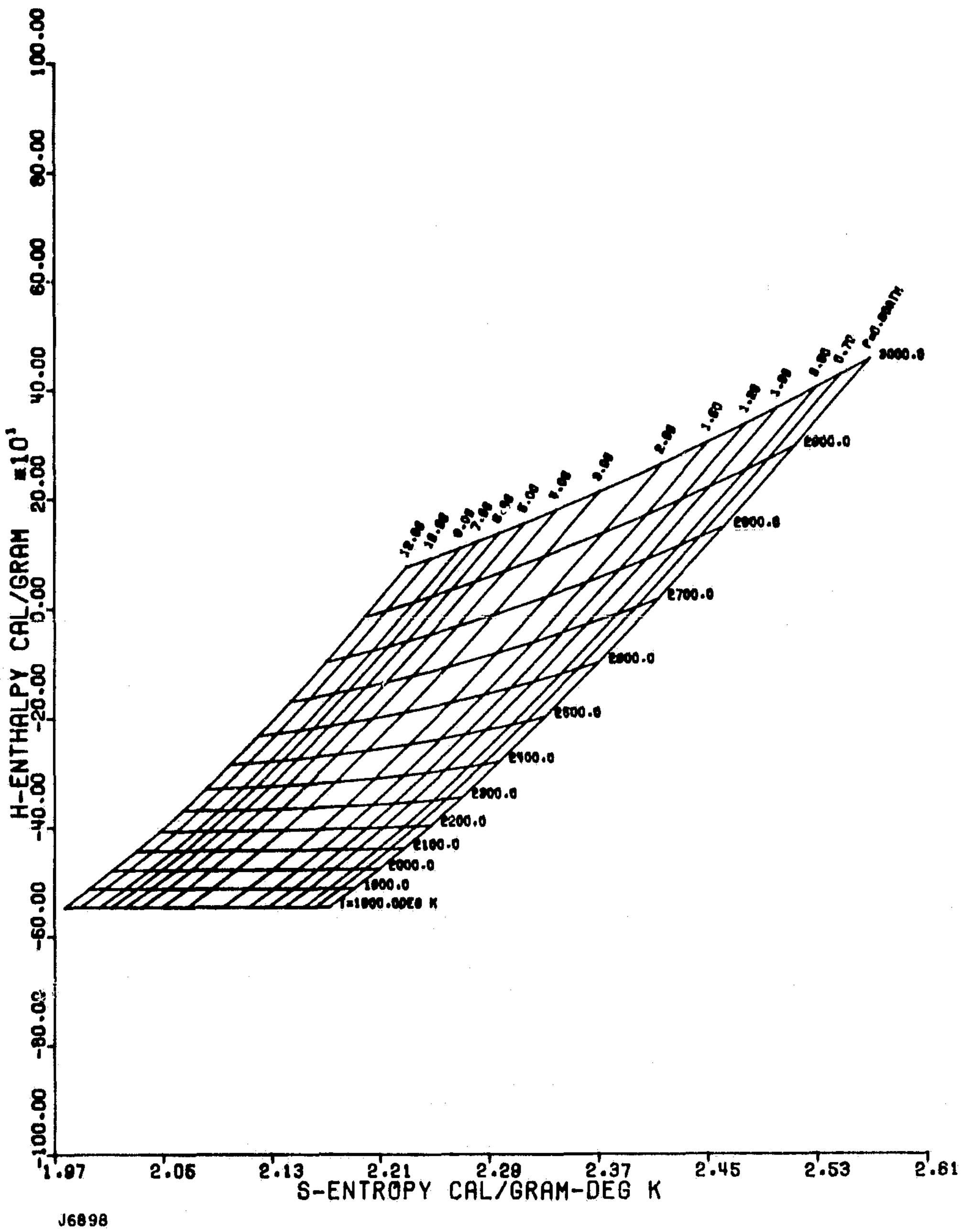

Figure 3-7 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

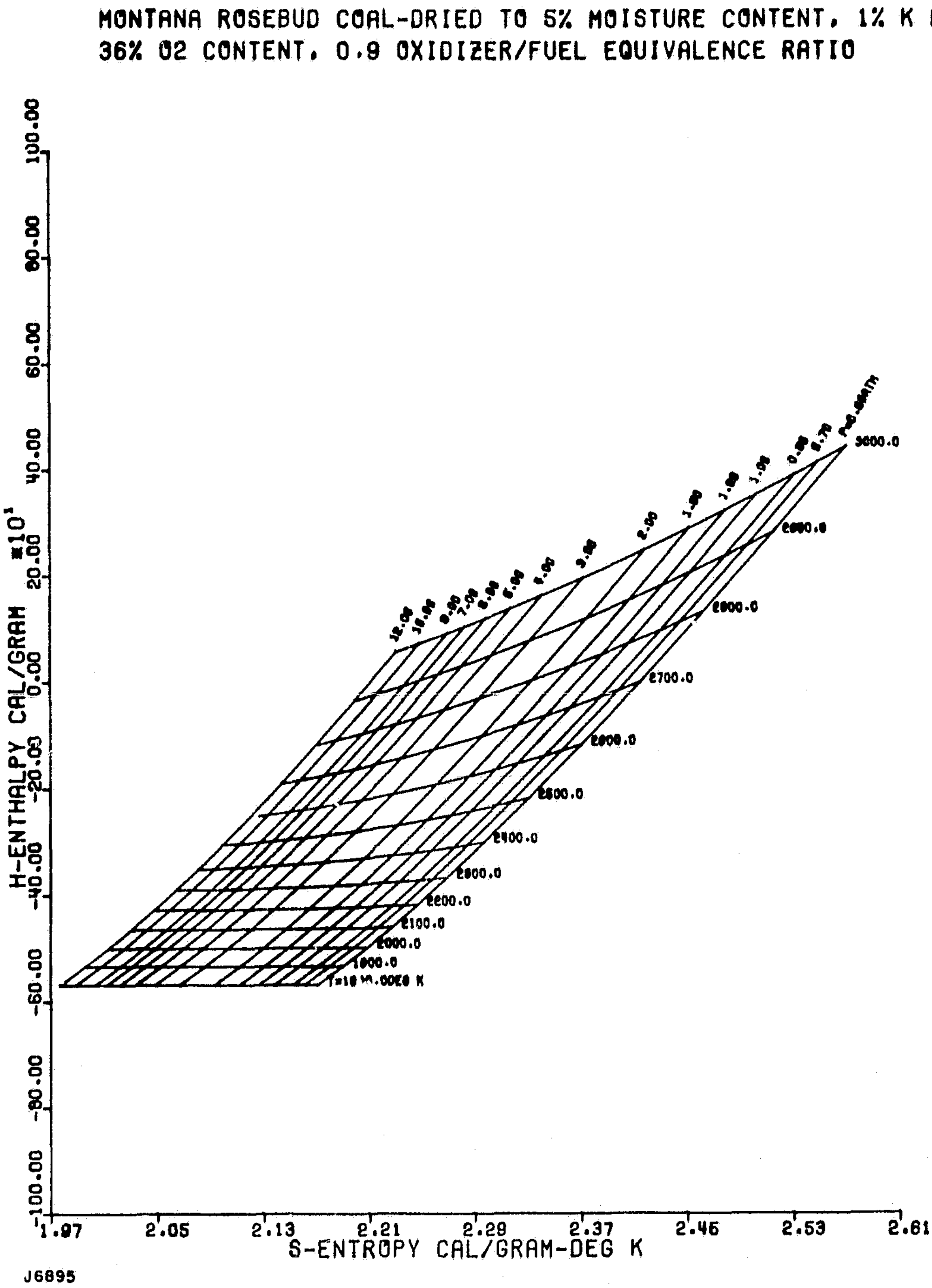

Figure 3-8 Mollier Chart, Combustion Products of Montana Subbituminous Coal and Oxygen Enriched Air

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3.1.1.2 Calculational Procedure

MHD generator performance has been calculated for both the 500 MW_e and the 200 MW_e plant sizes using the AERL MHD4 computer code. The details of the MHD4 program have been described previously.[2] The procedure used to determine the operating conditions of the MHD generator is similar to that of Reference 2. It is briefly described below.

For each combination of generator length, oxygen enrichment level and power plant size, a set of preliminary channel calculations are carried out to determine the magnetic field distribution that would yield the maximum MHD output while satisfying a prescribed set of electrical constraints. The values assigned to these critical constraints are the same as those in Tasks I and II, namely:

Max. Transverse Field	- $E_y \lesssim 4$ kV/m
Max. Axial Field	- $E_x \lesssim 3$ kV/m
Max. Transverse Current Density	- $J_y \lesssim 1$ A/cm^2
Max. Hall Parameter	- $\beta \lesssim 4$

During this set of calculations, the burner pressure and/or the streamwise variations of flow velocity and/or electrical loading are varied in order to satisfy all the prescribed constraints (both prescribed internal constraints and channel exit condition). An optimum magnetic field distribution is calculated; an example of which is shown in Figure 3-9. For this example, the channel has a constant load parameter, K = 0.7425. The E_{yc} = 4 kV/m condition predominate over major portions of this generator design. The β = 4 condition prevails beyond x = 9 m thus causing the drop in the magnetic field profile. The optimum magnetic field distributions obtained in such a manner are used as guidelines to determine the more realistic B-field profiles which are then utilized in the subsequent set of channel calculations.

A typical example showing the results of follow-on calculations using the corrected magnetic field distribution is shown in Figure 3-10. To arrive at these results, the magnetic field profile is specified while the value of the load parameter is readjusted until the desired length and exit pressure are obtained. Calculations for several values of burner pressure are required to ascertain the optimum pressure ratio across the MHD power train. This is accomplished by finding the burner pressure at which the net power output from the MHD generator, ($\mathbb{P}_{MHD} - \mathbb{P}_{comp} - \mathbb{P}_{oxy}$), is an optimum.

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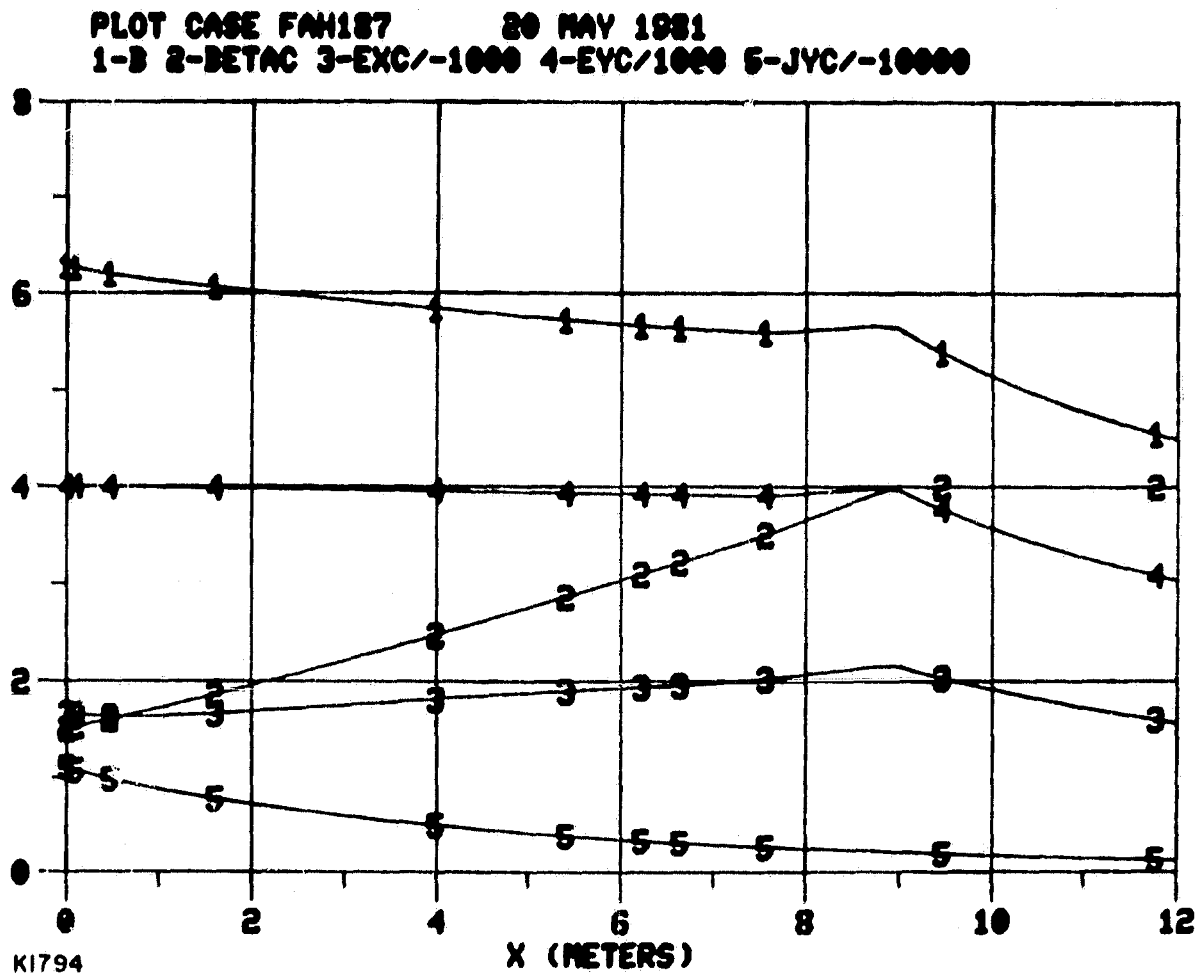

Figure 3-9 Streamwise Distributions of B-Field, β, Ex_C, Ey_C and Jy_C. Plant Size ≃ 200 MW_e, PB = 5.5 atm, $\dot{m}$ = 120.7 kg/sec, 32% Oxygen Enrichment, k = 0.7425, M_{inlet} = 0.885.

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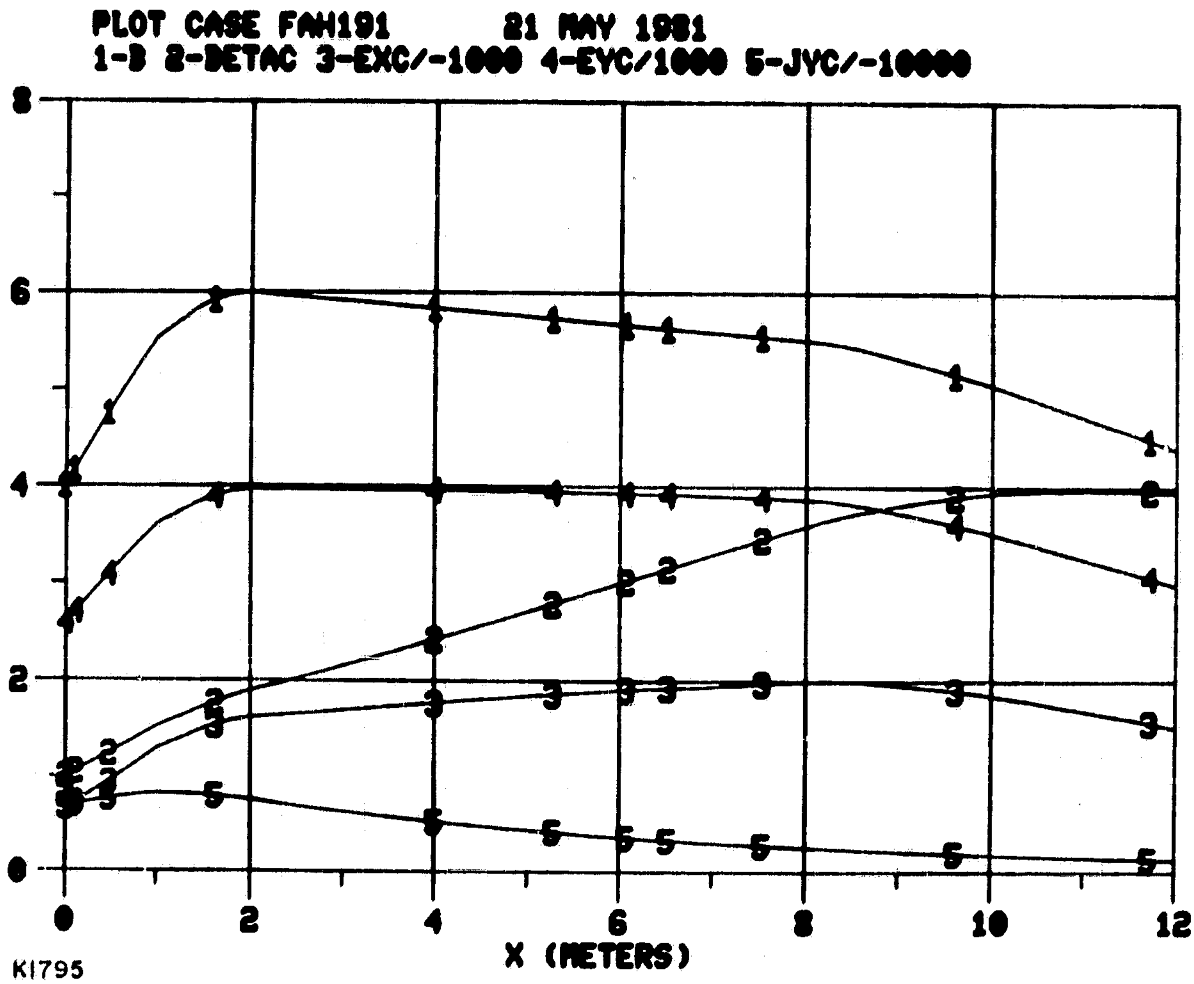

Figure 3-10 Streamwise Distributions of B, β, Ex_c, Ey_c and Jy_c. P_B = 5.25 atm, k = 0.7433, Other Conditions Same as in Figure 3-1.

The above procedure to determine the generator operating condition was carried out at each combination of generator length, oxygen enrichment level and power plant size.

3.1.1.3 Performance Calculations

The results of the channel calculations for the 500 MW_e and the 200 MW_e plants are presented in this section.

The effects of oxygen enrichment level on the MHD generator performance for the two different plant sizes (at fixed channel lengths) are summarized in Table 3-2. $\mathbb{P}_{MHD}$ is the gross MHD generator power output; $\mathbb{P}_{Net}$ is the net power output from the MHD topping cycle after subtracting the compressor power and oxygen production work. The values of the burner pressure (in units of NEMA atm) are those at which $\mathbb{P}_{Net}$ is a maximum for respective design assumptions. η_{ee} and η_{is} are the enthalpy extraction and isentropic efficiency, respectively.

The effects of channel length on the MHD generator performance (at selected levels of oxygen enrichment) are summarized in Table 3-3. The streamwise variations of the magnetic field and several important electrical parameters for these same channel designs are shown in Figures 3-11a through 3-11e and Figures 3-12a through 3-12e.

In general, the generator performance ($\mathbb{P}_{Net}$; η_{ee}) improves with increasing levels of oxygen enrichment and with increasing channel length (see Figure 3-13). However, the optimum oxygen enrichment level and channel length cannot be determined from MHD generator performance and topping cycle analysis solely, but must be arrived at by overall plant performance analysis and cost considerations. Thus, improved generator performance must be weighted against any adverse impact on waste heat recovery and steam plant efficiency (from increased channel heat loss), on magnet costs (from increased channel length), and on increased cost of the air separation unit (from increased oxygen enrichment).

Numerous generator design points were established during the course of the Task II and Task III studies. Although these channels were designed for various thermal input, oxygen enrichment level, channel length, Mach number and maximum magnetic field intensity, an attempt has been made to correlate the generator performances with some appropriate interaction parameter. For the purpose of present discussion, $\langle iK \rangle$ is defined as the integral of the product of local interaction parameter ($J_y B/P$) and a modified load parameter, $K(\gamma-1)/\gamma[1 + (\gamma-1)/2\ M^2]$, expressed as

$$\langle iK \rangle = \int_0^L \frac{j_y B}{P} \frac{K\ (\gamma-1)}{\gamma[1 + \frac{\gamma-1}{2} M^2]} dx$$

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TABLE 3-2

COMPARATIVE MHD CHANNEL PERFORMANCE AND DESIGN DATA FOR DIFFERENT DEGREES OF OXYGEN ENRICHMENT - 200 MW_e AND 500 MW_e PLANTS

Plant Sizes	~200 MW_e	~200 MW_e	~200 MW_e	~200 MW_e	~200 MW_e	~500 MW_e	~500 MW_e	~500 MW_e	~500 MW_e
Oxidizer O_2-Content-%O_2	30.0	32.0	34.0	35.0	36.0	30.0	32.0	34.0	34.5
Burner Pressure P_B - atm	4.93	5.45	5.97	6.23	6.48	6.23	7.00	7.52	7.78
Mass Flow $\dot{m}$ - kg/sec	127.20	120.70	114.96	112.33	109.90	284.20	269.70	256.90	253.90
Burner Temperature - °K	2752.20	2796.3	2837.40	2858.10	2878.00	2778.00	2823.50	2865.40	2876.30
Elec. Load Parameter, K	0.738	0.743	0.741	0.742	0.744	0.762	0.763	0.766	0.764
Inlet Mach Number	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Diffuser C_p	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
P_{MHD} (MW_e)	93.21	96.29	97.73	98.93	99.70	251.62	258.18	261.02	261.85
P_{Net} (MW_e)	59.97	61.33	61.32	61.87	62.07	168.49	171.85	171.45	171.23
η_{ee} (%)	17.70	18.55	19.14	19.45	19.69	21.19	22.06	22.62	22.75
η_{is} (%)	65.60	66.37	66.52	66.87	67.00	69.66	69.93	70.66	70.35
Maximum E_y (kV/m)	3.93	3.97	4.00	4.02	4.04	3.94	3.95	4.01	4.00
Maximum E_x (kV/m)	2.16	2.00	1.95	1.80	1.83	2.09	1.93	1.81	1.78
Maximum J_y (A/cm^2)	0.74	0.83	0.92	0.97	1.01	0.71	0.81	0.88	0.92
Maximum β	3.96	3.98	3.96	4.07	4.04	4.02	4.08	4.00	4.09
V_{Hall} (kV)	22.52	20.72	19.82	19.11	18.42	30.34	27.99	25.78	25.58
$(L/D)_{averaged}$	12.79	13.29	13.8	14.04	14.28	13.2	13.75	14.22	14.37
Length (m)	12.0	12.0	12.0	12.0	12.0	18.0	18.0	18.0	18.0
$q_{Wall\ Loss}$ (MW)	23.44	25.68	27.86	29.05	30.14	49.94	54.3	59.89	61.49

TABLE 3-3

COMPARATIVE MHD CHANNEL PERFORMANCE AND DESIGN DATA FOR DIFFERENT CHANNEL LENGTHS - 200 MW_e AND 500 MW_e PLANTS

Plant Size	~200 MW_e	~200 MW_e	~200 MW_e	~200 MW_e	~500 MW_e	~500 MW_e	~500 MW_e
Volume % O_2	32.0	32.0	32.0	32.0	34.0	34.0	34.0
P_B (NEMA atm)	5.19	5.45	5.71	5.97	7.52	7.78	8.04
$\dot{m}$ (kg/sec)	120.7	120.7	120.7	120.7	256.9	256.9	256.9
T_o (°K)	2793.2	2796.3	2799.4	2802.3	2865.4	2867.7	2870.0
K_{ext}	0.739	0.743	0.746	0.742	0.766	0.764	0.760
M_{inlet}	0.89	0.89	0.89	0.89	0.89	0.89	0.89
Diffuser C_p	0.6	0.6	0.6	0.6	0.6	0.6	0.6
P_{MHD} (MW_e)	93.06	96.29	96.94	100.96	261.02	265.4	267.38
P_{Net} (MW_e)	58.90	61.33	63.29	64.53	171.45	174.68	175.45
η_{ee} (%)	17.92	18.55	19.06	19.45	22.62	23.00	23.18
η_{is} (%)	65.90	66.37	66.53	66.33	70.66	70.76	70.47
Maximum E_y (kV/m)	3.96	3.97	3.98	3.97	4.01	4.00	3.98
Maximum E_x (kV/m)	2.24	2.00	1.83	1.70	1.81	1.70	1.68
Maximum J_y (A/cm^2)	0.86	0.83	0.81	0.81	0.88	0.88	0.89
Maximum B	3.91	3.98	4.04	3.95	4.00	3.96	3.97
V_{Hall} (kV)	18.92	20.72	22.49	24.15	25.78	27.28	28.39
$(L/D)_{averaged}$	11.05	13.29	15.52	17.72	14.22	15.72	16.54
Length (M)	10.0	12.0	14.0	16.0	18.0	20.0	21.0
$q_{Wall\ Loss}$ (MW_e)	22.63	25.68	28.60	31.34	59.89	64.3	57.05

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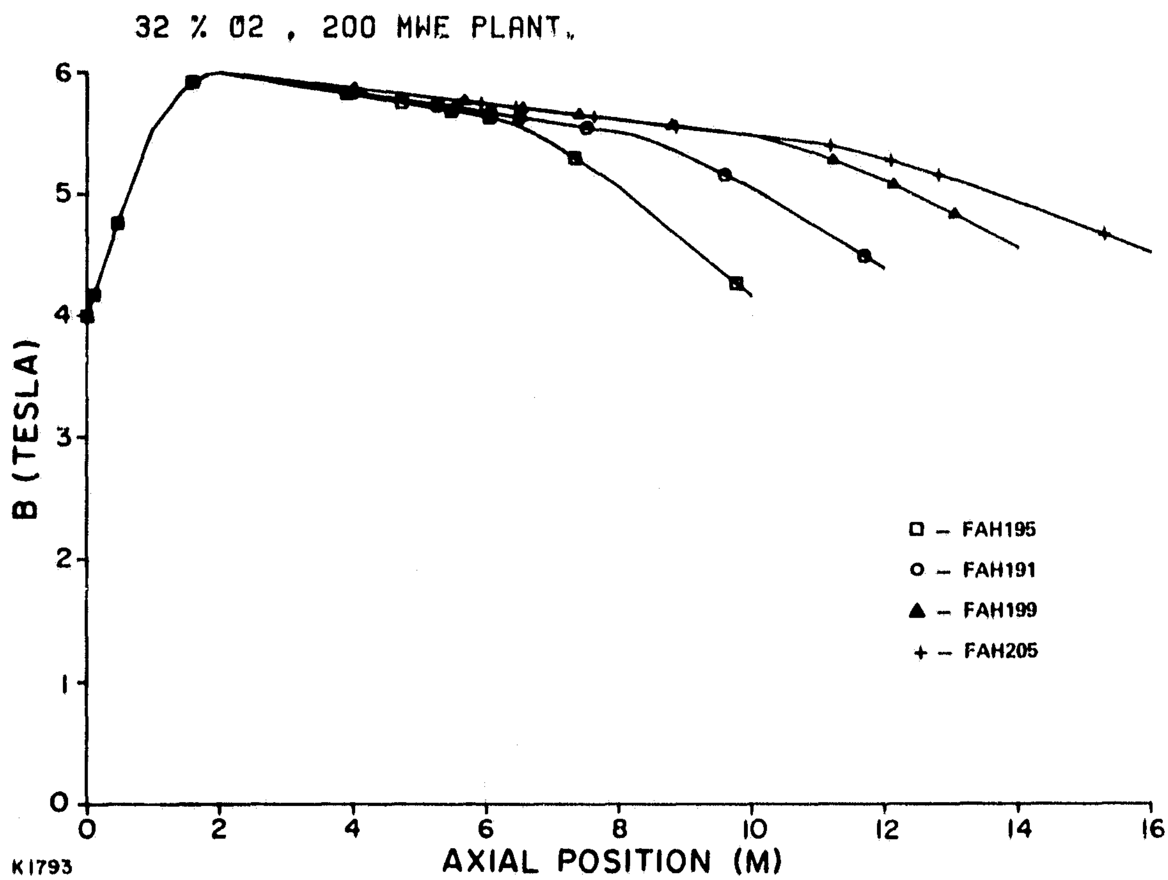

Figure 3-11a Streamwise Variations of the Prescribed Magnetic Fields. Plant Size ≃ 200 MW_e. Oxygen Enrichment = 32%. Length = 10, 12, 14 and 16 m.

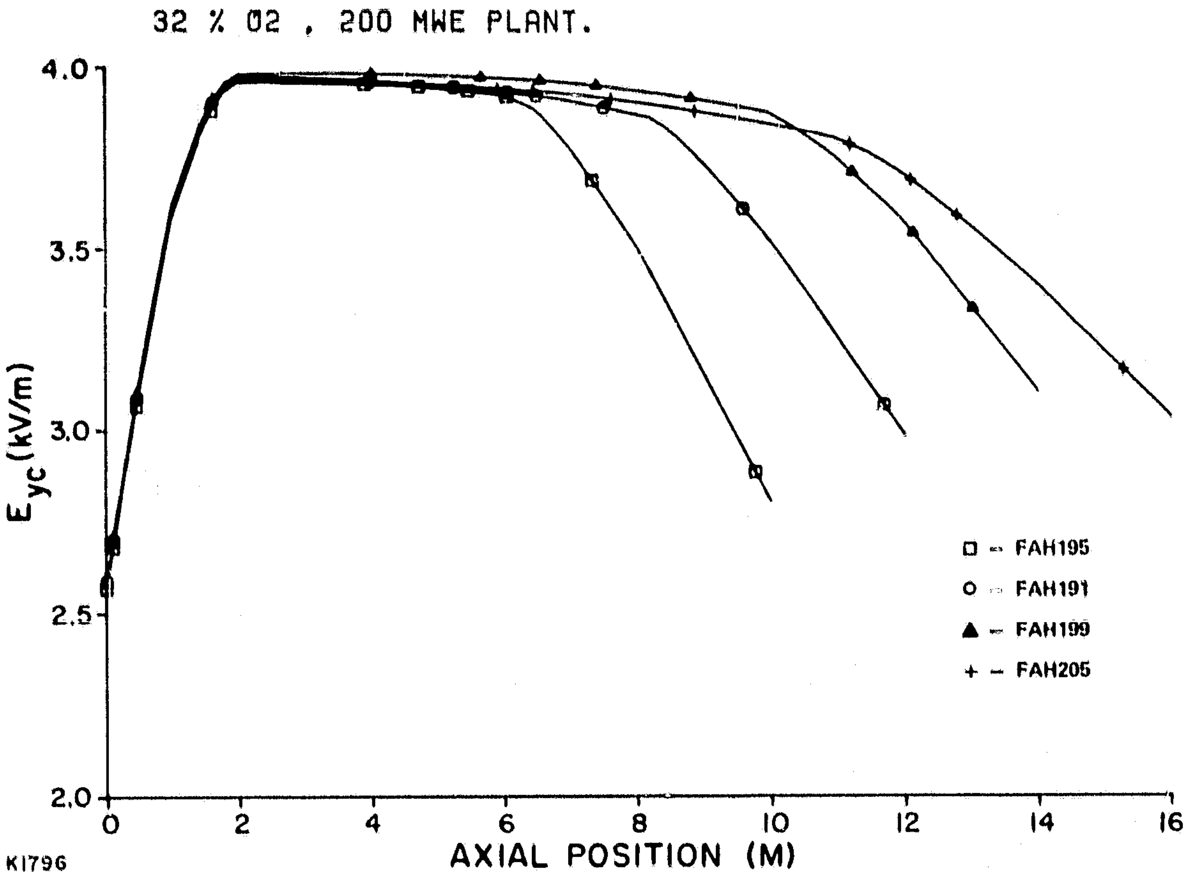

Figure 3-11b Streamwise Variations of the Transverse Electric Field. Plant Size $\simeq$ 200 MW_e. Oxygen Enrichment = 32%. Length = 10, 12, 14 and 16 m.

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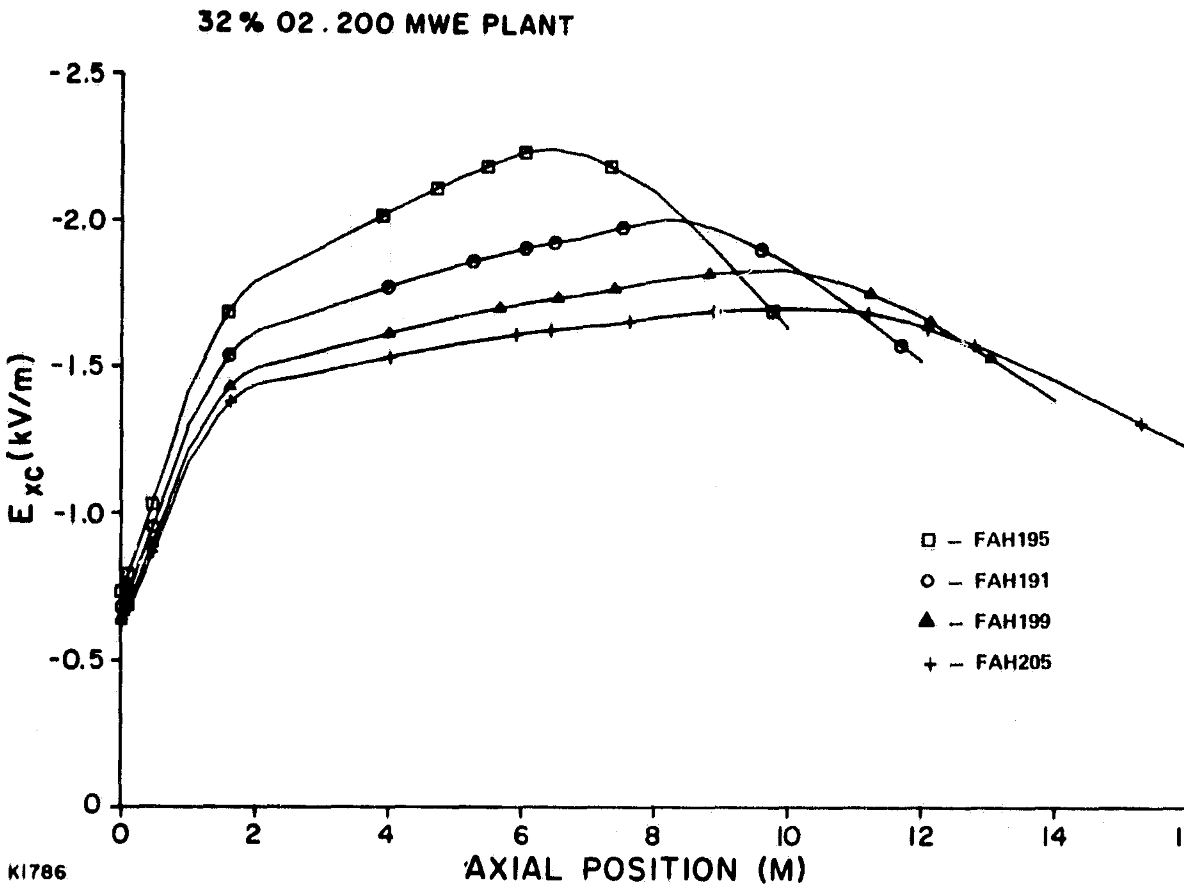

Figure 3-11c Streamwise Variations of the Axial Electric Fields. Plant Size ≃ 200 MW_e. Oxygen Enrichment = 32%. Length = 10, 12, 14 and 16 m.

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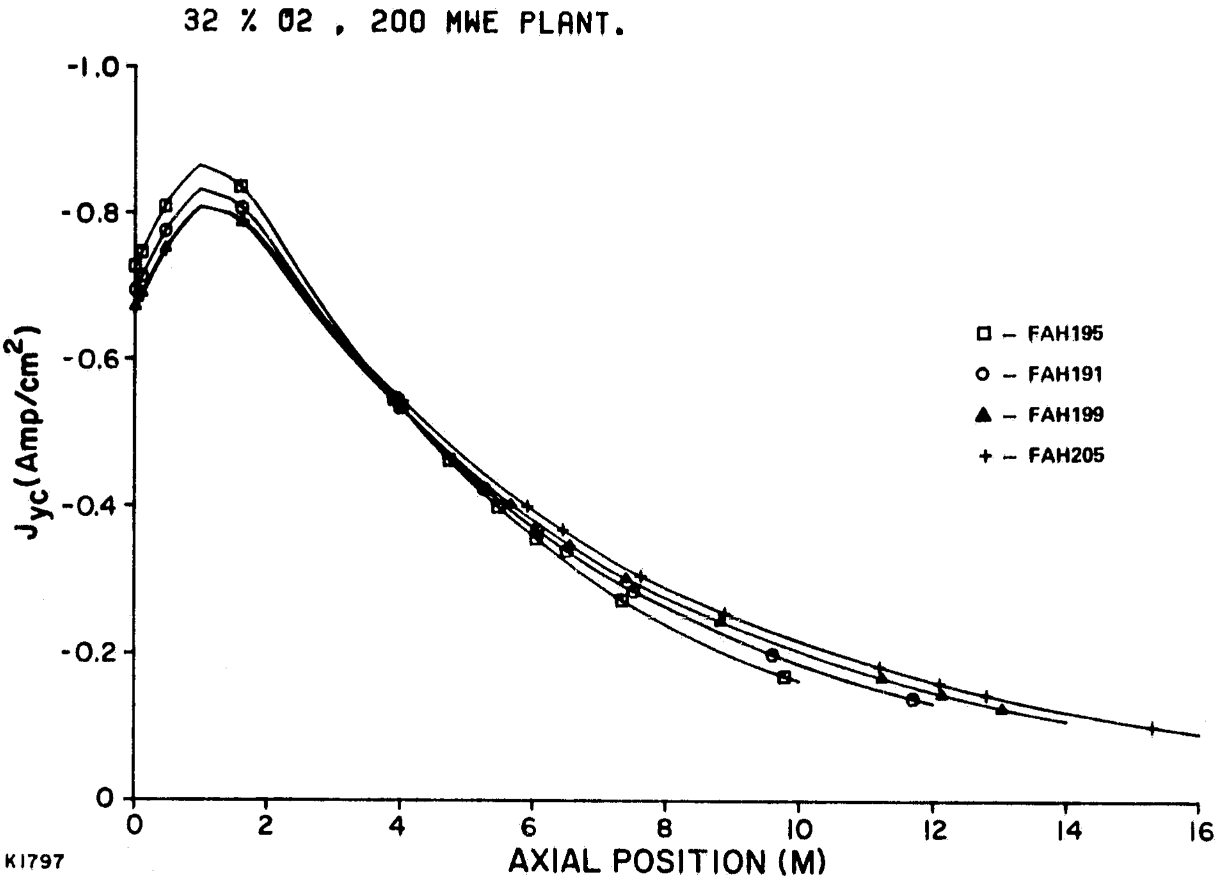

Figure 3-11d Streamwise Variations of the Transverse Current Densities. Plant Size $\simeq$ 200 MW_e. Oxygen Enrichment = 32%. Length = 10, 12, 14 and 16 m.

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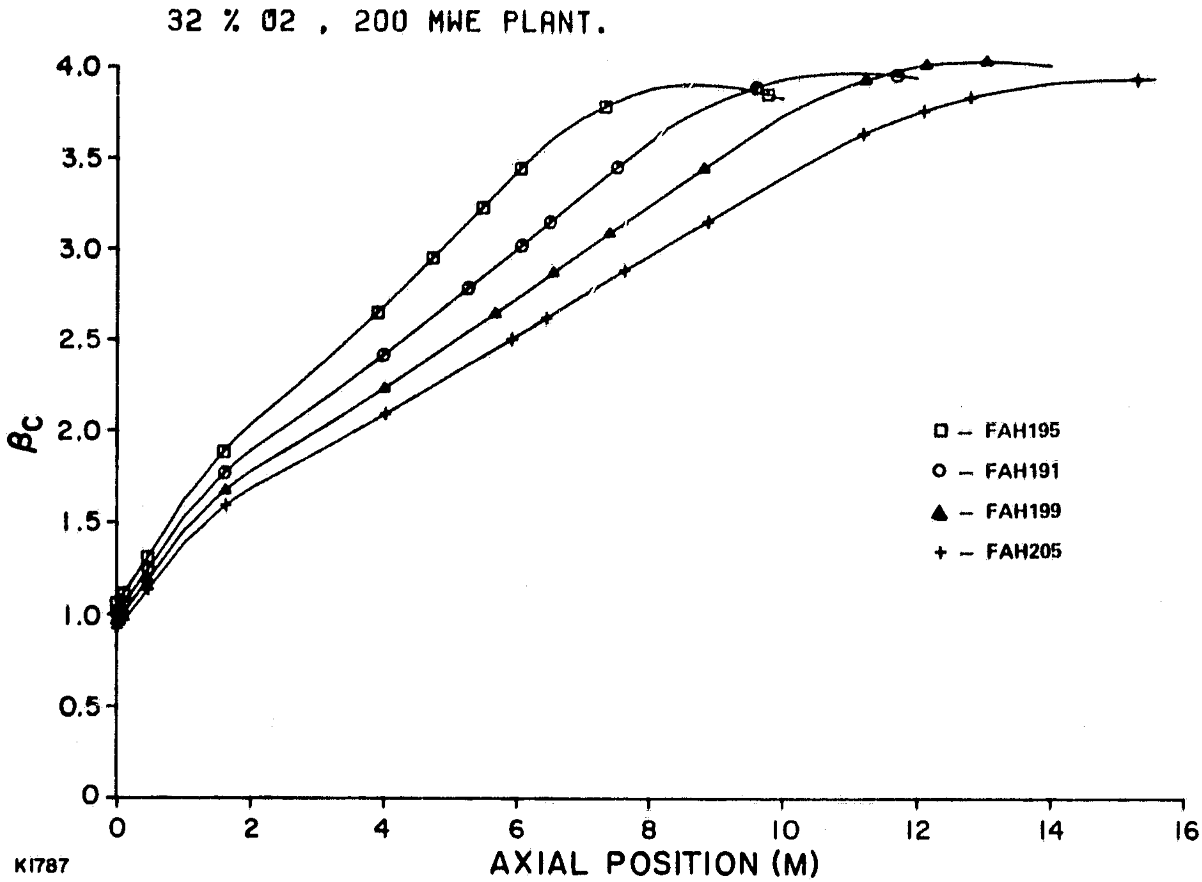

Figure 3-11e Streamwise Variations of the Hall Parameters. Plant Size $\simeq$ 200 MW_e. Oxygen Enrichment = 32%. Length = 10, 12, 14 and 16 m.

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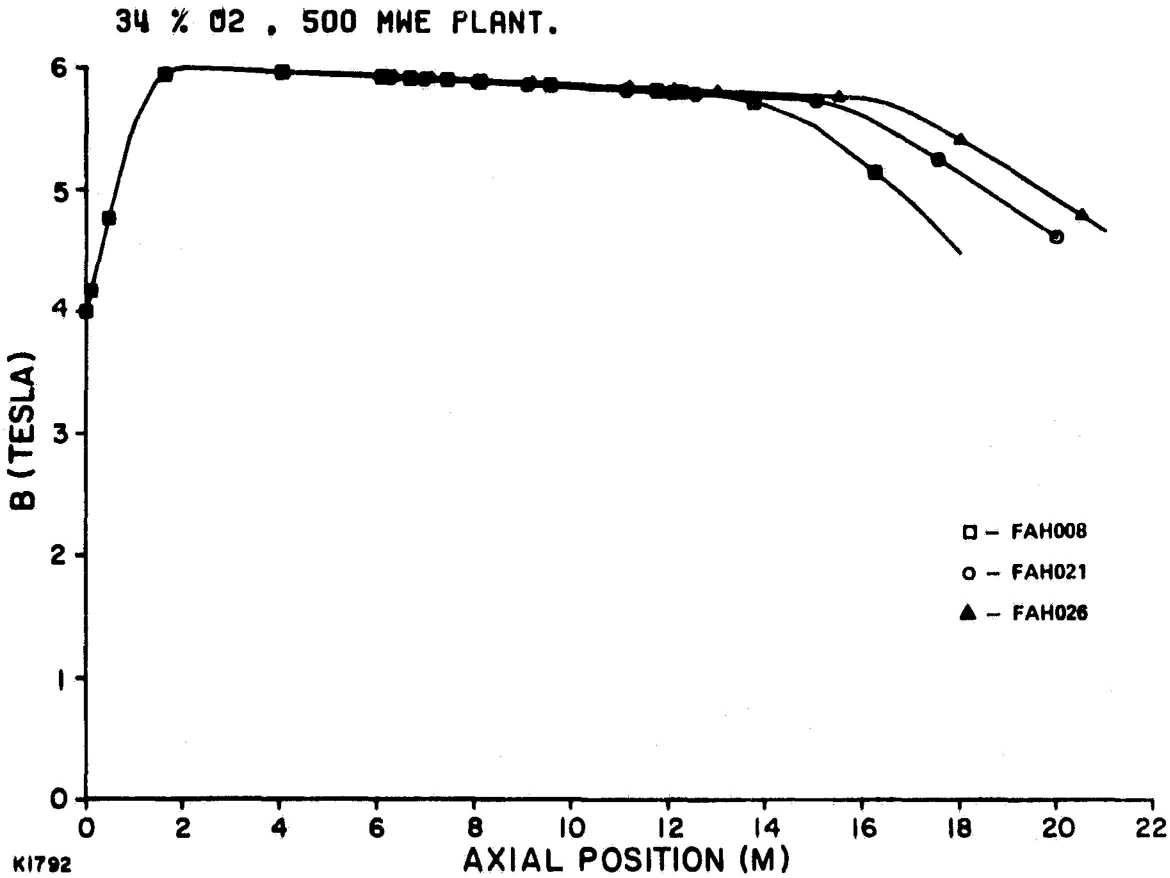

Figure 3-12a Streamwise Variations of the Prescribed Magnetic Fields. Plant Size ≃ 500 MW_e. Oxygen Enrichment = 34%. Length = 18, 20, and 21 m.

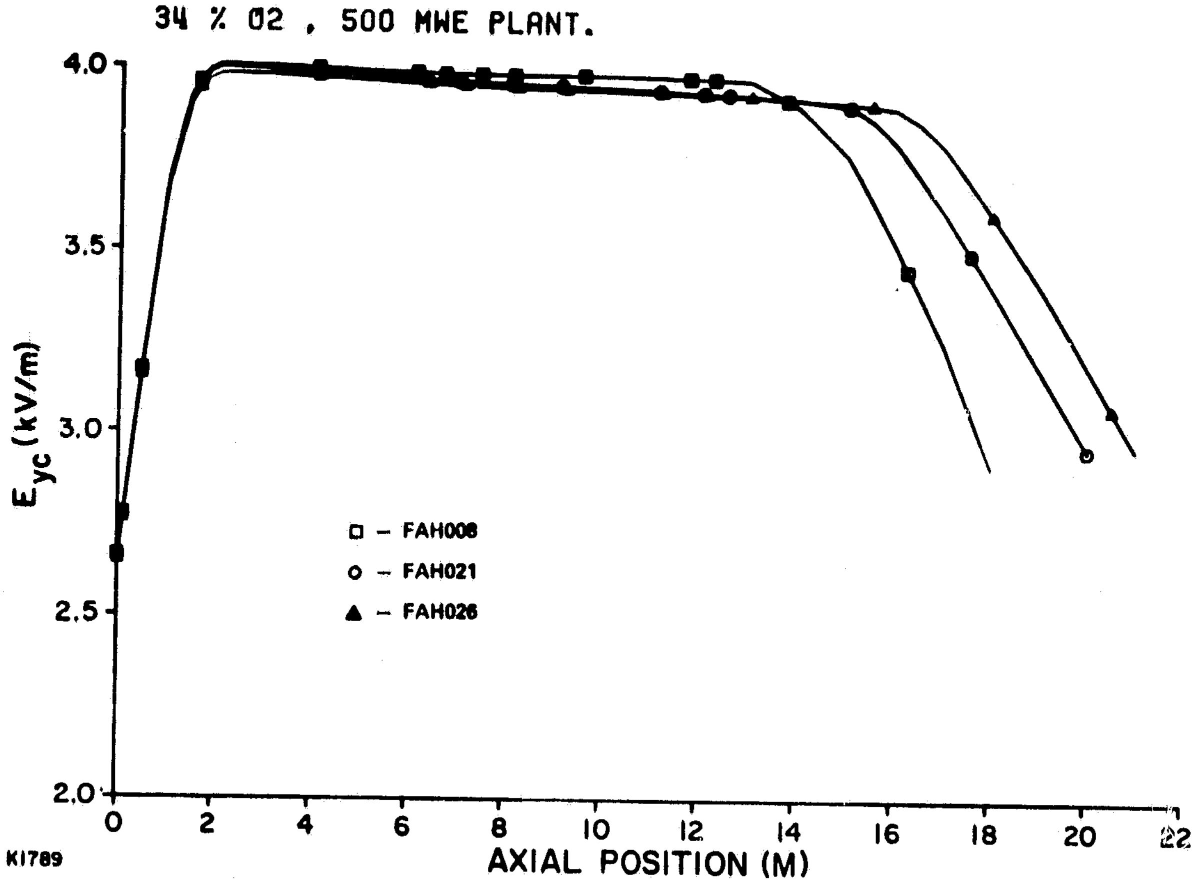

Figure 3-12b Streamwise Variations of the Transverse Electric Fields. Plant Size ≃ 500 MW_e. Oxygen Enrichment = 34%. Length = 18, 20, and 21 m.

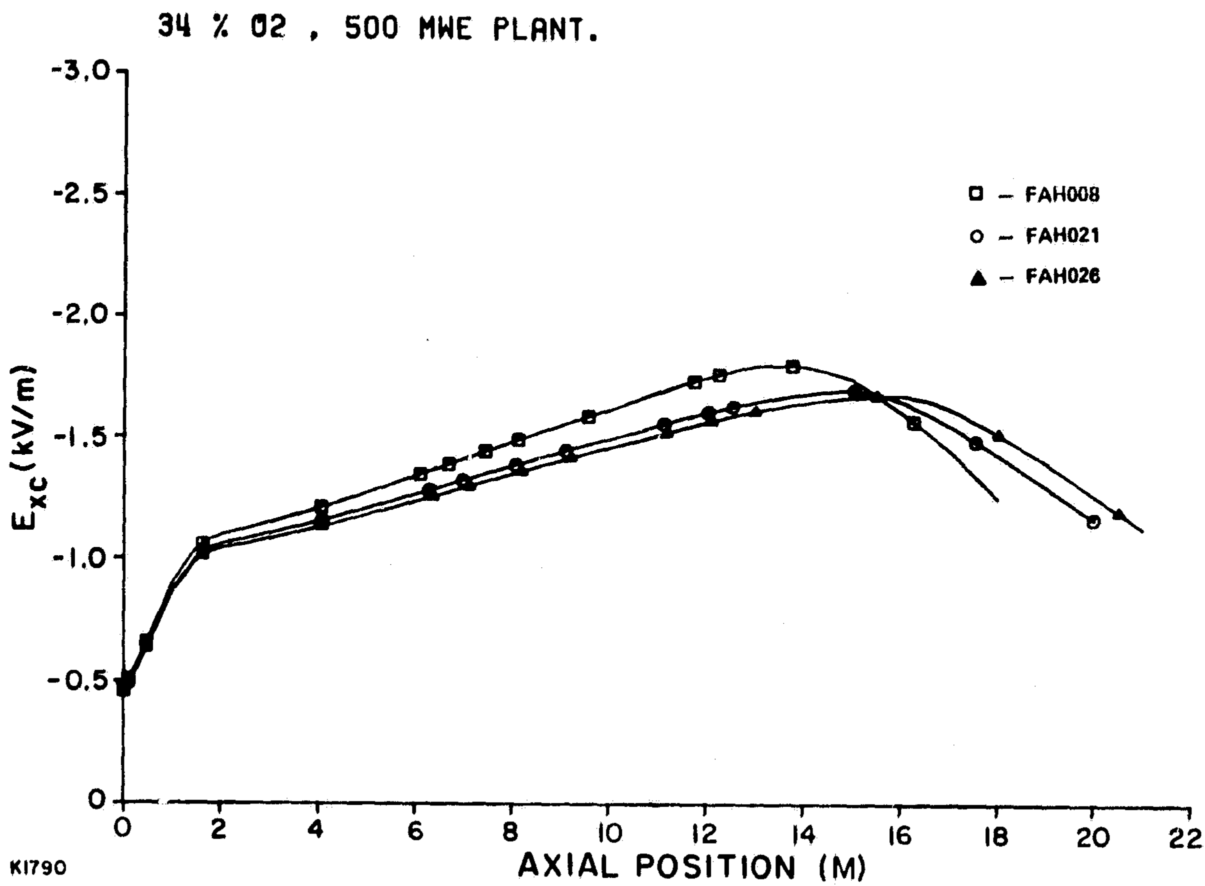

Figure 3-12c Streamwise Variations of the Axial Electric Fields. Plant Size ≃ 500 MW_e. Oxygen Enrichment = 34%. Length = 18, 20, and 21 m.

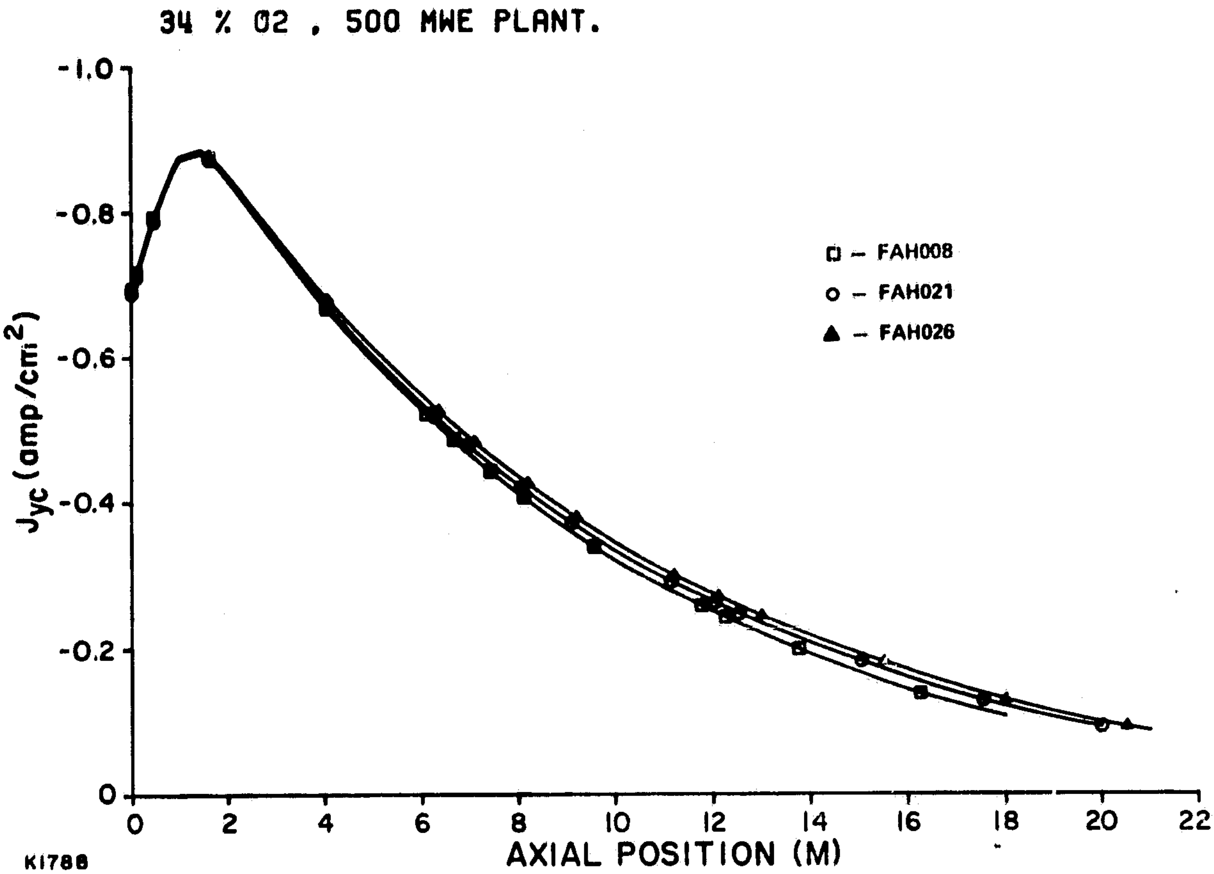

Figure 3-12d Streamwise Variations of the Transverse Current Densities. Plant Size ≃ 500 MW_e. Oxygen Enrichment = 34%. Length = 18, 20, and 21 m.

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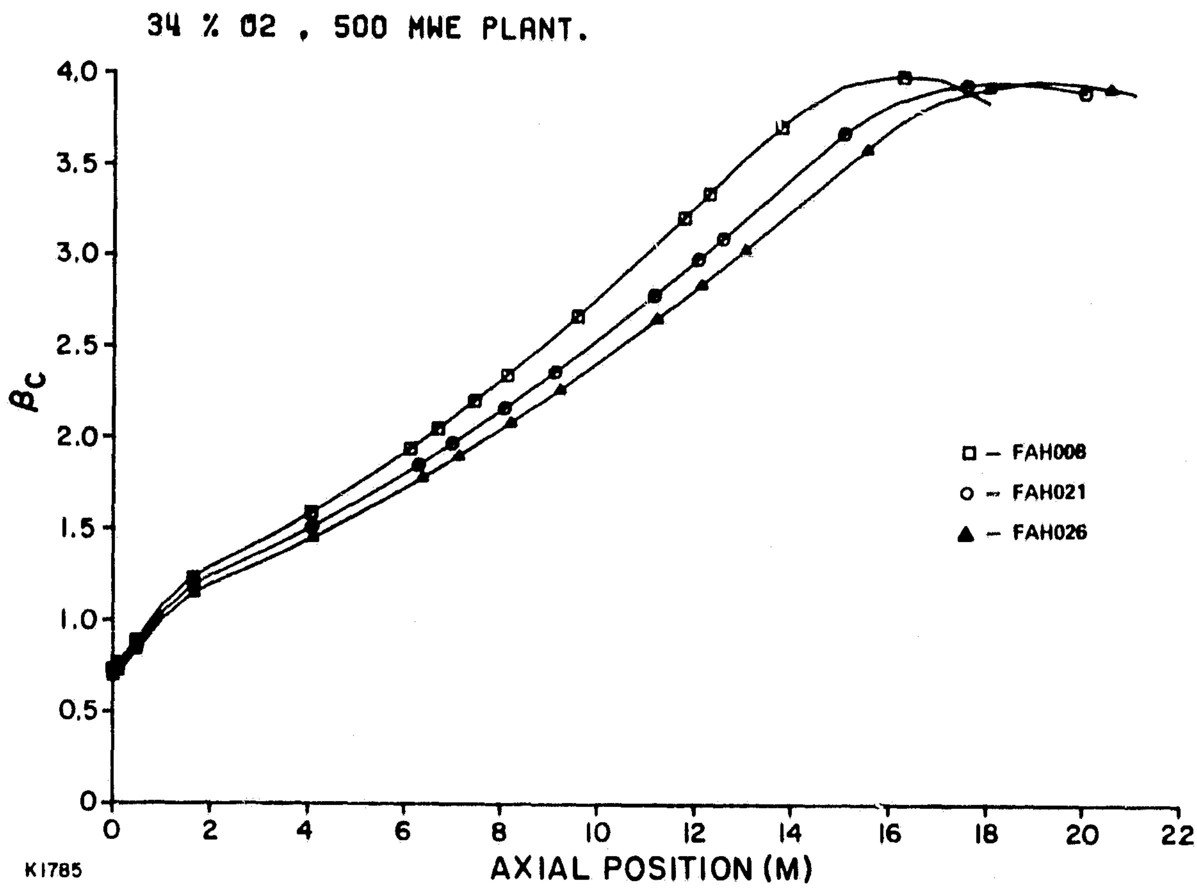

Figure 3-12e Streamwise Variations of the Hall Parameters. Plant Size ≃ 500 MW_e. Oxygen Enrichment = 34%. Length = 18, 20, and 21 m.

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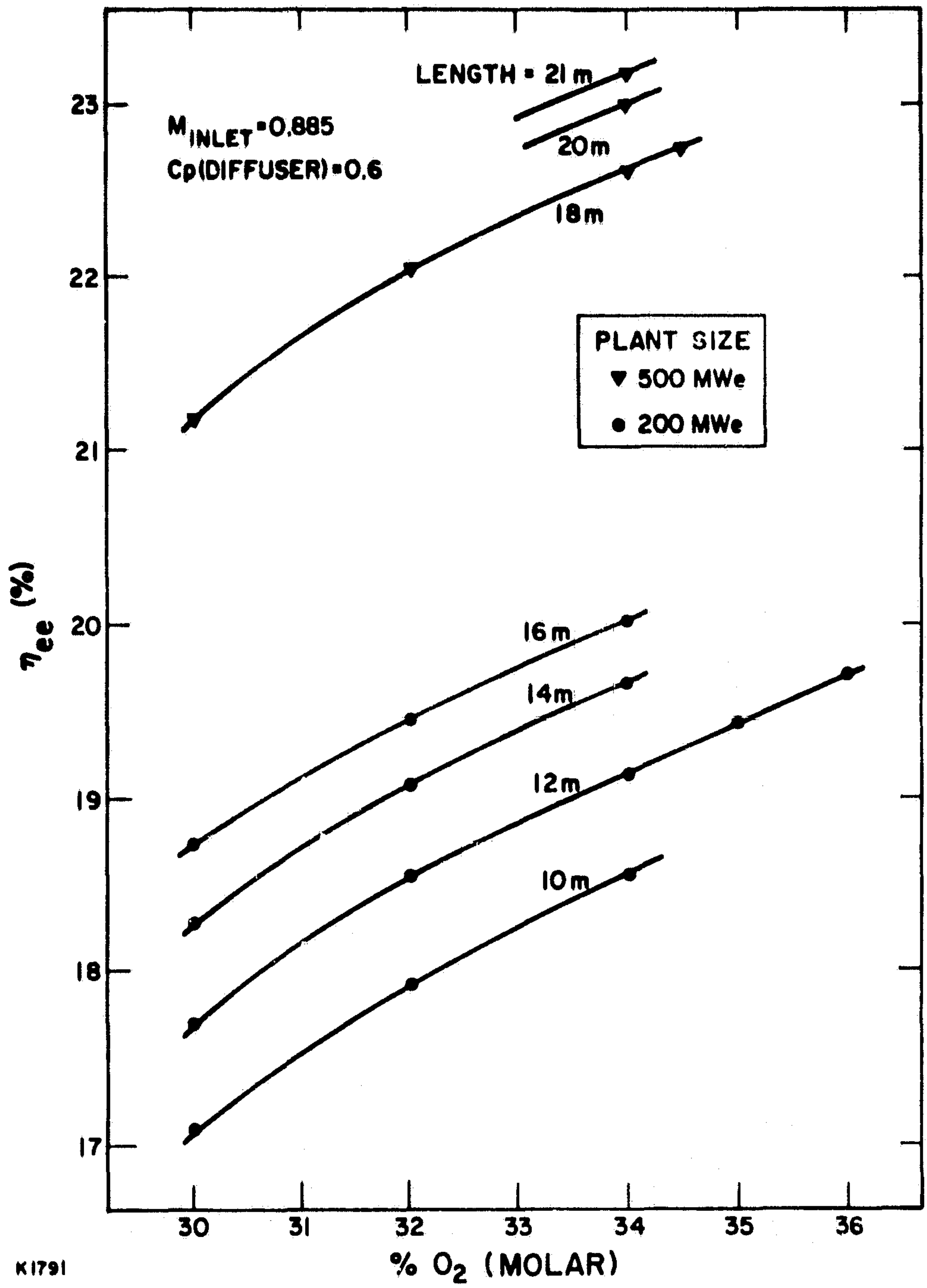

Figure 3-13 Enthalpy Extraction vs Oxygen Enrichment Level for Various Channel Lengths and Plant Sizes

It can be shown from the ideal one-dimensional-flow formulation that

$$(\eta_{ee})_{ideal} = \langle iK \rangle$$

The plots of enthalpy extraction versus $\langle iK \rangle$ of the generator designs for the plant sizes of Task III are shown in Figure 3-14. In addition, the results of the generator designs for the nominal 950 MW_e plant from Task II are included in the figure. For comparison, $(\eta_{ee})_{ideal}$ is also plotted in Figure 3-14.

It is observed that the calculated channel performance data points (from the MHD4 program) collapse onto several distinct curves which are only a function of the plant size. Furthermore, for a given flow interaction, the channel performance deviates further from the ideal prediction with decreasing plant size. This trend, as expected, is attributed to the relative increase of surface boundary losses because of the increase of surface/volume ratio with decreasing mass flow rates and plant size. At each plant size, generators with longer lengths and higher enrichments will have higher enthalpy extraction, but also will deviate further from the ideal prediction due to the relative increase of boundary losses.

3.1.1.4 Preliminary Supersonic Channel Calculations

This subsection includes a few comments and preliminary data for the alternative use of supersonic channel operation for early commercial MHD power plant applications. Investigation of supersonic channel operation was beyond the scope of work in this study. However, since supersonic channel operation is considered to offer a potential alternative to subsonic channel operation for early MHD power plants this subsection is included for general information and completeness.

It is clear that the cost and risk associated with the superconducting magnet are important considerations. Therefore, the possible use of a lower magnetic field which is generally accompanied by supersonic operation might very well be attractive, particularly for the first commercial plant. This would reduce the cost and risk associated with the magnet which by far is the most significant cost item of the MHD components. It is also mentioned that, at present, there is considerably more MHD experience with supersonic channel operation. It is recognized that the final selection of supersonic versus subsonic operation is influenced by several other considerations than those already mentioned related to MHD generator performance, risk and cost

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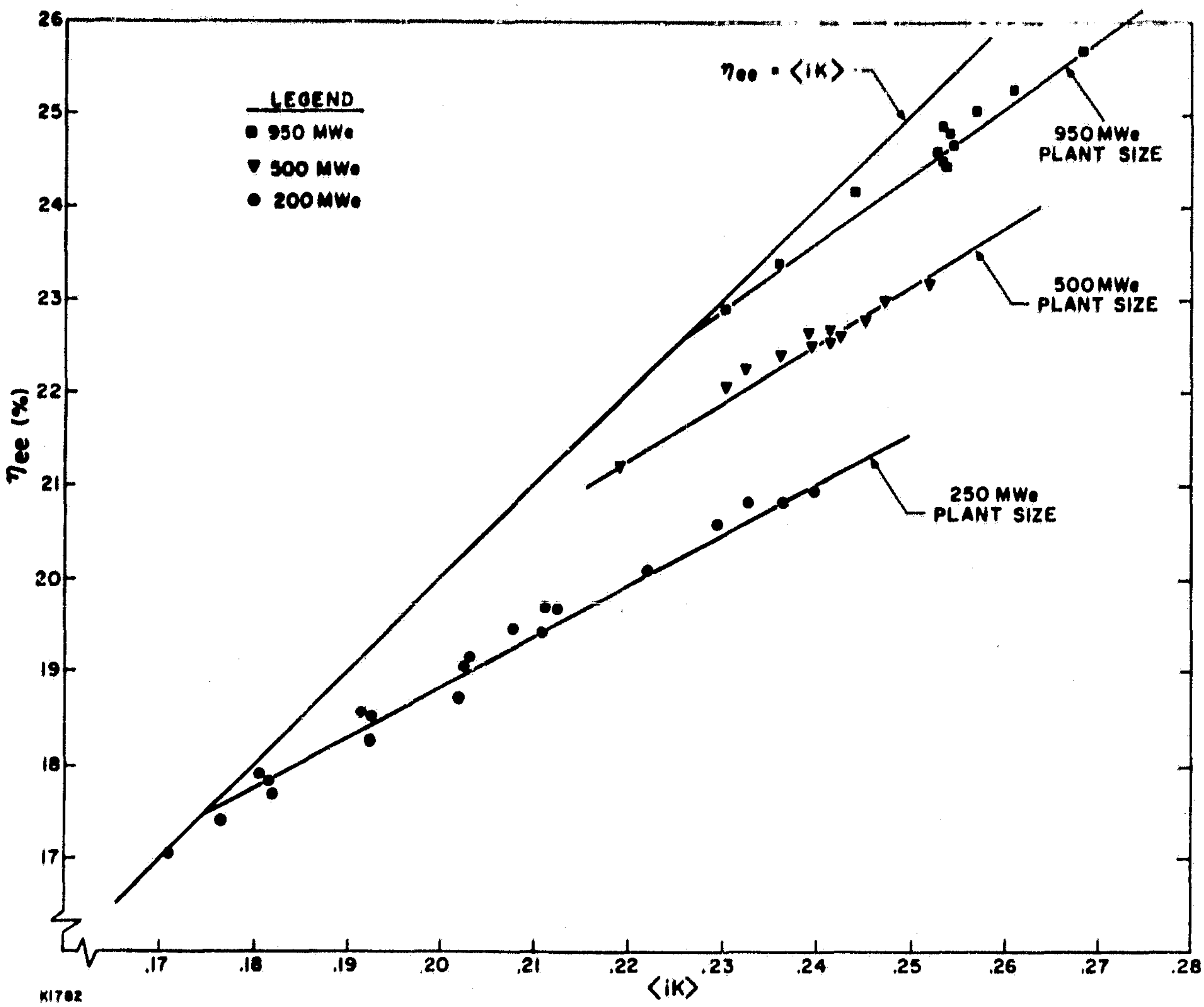

Figure 3-14 Enthalpy Extraction vs <ik>: Comparison of MHD4 Results with Ideal 1-D Results

(particularly the magnet). Other important considerations include part-load operation, effects between combustor and MHD generator operation (uncoupled for supersonic flow operation), diffuser performance, and oxygen plant size and cost (degree of oxygen enrichment).

Initial comparative MHD generation design data for subsonic and supersonic channel operation for two different plant sizes are listed in Table 3-4. The data for the subsonic channel for the 950 MW_e plant were developed in the CSPEC (Task II) activity. The data for the supersonic channel operations are preliminary. The supersonic MHD generator designs are based on the same coal thermal input as the corresponding subsonic cases. However, the peak magnetic field strength has been reduced from 6 T to 4.5 T and the degrees of oxygen enrichment of the combustion air has been increased.

It is important to note that the preliminary supersonic designs show small decreases in MHD generator performance and net power output whereas the stored magnetic energy is reduced to half or less of that at subsonic operation. Thus, a relatively small reduction in plant performance can be expected for a significant reduction in magnetic field, and hence magnet cost and risk. The size of the oxygen plant has been increased up to 20% for supersonic operation, which increases its cost. Further investigations and trade-off analysis between subsonic and supersonic MHD generator operation are needed. These should include controls and part-load operation and also mixed flow (supersonic inlet; subsonic exit) generator operation.

3.1.2 MDH Channel Mechanical Design

3.1.2.1 Design Basis

The mechanical design selected for the MHD generator channels for this study 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.

TABLE 3-4

PRELIMINARY COMPARATIVE LARGE-SCALE MHD GENERATOR DESIGN DATA FOR SUBSONIC AND SUPERSONIC CHANNEL OPERATIONS

Plant Size	Subsonic 950 MW_e	Supersonic 950 MW_e	Subsonic 200 MW_e	Supersonic 200 MW_e
Peak Magnetic Field (Tesla)	6.0	4.5	6.0	4.5
O_2-Content in Oxidizer (molar %)	34	40	32	35
P_o (atm, NEMA)	8.3	10.8	5.45	5.96
T_o (°K)	2881	2991	2796	2856
$\dot{m}$ (kg/sec)	472.0	415.45	120.7	112.3
Inlet Mach Number	0.885	1.20	0.885	1.20
Elec. Load Parameter	0.786	0.759	0.944	0.736
Length (m)	21.5	20.0	12.0	12.0
P_M (MW_e)	525	509.4	96.29	90.85
P_{Net} (MW_e)	355	325.3	61.33	54.43
η_{ee} (%)	24.6	24.51	18.55	17.90
η_{is} (%)	74.0	69.9	66.37	62.80
η_M (%)	16.63	15.65	12.06	10.70
Maximum E_y (kV/m)	4.00	3.99	3.97	3.96
Maximum E_x (kV/m)	1.77	1.83	2.00	2.03
Maximum J_y (A/cm^2)	0.82	1.00	0.83	0.81
ε_{max}	3.93	3.90	3.98	3.90
Channel Volume m^3	61.8	39 42	10.1	8.73
Magnet Stored Energy	1.0 (normalized)	0.37	1.0 (normalized)	0.51
O_2-Plant Size	1.0 (normalized)	1.22	1.0 (normalized)	1.15

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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 noncurrent-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 Figures 3-2 and 3-3 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 ~ 2-3 mm thick and to have a surface temperature of ~ 1800°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 in. 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 in. wide which with a 0.075 in. thick insulator yields an electrode pitch of 0.70 in. This results in an interelectrode voltage of slightly more than 30 V in

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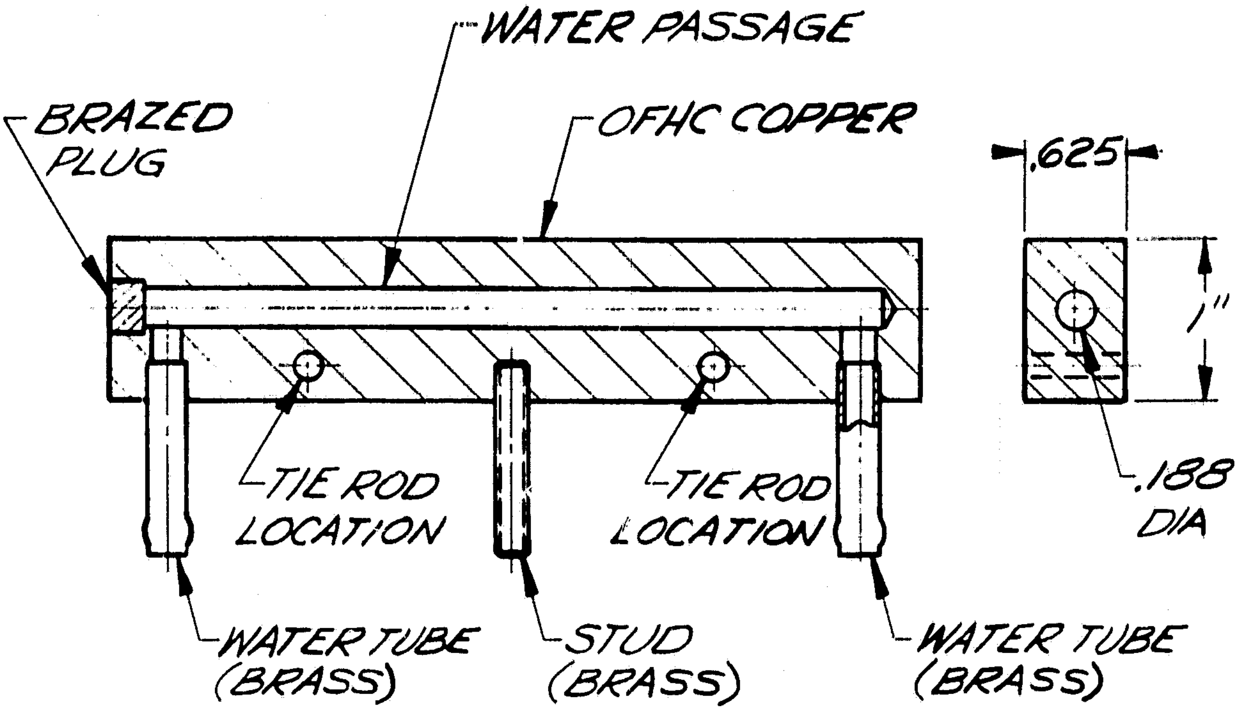

J2745 Figure 3-15 Electrode Structure (Schematic) the region of maximum electric field towards the exit of the channel. This value of interelectrode voltage has been experimentally demonstrated to be below that which can be withstood by the BN insulator which separates the electrodes.

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 walls contour. The total electrode length varies from the inlet to the exit of the channel in accordance with the plot of "h" in Figures 3-2 and 3-3. It is likely that transverse electrode segmentation will be necessary to limit the current from each segment to some maximum value. This is an area which is currently under investigation. Segmentation can be provided, 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 (BN) strips typically 0.075 in. 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 insulator is recessed and the resulting groove is filled with castable alumina. This provides an effective slag attachment area and 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.

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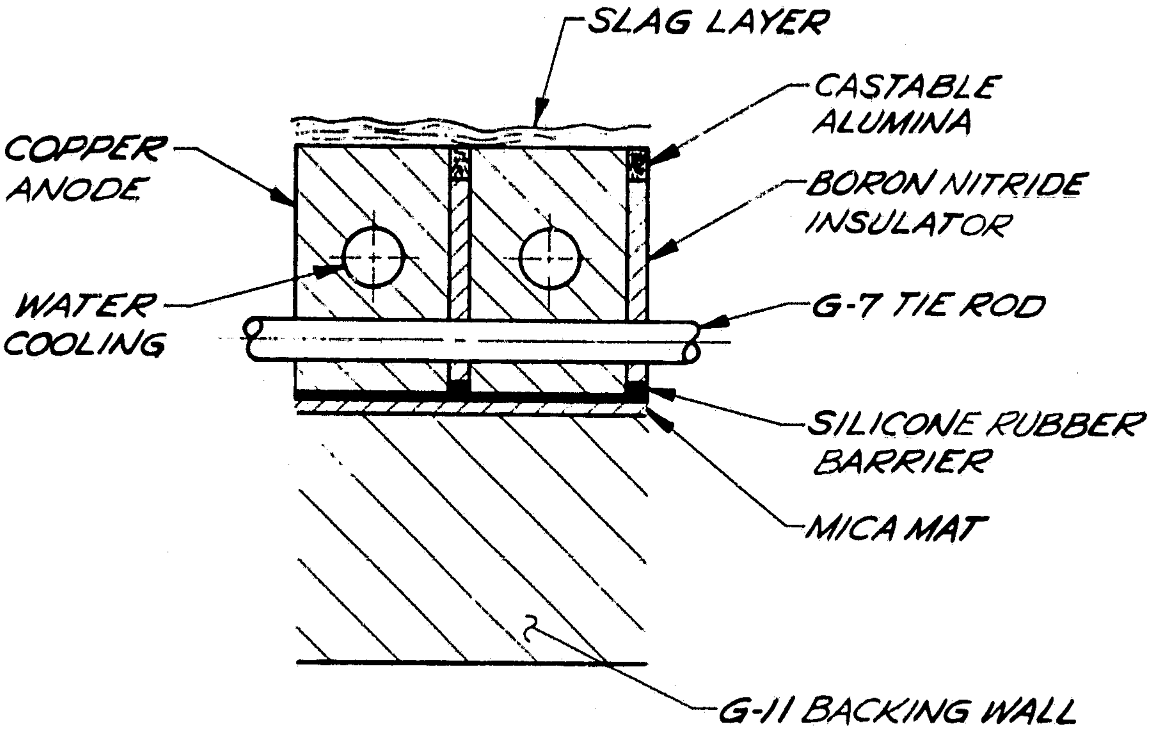

ANODE WALL ASSEMBLY (SCHEMATIC)

J2746

Figure 3-16 Electrode Assembly (Schematic)

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 in. 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 Figures 3-2 and 3-3. 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 equipotential 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 3-5.

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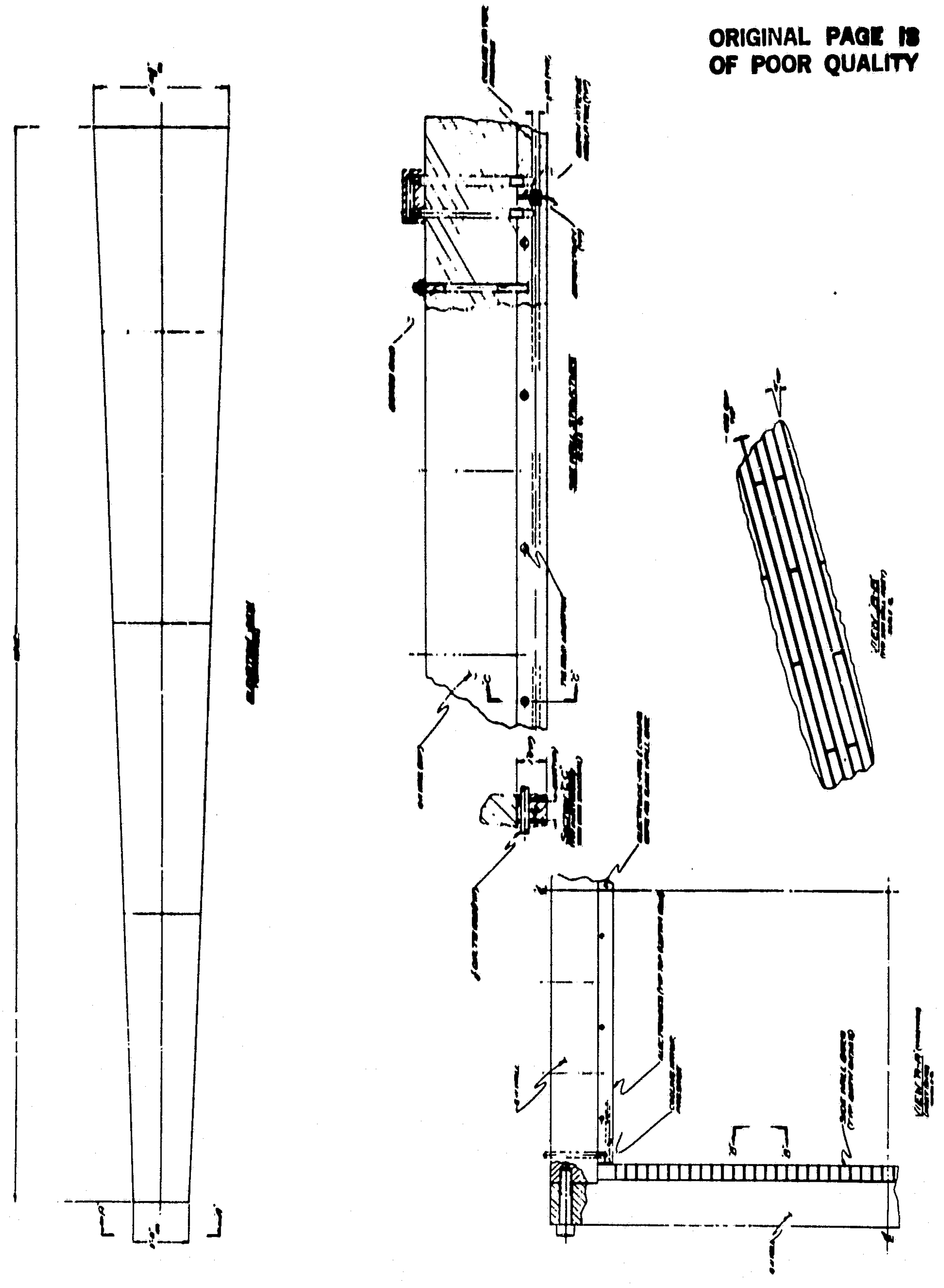

Figure 3-17 MHD Generator Channel

TABLE 3-5

CHANNEL WEIGHT SUMMARY

	$200\ MW_e$	$500\ MW_e$
Copper Extrusions	19,100 lbs	40,500 lbs
G-11 Sidewalls	8,500	22,600
Tungsten-Copper	950	2,000
BN Insulators	600	1,200
Fasteners, Misc. Hardware	2,200	4,700
	31,350 lbs	71,000 lbs
Platinum	1,680 oz	3,565 oz

3.1.2.6 Magnet Warm Bore

Efficient utilization of the magnet warm bore volumé is important because it affects 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 further 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% 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 estimated that 10 in. clearance space on all sides between the channel and magnet warm bore tube would accommodate all the piping, wiring and channel support and transport mechanism for the 500 MW_e plant. For the smaller 200 MW_e plant it was estimated that a 9 in. clearance space would be required. 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

The criteria for the successful selection of control and consolidation networks were described in References 2 and 4. In this section, the preliminary load networks selected for the diagonal generators of the 500 MW_e and the 200 MW_e plants will be described.

In Figures 3-18 and 3-19, the schematics of the multiloaded generator are presented. A four-terminal load connection was selected for the 500 MW_e plant and a three-load network for the 200 MW_e plant. The locations and numbers of mid-channel taps and the amount of current collected by each tap are determined based on the following constraints: the tangent of the diagonal connecting angle should not exceed 4, current density should not exceed 1 amp/cm^2, and the current delivered by a mid-channel tap should not exceed $\sim$ 35% of the total current collected by all the electrodes. The last design criteria have been somewhat arbitrarily selected to prevent serious current nonuniformities from being induced in the plasma.

Simpler load connections (fewer loads) can be considered than those shown in Figures 3-18 and 3-19. The simpler connections would provide the same efficiency at the nominal design condition but uncertainties arise concerning the part-load performance. Channel loading and controls is an area which requires further investigation and development work before a practical optimum design can be determined for commercial operation.

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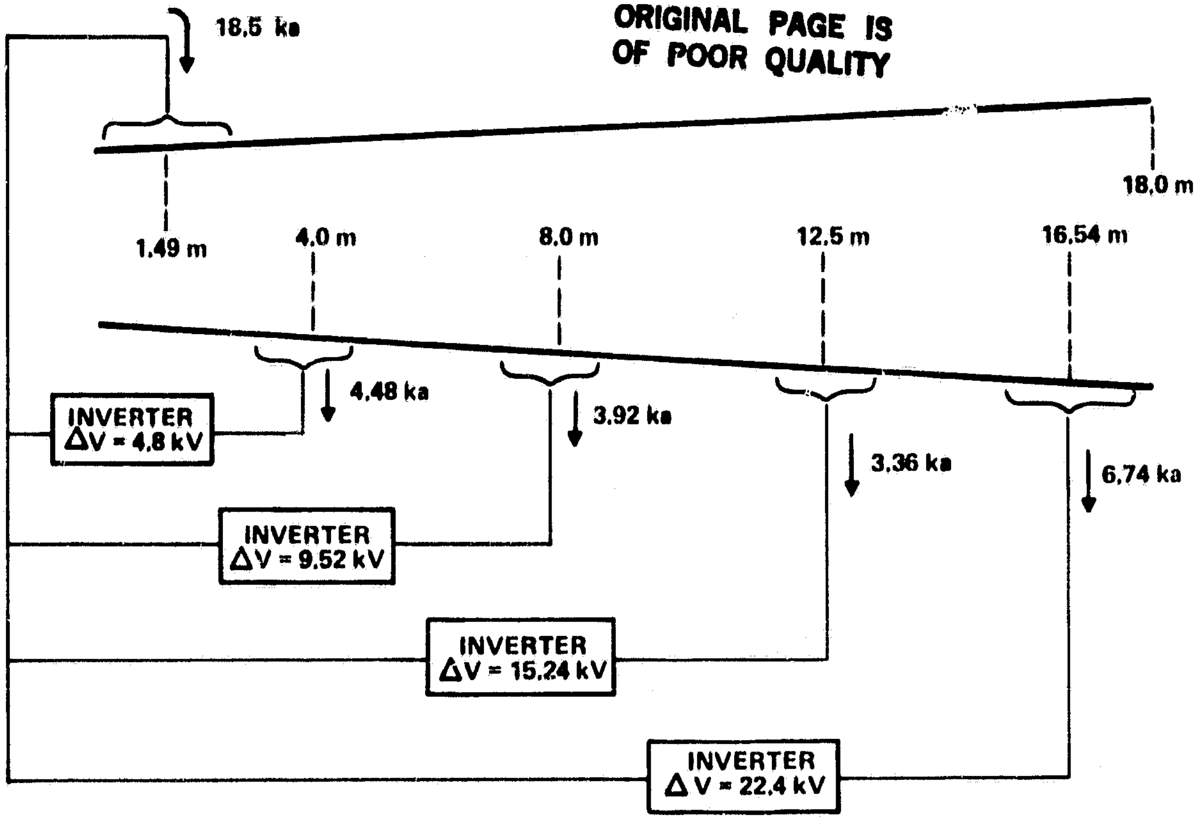

INVERTERS	kV	ka	MW
1ST MID-CHANNEL TAP	4.8	4.48	21.5
2ND MID-CHANNEL TAP	9.52	3.92	37.3
3RD MID-CHANNEL TAP	15.24	3.36	51.2
CATHODE TAP	22.4	6.74	151.0
		18.5	261.0

K1781

Figure 3-18 Four Terminal Parallel Diagonal Load Connection for the 500 MW_e Plant

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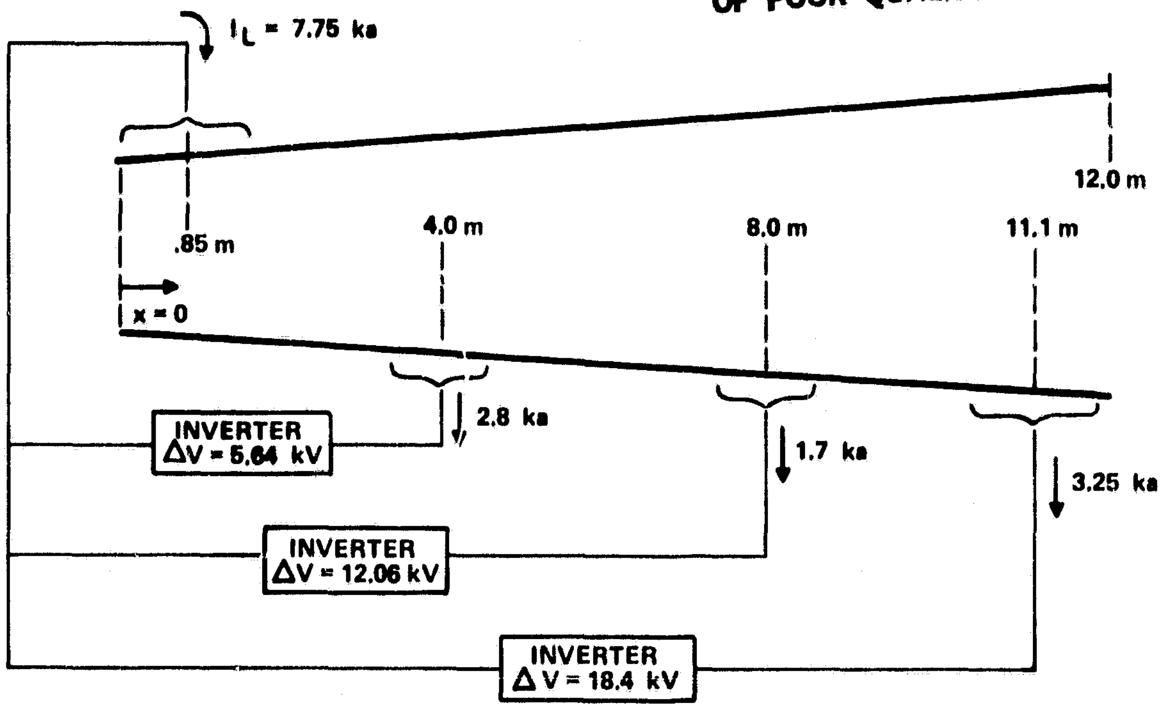

INVERTERS	kV	ka	MW
1ST MID-CHANNEL TAP	5.64	2.8	15.8
2ND MID-CHANNEL TAP	12.06	1.7	20.5
CATHODE TAP	18.46	3.25	60.0
		7.75	96.3

K1780

Figure 3-19 Three Terminal Parallel Diagonal Load Connection for the 200 MW_e Plant

3.2 SUPERCONDUCTING MAGNET

The design and cost analyses of the superconducing magnet for both plants were all based on the magnet design concept previously described for the larger Task II (CSPEC) plant (Reference 2) and which was originally developed in the Conceptual Design of the ETF (Reference 5).

Scaling was possible because the magnetic field for all magnets was about the same ($\sim$ 6 T) and the basic design principles used in estimating the cost, weight and dimensions of the magnet were applicable for all sizes. The magnetic field distribution and 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.

The principal design approach otherwise was to utilize a modular magnet construction with prefabrication and simple machining and welding. In this way field construction and assembly work is minimized which again minimizes construction costs.

Superconducting magnet design data for the 500 MW_e and 200 MW_e plants with dimensions and weights are summarized in Table 3-6. The magnet size, field distribution and internal forces were established with computer analysis of the electrical windings.

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 and have a 45° rectangular saddle shape. The principal direction of the magnet field is horizontal.

The warm bore area is square to match the channel cross-section geometry. The utilization of the magnet bore decreases with magnet bore size or decreasing plant size as expected.

Scaling factors for the different commercial sized magnets (from the original ETF magnet developed in Reference 5) were based on computer calculations and analysis of the magnet winding ampere turns, winding mean turn length, allowable current density, size of the structural steel and size of the vacuum container.

TABLE 3-6

SUPERCONDUCTING MAGNET DESIGN DATA

Plant Size		500 MW_e	200 MW_e
Magnetic Field (peak)	Tesla	6	6
Active Channel Length	m	18.0	12.0
Inlet Warm Bore Dim. (Square)	m	1.40	1.19
Outlet Warm Bore Dim. (Square)	m	2.52	1.84
Bore Utilization*		0.43	0.37
Overall Height (H)	m	16.5	12.0
Overall Width (W)	m	11.0	9.0
Overall Length (L)	m	23.0	17.0
Stored Energy	10^9 J	3.4	1.8
Winding Assembly Weight	ton (met.)	1126	715
Structure Containment Weight	ton (met.)	657	309
Vacuum Tank Weight	ton (met.)	563	414
Total Weight Including Refrigeration System	ton (met.)	2381	1459

* Channel volume/magnet bore volume

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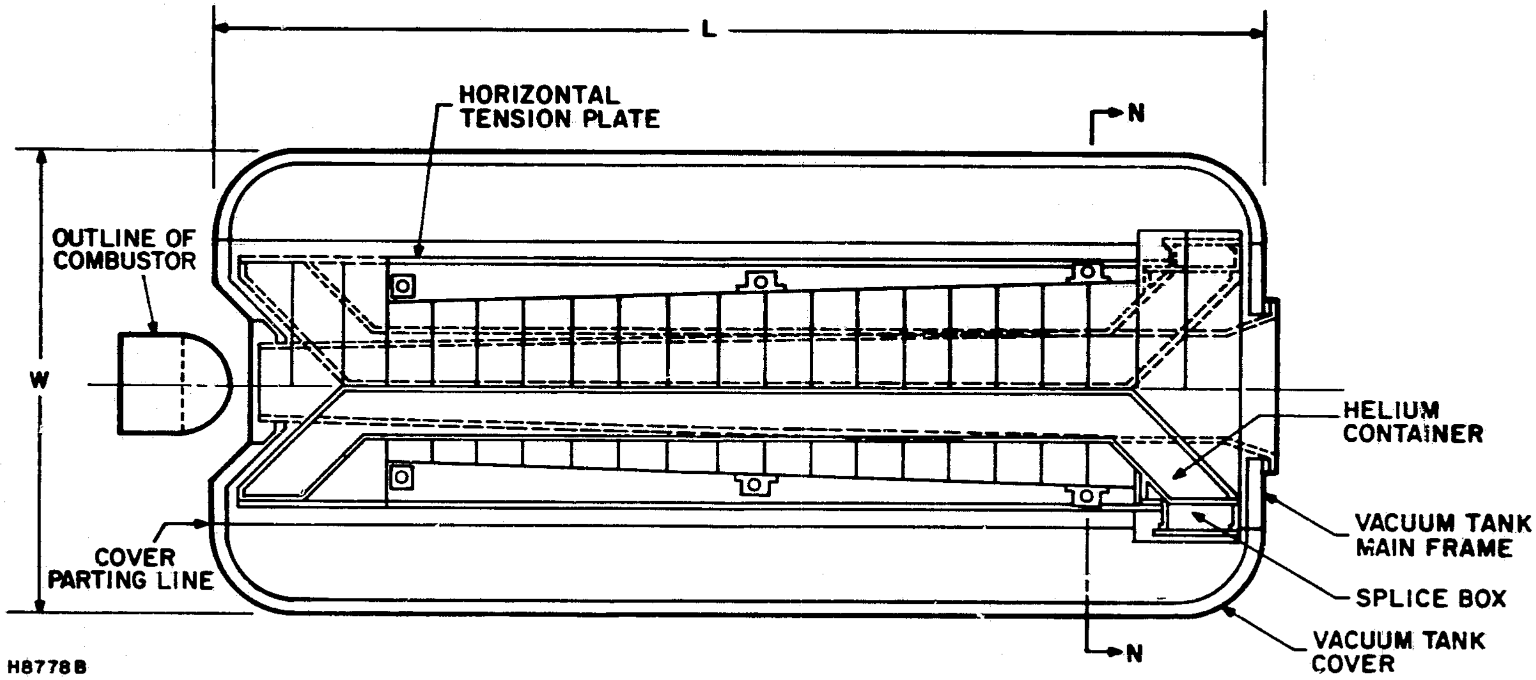

Figure 3-20 Magnet Plan View

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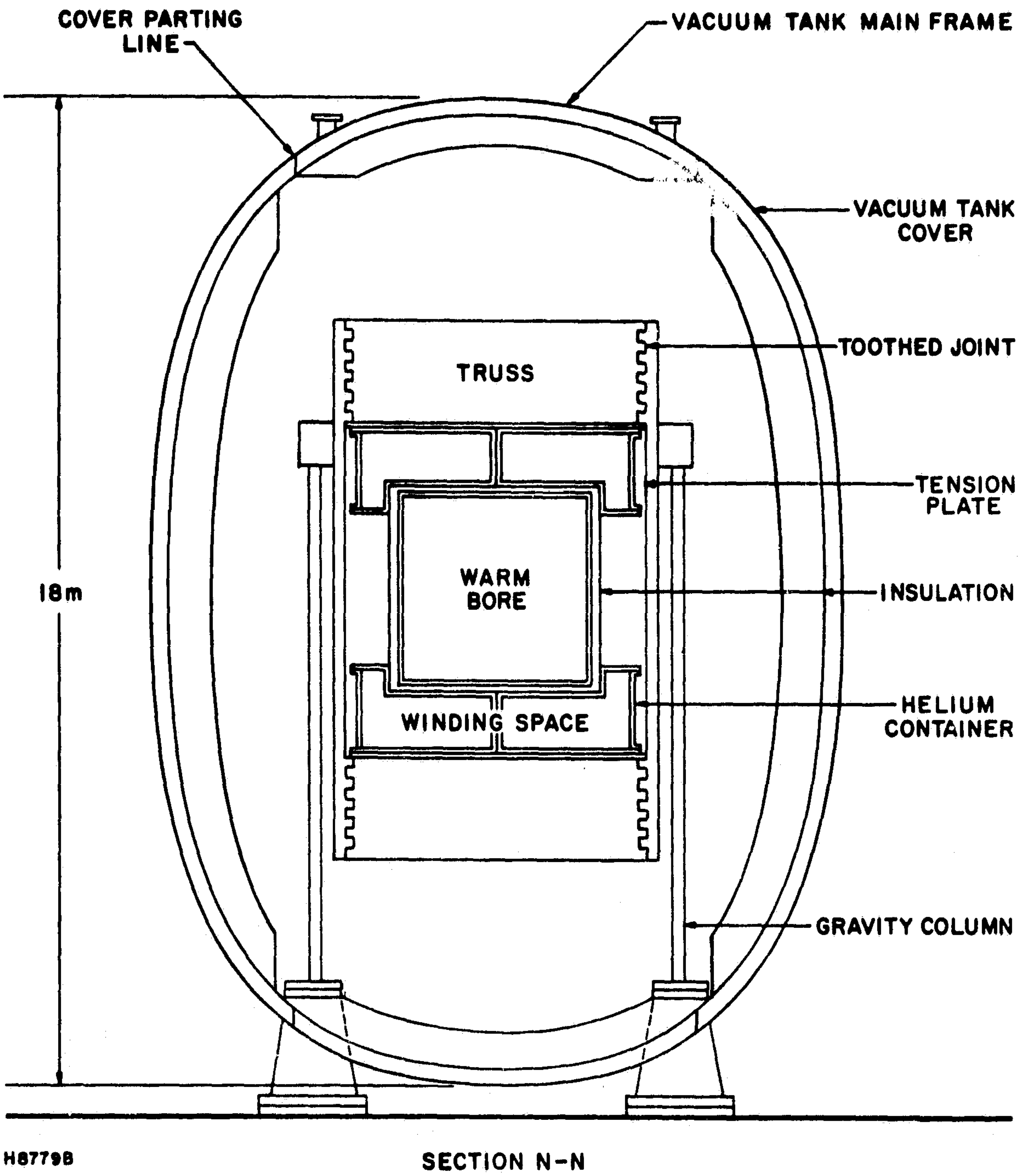

Figure 3-21 Magnet Cross Section

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As mentioned above, the magnet design used in this program study was modeled after the one proposed and described for the ETF (Reference 5) design.

In the last year, a new and novel magnet design concept has been innovated at AERL. This is a so-called roll-apart superconducting magnet design consisting of two separate windings, structures and vacuum containers. These would be assembled around the MHD channel, to produce the required magnetic field.

A roll-apart magnet design offers very easy access to the channel since the magnet can be removed or rolled apart. This may have advantages for MHD flow train maintenance and channel replacement. In addition, and possibly the main potential advantage of a roll-apart magnet design is that it offers opportunities for utilizing the space between the two halves of the magnet for location of channel supports, electrical conductors, coolant piping, etc., resulting in better utilization of the magnet bore and thus a smaller and less costly magnet.

The possible use of a roll-apart magnet design for commercial MHD power plant applications was beyond the scope of this program study effort. However, its main features are included here for general interest. Further investigations and design studies of this novel magnet design concept need to be conducted to determine its attractiveness.

3.3 COAL COMBUSTOR

3.3.1 General

Development efforts in coal combustion have so far been limited. Therefore, very limited information is available regarding practical coal combustor designs, actual operating conditions and interfacing with the MHD channel and power system components. All of the design data presented here are recognized as preliminary and are expected to be modified or revised as further information becomes available from further studies and experimental work on MHD coal combustion.

The combustor design selected for the Task III plant analysis was a single-stage combustor configuration similar to that used in Tasks I and II of this program study. Its potential major advantages are low heat loss, effective carbon utilization and simplicity. It is recognized that DOE has a two-stage combustor under development by TRW, and that this two-stage combustor design now is considered a promising MHD combustor concept. However, very little information is presently available on the design of such a two-stage combustor for commercial power plant application. The limited efforts under this contract did not allow for pursuing a two-stage combustor design concept further. Also, the use of the same single-stage combustor design in Tasks II and III provides a common basis for an evaluation of the effects of variations of plant size.

The combustor design used for this study is shown on the drawing in Figure 3-22 and 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.

3.3.2 Mechanical Design

The combustor is designed to operate at a pressure level slightly higher than the channel inlet pressue. 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 emission 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

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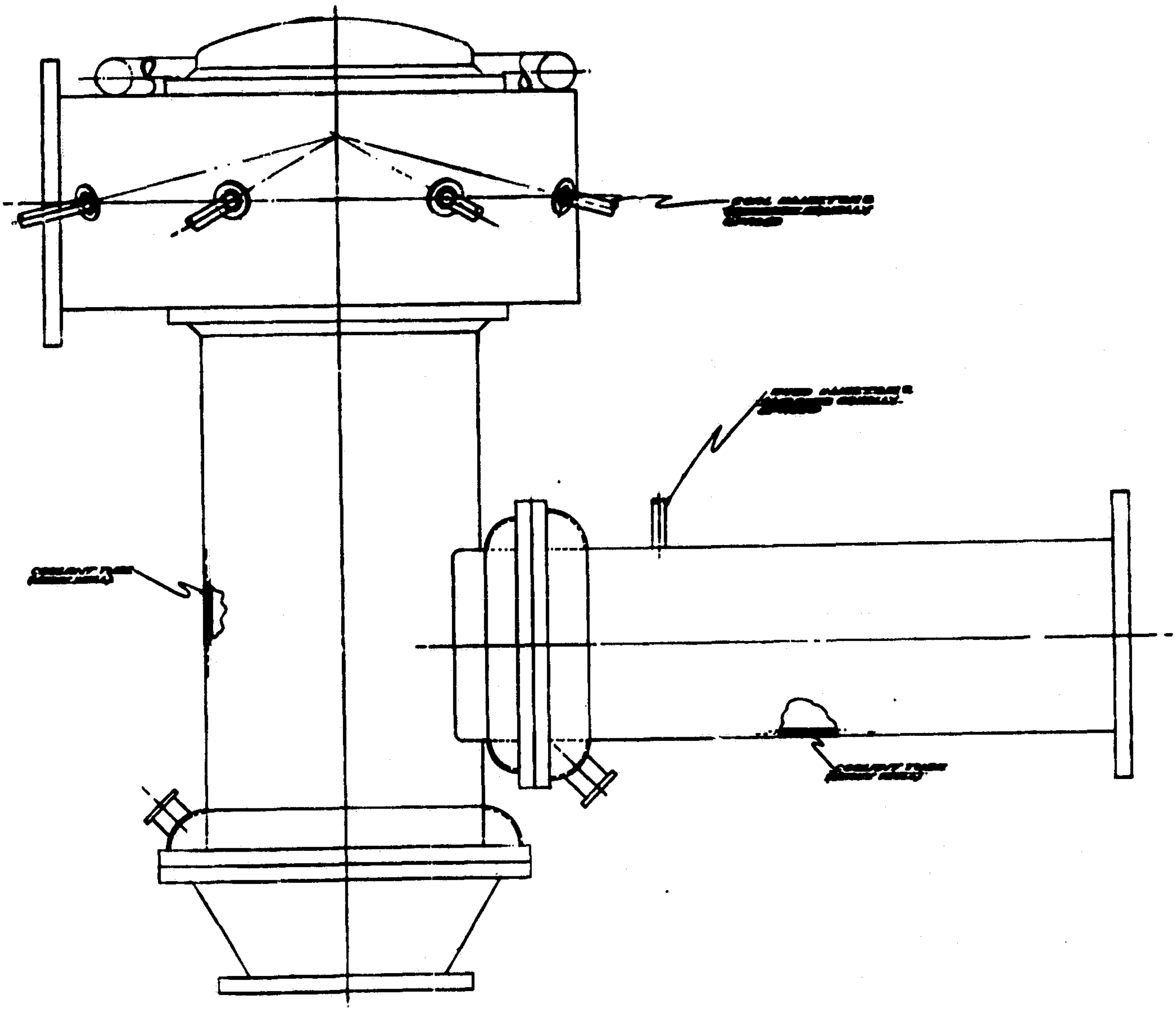

Figure 3-22 Coal Combustor

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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.

The injectors are equally spaced around the periphery of the combustor and directed radially at an angle of 30^{o} above the horizontal plane. This orientation has been selected to provide optimum utilization of injection momentum, homogeneity of combustion products and separtaion 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 is 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 is designed for a minimum bulk residence time of $\sim$ 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 $\sim$ 3 was selected considering combustor flow fields, flow gas velocity, heat loss and slag rejection. An outline drawing giving the principal combustion chamber dimensions for the 200 MW_e and 500 MW_e plants in shown in Figure 3-23.

The combustion products exit the combustor through a horizontal duct. The dimensions of the duct are essentially governed by the channel inlet geometry and the size of the SC magnet dewar which determines how close the combustor can be located to the channel inlet. Seed is injected near the inlet of the duct through eight nozzle type injectors which are mountd 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 in excess of the time required 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 3-7.

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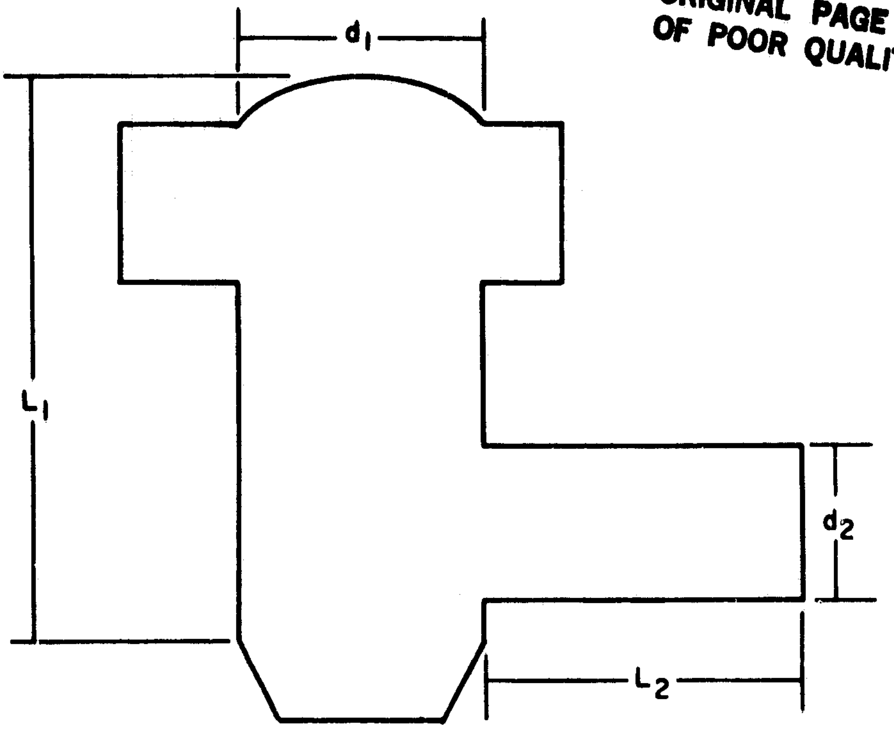

COMBUSTOR DIMENSIONS AND WEIGHT

	200 MW_e	500 MW_e
d_1 – m	1.45	1.70
d_2 – m	0.82	1.04
L_1 – m	4.50	5.20
L_2 – m	3.00	3.60
Weight – Lbs.	31,230	44,000

K2128

Figure 3-23 Combustor Outline

TABLE 3-7

COMBUSTOR WEIGHT SUMMARY

	500 MW_e	200 MW_e
Stainless Steel Plate	16,600 lbs	12,200 lbs
Inconel 600 Tubing	12,400	9,000
Flanges and Manifolds	7,500	5,000
Refractory	7,500	5,000
	44,000 lbs	31,200 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 combustor heat loss at nominal operating conditions was computed to be 37.8 MW for the 500 MW_e plant and 18.6 MW for the 200 MW_e plant. This corresponds to an average specific heat loss/unit of combustor surface area of about 250,000-300,000 BTU/ft^2/hr. These values are in line with those observed from operation of smaller experimental coal combustors and taking into account the higher radiant heat loss which will be inherent to the larger units.

The burner is cooled by high-pressure boiler feedwater. 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 polyamide 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. Polyamide 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 successfullly 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 subsection 3.10.3.

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

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3.4.1 General Considerations

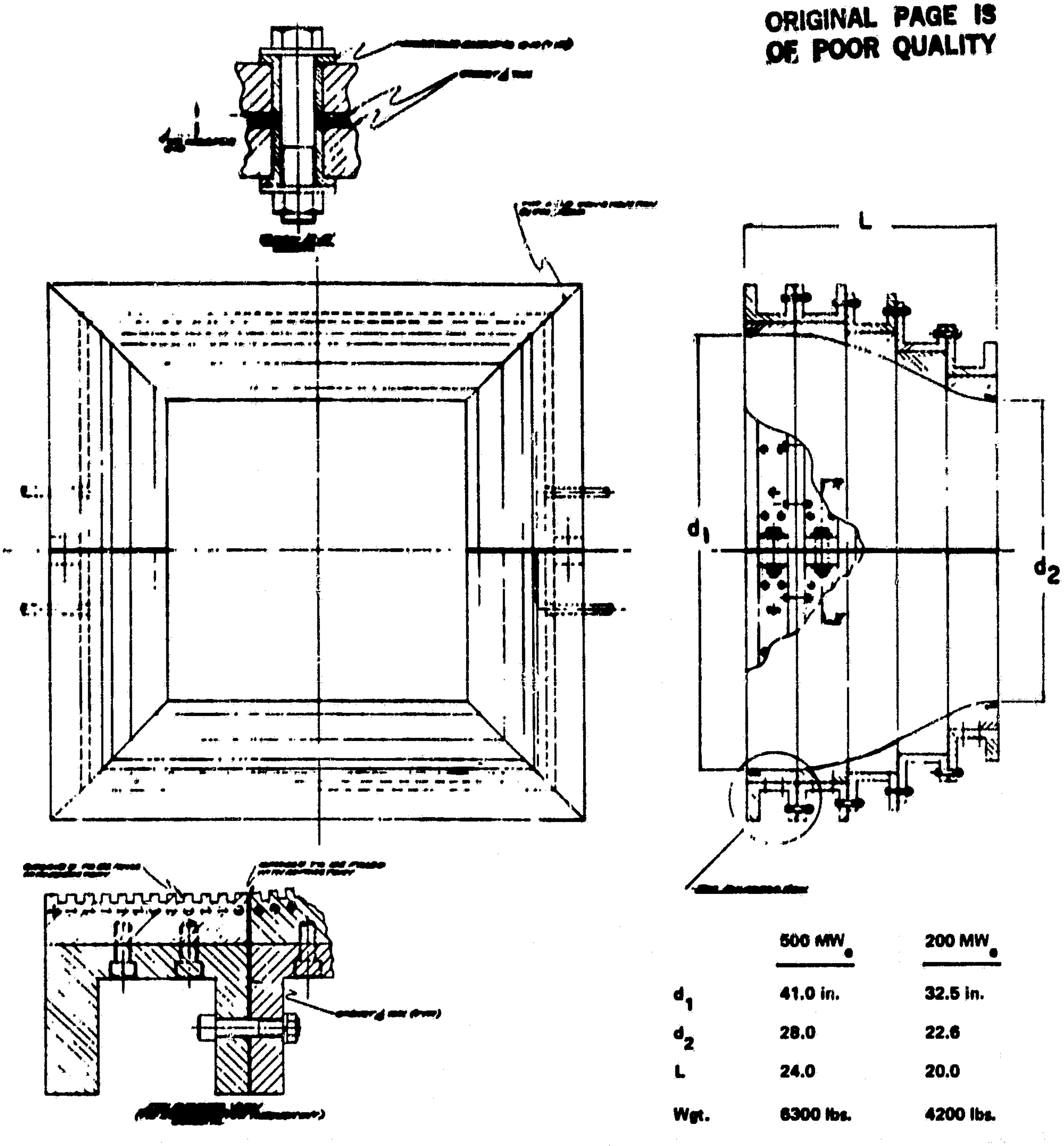
The primary function of the generator inlet nozzle is to accelerate the high-temperature gases produced in the burner to the velocity required at the channel inlet. Ideally the nozzle should be as short as possible to minimize heat transfer losses while maintaining an ample radius of curvature in the 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 with the principal dimensions and some of the details of construction is 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 provide 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.

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 3-24.



	500 MW_e	200 MW_e
d_1	41.0 in.	32.5 in.
d_2	28.0	22.6
L	24.0	20.0
Wgt.	6300 lbs.	4200 lbs.

Figure 3-24 MHD Generator Inlet Nozzle

3.4.3 Nozzle Cooling

The total heat load to the nozzle walls at full load design operating conditions has been calculated to be 3.8 MW and 2.6 MW for the 500 MW_e and 200 MW_e plant, respectively. For each nozzle a wall slag layer at an average temperature of 1850°K was assumed. The calculated average wall heat loss for both nozzles is about 180 W/cm^2 with a maximum of about 240 W/cm^2 occuring in the region of the throat. The wall heat loss is absorbed by the high-pressure boiler feedwater which is circulated through the cooling passages at sufficient high velocity to provide the necessary heat transfer. Pressure in the cooling system is maintained at a sufficiently high level to avoid local boiling.

3.5 DIFFUSER AND TRANSITION SECTION

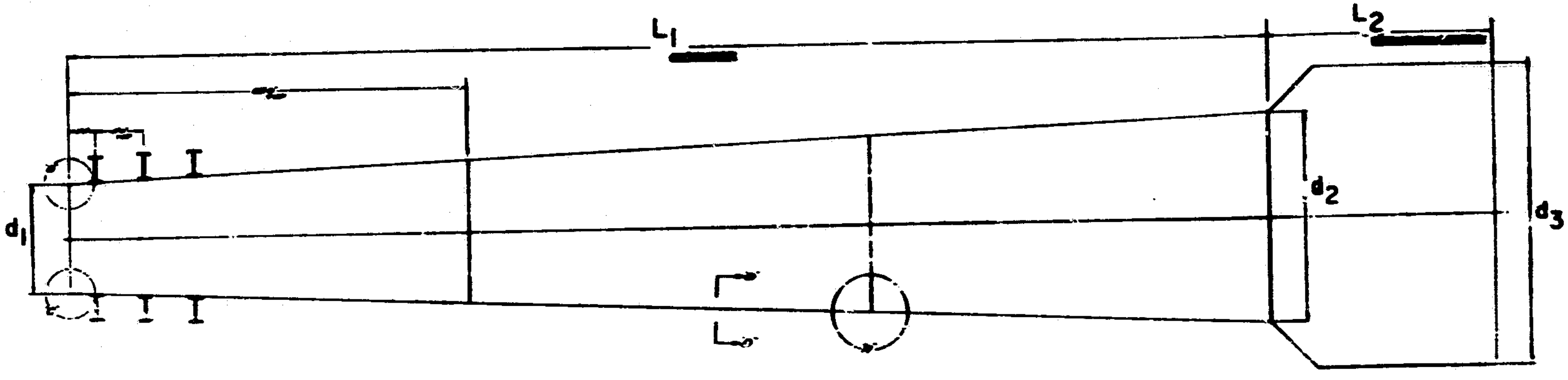
The primary function of the diffuser and transition section is to efficiently decelerate the high velocity gas exiting from the MHD generator channel. The diffuser must also provide acceptable gas entry conditions to the bottoming plant HRSR system. This requires that the gas is decelerated to a velocity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

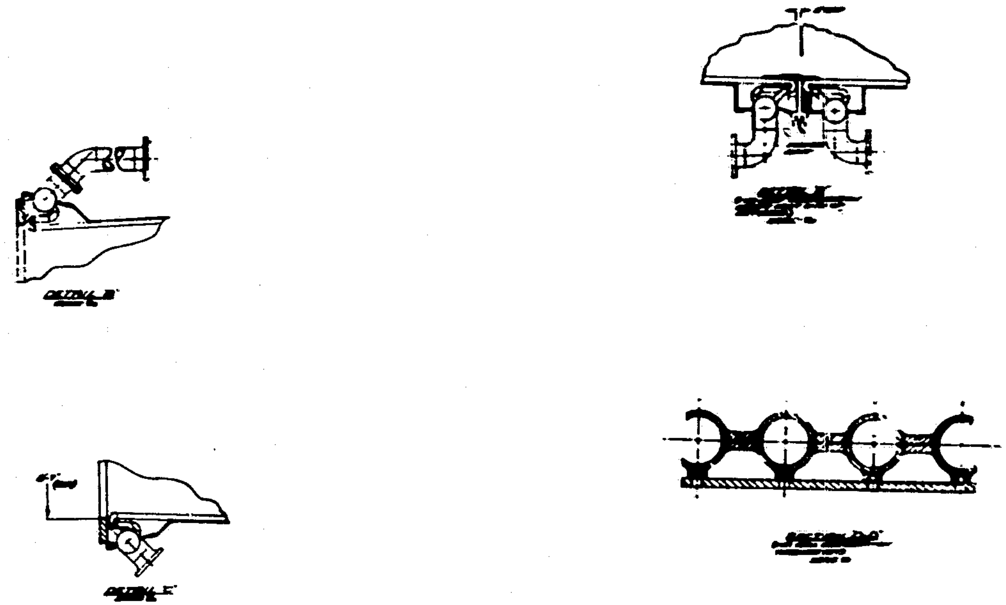
The geometry selected for the diffuser is based upon the limited data available for diffuser performance with nonsymmetric flows having relatively thick boundary layers. The design consists of a two-dimensional diverging duct with plane walls having an exit to inlet area ratio of 4.0 and a wall half-angle of 2.5^o. A drawing of the proposed design with the principal dimensions for the 200 MW_e and 500 MW_e plants is shown in Figure 3-25.

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 regular 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^{o}K. The total heat loss from the diffuser and transition section was calculated to be 28.8 MW for the 500 MW_e plant and 13.5 MW for the 200 MW_e plant. 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 ~ 3.6 in. for the 500 MW_e plant and 2.5 in. for the 200 MW_e plant. This horizontal expansion along with a vertical downward thermal expansion of ~ 5 in. in the radiant boiler must be accommodated 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 3-25, it is proposed that expansion joints be placed between the first and





	200 MW_e	500 MW_e
d_1	1.39 m	2.02 m
d_2	2.62	3.84
d_3	3.28	4.62
L_1	14.1	20.85
L_2	3.2	4.5

Figure 3-25 Diffuser and Transition Section

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 accommodate the horizontal movement and hydraulic actuators to compensate for the vertical movement and to maintain proper alignment.

A weight summary of the primary materials used in the fabrication of the diffuser and transition sections is given in Table 3-8.

TABLE 3-8

DIFFUSER AND TRANSITION SECTION WEIGHTS

	$200\ MW_e$	$500\ MW_e$
Stainless Steel Plate	3,500 lbs	7,000 lbs
Carbon Steel Plate	22,000	48,000
Coolant Tubing	28,000	61,000
Coolant Manifolds	13,000	28,000
I-Beams	9,500	21,000
	76,000 lbs	165,000 lbs

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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 with extremes in gas temperatures, composition and solids loading. 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 cirulation multi-chamber 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°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°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 chanber 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 soot blowers. 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. Materials suitability in the reducing or seed-laden MHD environment is still not verified. The materials selections for these conceptual designs are preliminary pending results of the materials evaluation of the HRSR program.

5) <u>System Operating Conditions</u> - The design is based on steam turbine inlet conditions of 2400 psia/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.

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

The basic steam generator configuration is the same as that used for the larger 950 MW_e plant in Task II which is shown in Figure 3-26. The outlines of the steam generators for the 500 MW_e plant and 200 MW_e plant are shown schematically in Figures 3-27 and 3-28. Data for the heat absorbing surfaces are summarized in Table 3-9. Surface assembly details for the 200 MW_e unit are presented in Table 3-10.

3.6.1.2 Radiant Slag Furnace

The slag furnace chamber is designed to cool the MHD gas in a controlled manner from the diffuser exit temperature of 3744°F for the 200 MW_e plant and 3721°F for the 500 MW_e plant to 2900°F. This chamber has a wetbottom and is lined with a high alumina refractory (1-4 in. thick). Its dimensions are 30 ft x 30 ft x 80 ft for the 200 MW_e plant design and 38.5 x 38.5 ft x 96 ft for the 500 MW_e plant design. The gas enters horizontally through a single opening near the bottom of the chamber and moves upwards at a velocity of about 30-35 fps. The average uniform gas cooling rate will be less than 400°F/sec, which will provide a gas dwell

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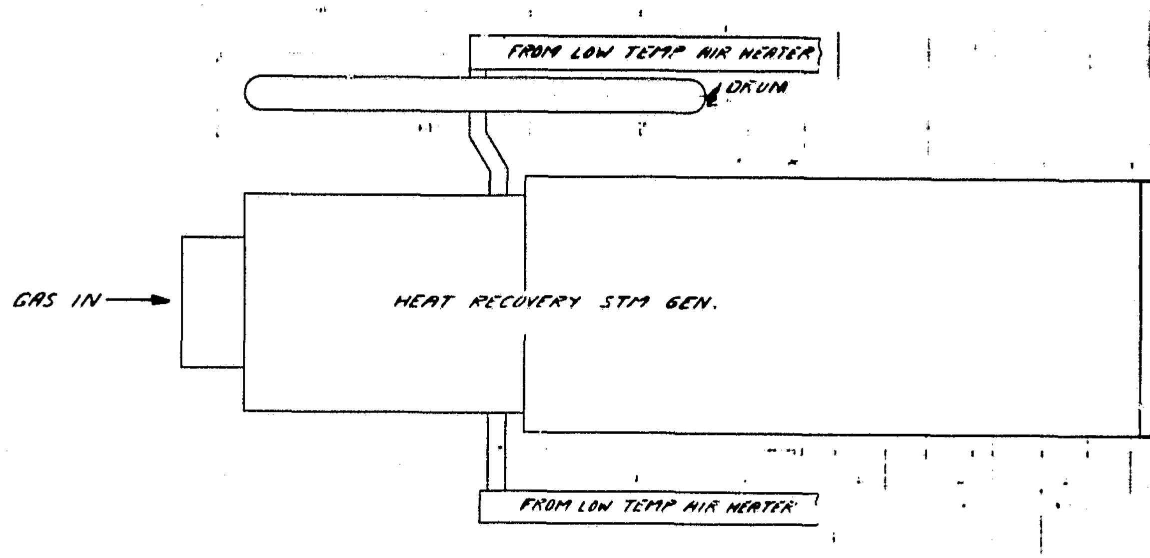

Figure 3-26 Typical Stream Generator Pl

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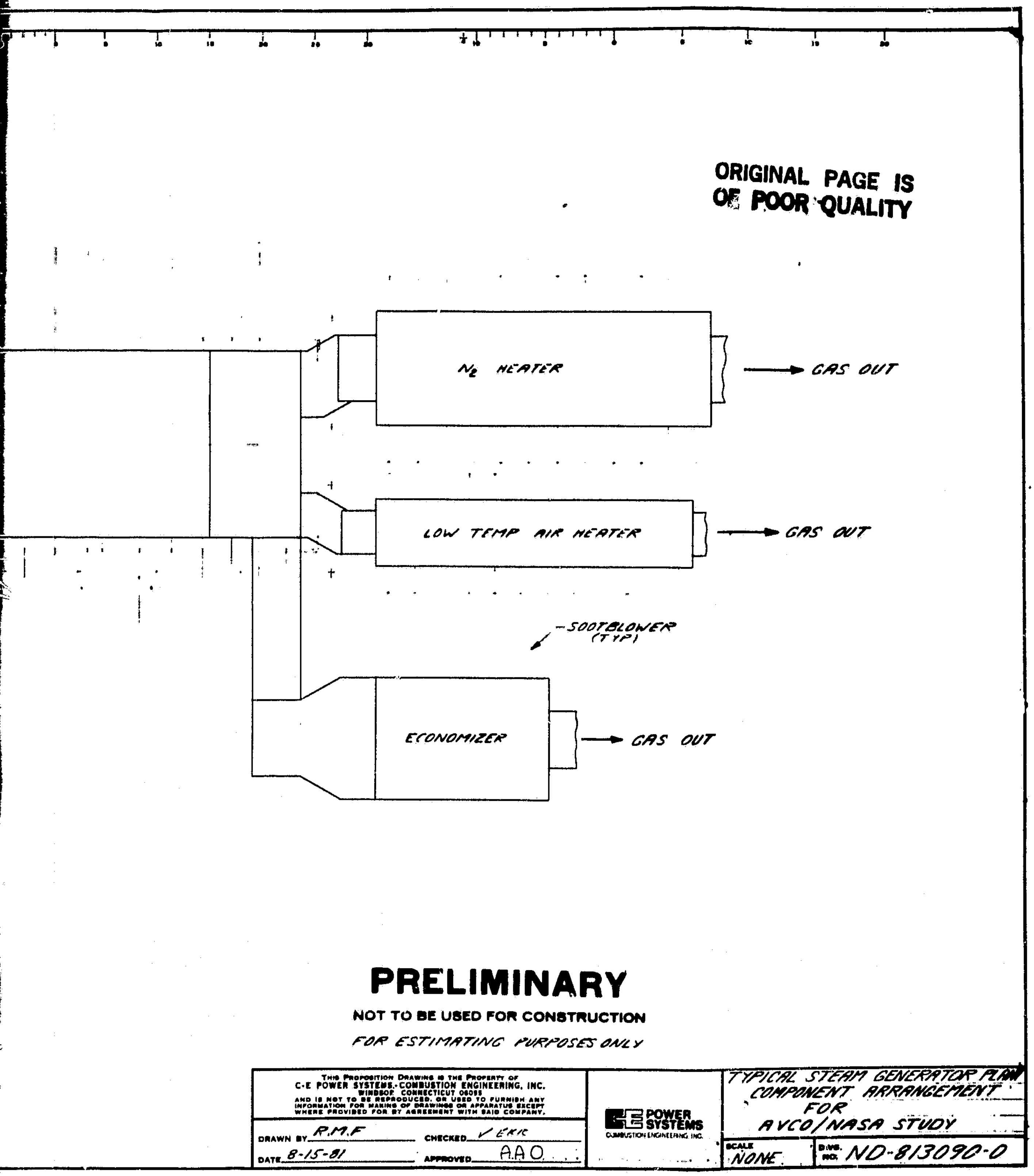

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eam Generator Plant Component Arrangement

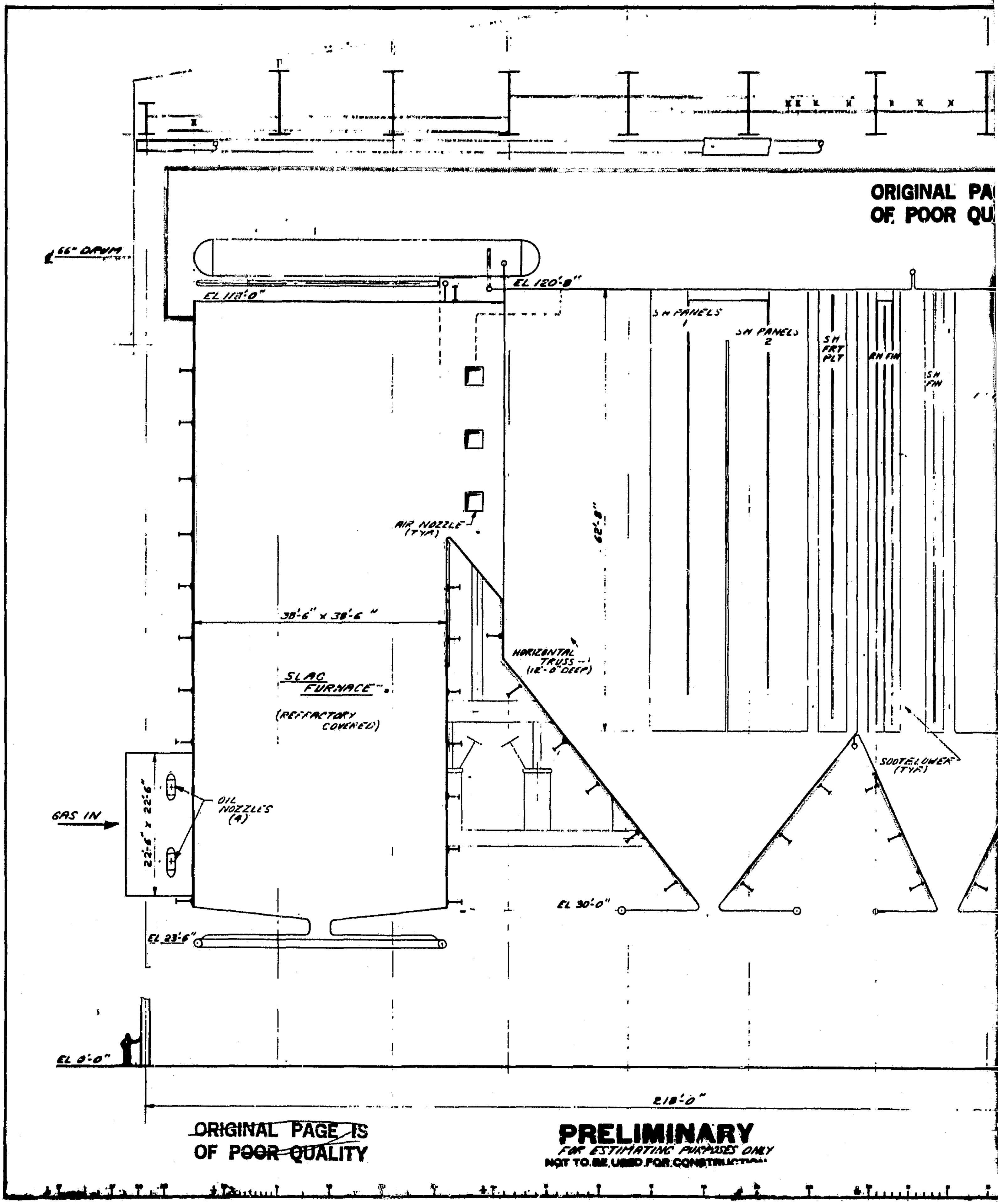

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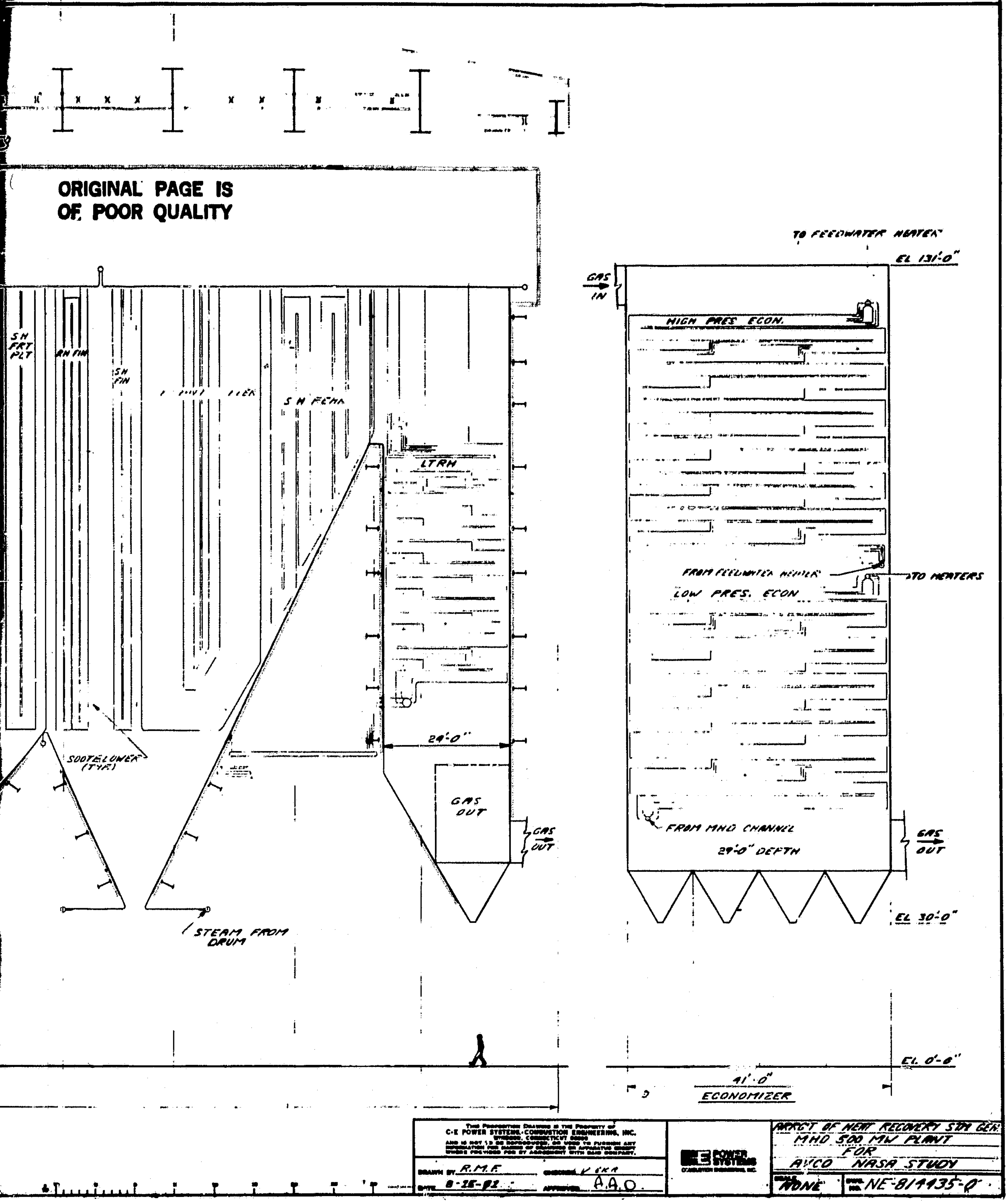
Figure 3-27 Arrangement of Hea
for 500 MW_e MHD Pl



angement of Heat Recovery Steam Generator
500 MW_e MHD Plant

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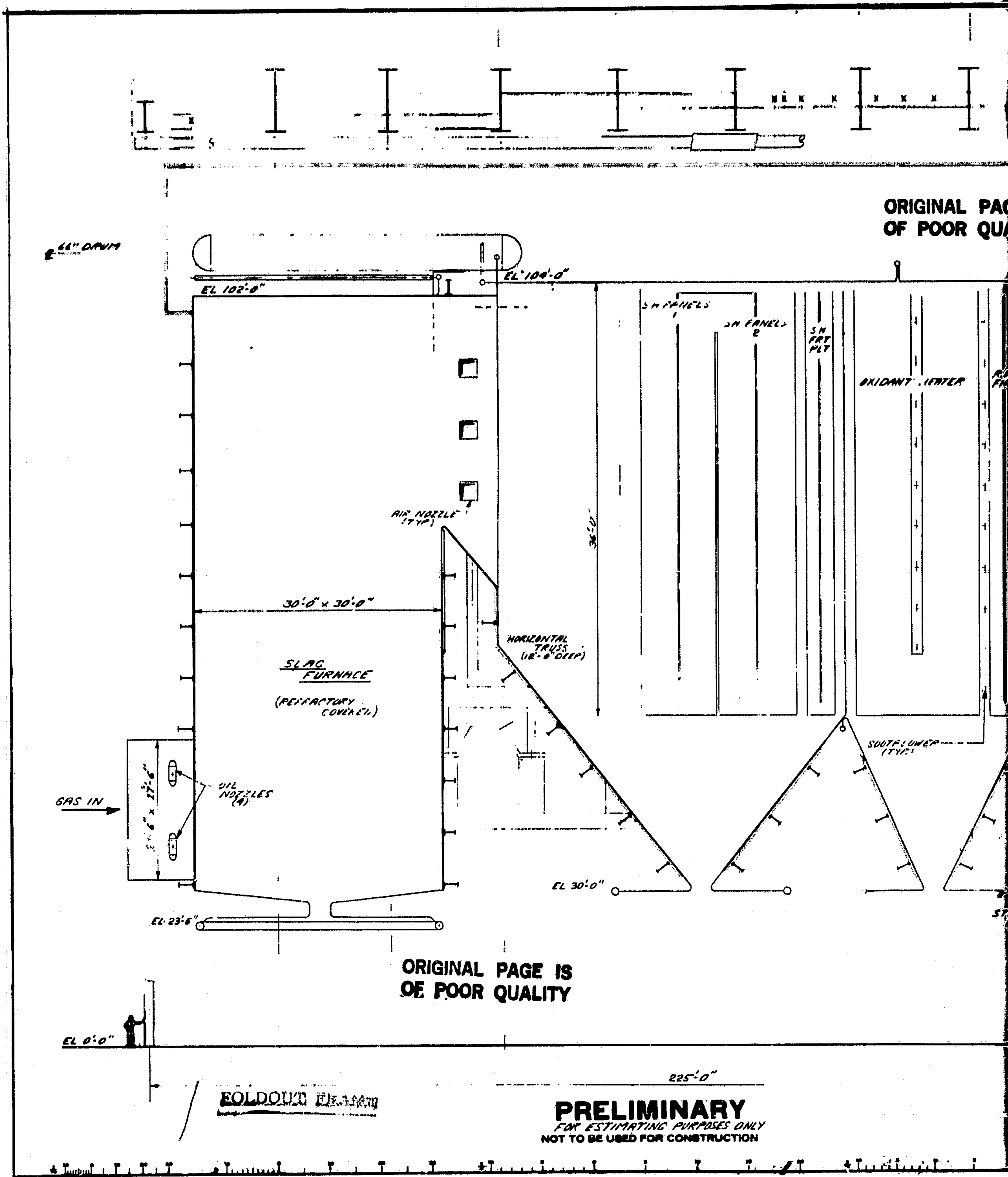
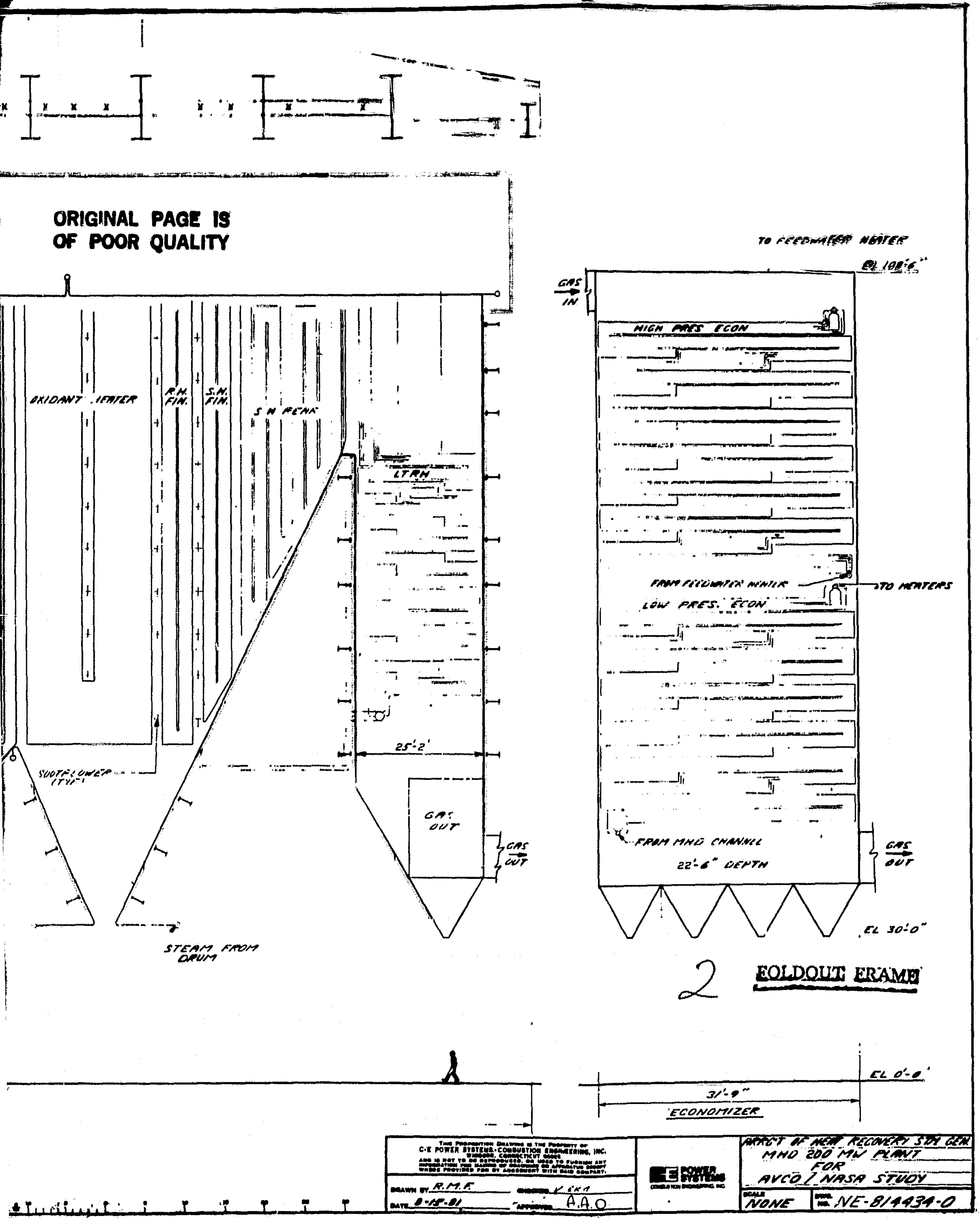


Figure 3-28 Arrangement of Heat R
for 200 MW_e MHD Plant



ment of Heat Recovery Steam Generator
) MW_e MHD Plant

TABLE 3-9

STEAM GENERATOR DESIGN SUMMARY

Section	Surface, Ft^2 500 MW_e	Surface, Ft^2 200 MW_e	Material
Superheater	171,716	88,122	192, 213T22, 213T11, 213 TP347H
Reheater 213TP	155,475	109,620	192, 213T22, 213T9, 304H
Oxidant Heater	172,749	26,000	192, 213 T22, 213TP 304H Incoloy 800
Economizer	244,037	109,241	192
Low Temp. Air Heat	166,312	74,425	192
Low Temp. N_2 Heat	309,955	128,705	192
Evaporator and Steam Cooled Walls	17,576		210C

TABLE 3-10

STEAM GENERATOR ASSEMBLY DETAILS

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

SRS - Seed Recovery Section

CS - Convective Section

RP - Rear Pass

E - Economizer Section

LA - LT Air Section

LN - LT N_2 Section

*Figures in parenthesis apply to 500 MW_e plant only.

time above 2900°F of about two seconds to ensure NOx emission control. The waterwalls are formed by 2 in. OD SA210C carbon steel tubes fusion welded on 2-1/2 in. centers, with aluminizing on the furnace side for corrosion protection.

Four oil guns (415 x 10^6 Btu/hr for the 200 MW_e design or 925 x 10^6 Btu/hr for the 500 MW_e design) 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 warm up the steam generator. Consideration will 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 (Final Oxidation and Seed Condenser)

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 nearly instantaneous at these temperatures. The final flue gas composition contains 5% excess air.

The gas mixture enters the secondary section through an 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 and sent on for seed reprocessing.

The waterwalls are formed by 2 in. OD SA210C carbon steel tubes fusion welded on 2-1/2 in. centers. The tubes will be ~ 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 for the 200 MW_e design, it passes over the oxidant preheat, finishing reheat, finishing superheat, and rear superheat surfaces prior to entering the rear pass. For the 500 MW_e design, the oxidant preheat section follows the finishing superheat section. The roof and walls are steam cooled.

C-2

It is expected that additional seed material will fall out of the gas stream throughout this section, 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 700-725F. At the rear pass exit, the gas splits into three streams. Roughly half 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 MHD gas to about 300 F. The economizer section also contains dry bottom hoppers and numerous sootblowers for removal and collection of the seed material that might adhere to the surfaces.

3.6.1.6 Low-Temperature Air and Nitrogen Heaters

The low-temperature air and nitrogen heaters, while not part of the main steam generator, operate in parallel with the economizer using the 700 F MHD exhaust gas. The air heater preheats ambient air to 600 F for completion of combustion in the steam generator. The nitrogen heater preheats nitrogen from the oxygen plant to 600 F to be used for coal drying. The MHD gas leaves the low temperature heaters at 200 F and mixes with the 300 F gas leaving the economizer section to produce a gas cleanup inlet temperature of roughly 250 F.

The heaters are dry bottom sections and are equipped with numerous soot blowers for removal and collection of any seed material that might adhere to the surfaces.

3.6.1.7 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 seed recovery section; the front platen, also located in the seed recovery 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.

3.6.1.8 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 585 psig and 643°F for the 200 MW_e system and 445 psig and 587°F for the 500 MW_e system. After leaving the low-temperature section, the steam passes through the finishing section, leaving at 535 psig and 1000°F for the 200 MW_e system and 399 psig and 1000°F for the 500 MW_e system. Desuperheat capability, with up to 75°F temperature control, is provided at the inlet to the low temperature section.

3.6.1.9 Oxidant Preheater Design

The oxidant preheater, located in the convective section, is designed to preheat the oxygen-enriched air for the primary combustor. The oxidant, at the compressor outlet condition of 5.6 atm and 466°F for the 200 MW_e system, and 7.7 atm and 554°F for the 500 MW_e system, enters and leaves the preheater through the manifolds at the top of the unit. The preheater outlet temperature is 1200°F. In the 500 MW_e plant design as in the original 950 MW_e plant design, the oxidant preheater is located after the finishing superheat and reheat sections. In the 200 MW_e plant design, the oxidant preheater was relocated ahead of the finishing sections. Because of possible high metal temperatures in this parallel flow preheater, high-temperature Incoloy 800 steel is specified for some sections.

3.6.1.10 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/270°F into the low-pressure section and 3000 psig/440°F into the high-pressure section.

3.6.1.11 Low-Temperature Air and Nitrogen Heater Design

The low-temperature air and nitrogen heaters shown in Figures 3-29 and 3-30 are located behind the steam generator rear pass section and are designed to preheat ambient air and nitrogen to about 600°F for burnout and coal drying, respectively. 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.

3.6.1.12 Instrumentation and Controls

The steam generator for the MHD Commercial Plant is a balanced draft, controlled circulation unit with reheat. The steam generator recovers rejected heat energy from the high-temperature channel exhaust gas thereby increasing the overall cycle efficiency. Other than during warmup, there will be no conventional fuel input to the boiler. The electric load will be shared between the MHD channel and the turbine generator and the load must fluctuate in unison.

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 Furnance Draft Controls

The furnace will be a balanced draft unit: the oxidant compressor will be the equivalent of the FD fan; the furnace draft will be controlled by the ID fan. A conceptual schematic is shown in Figure 3-31.

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 setpoint.

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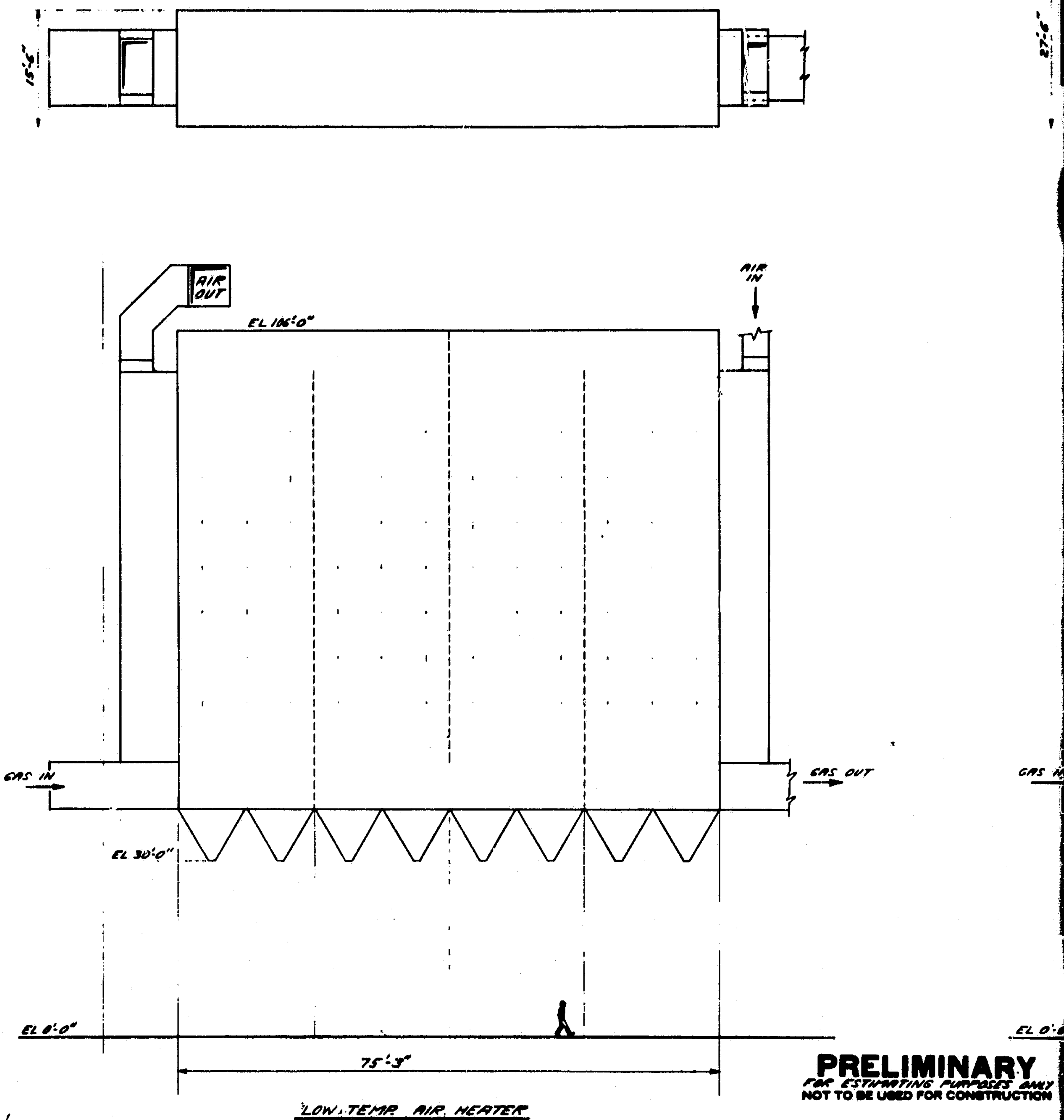

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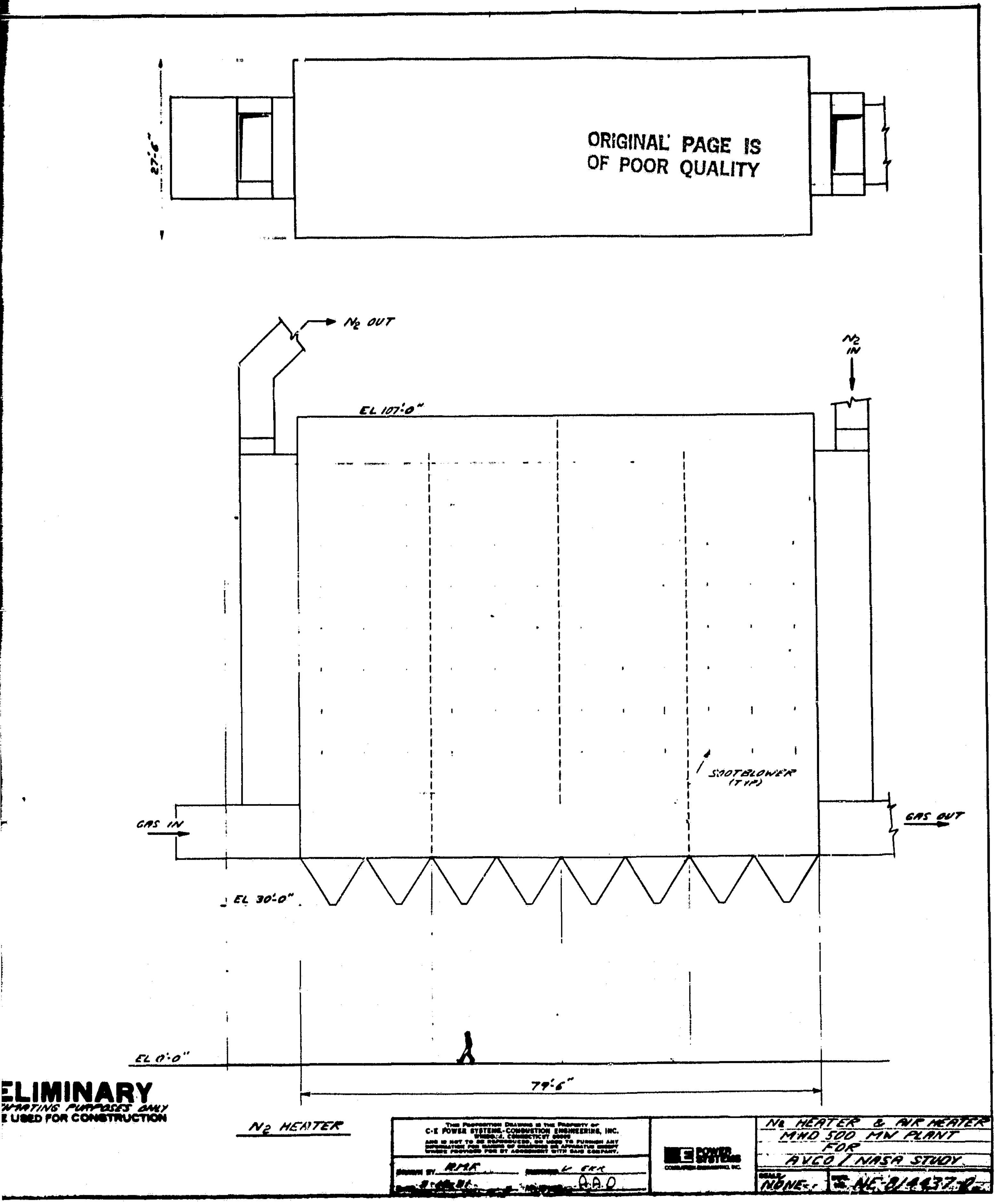
Figure 3-29 N_2 Heater and Air He



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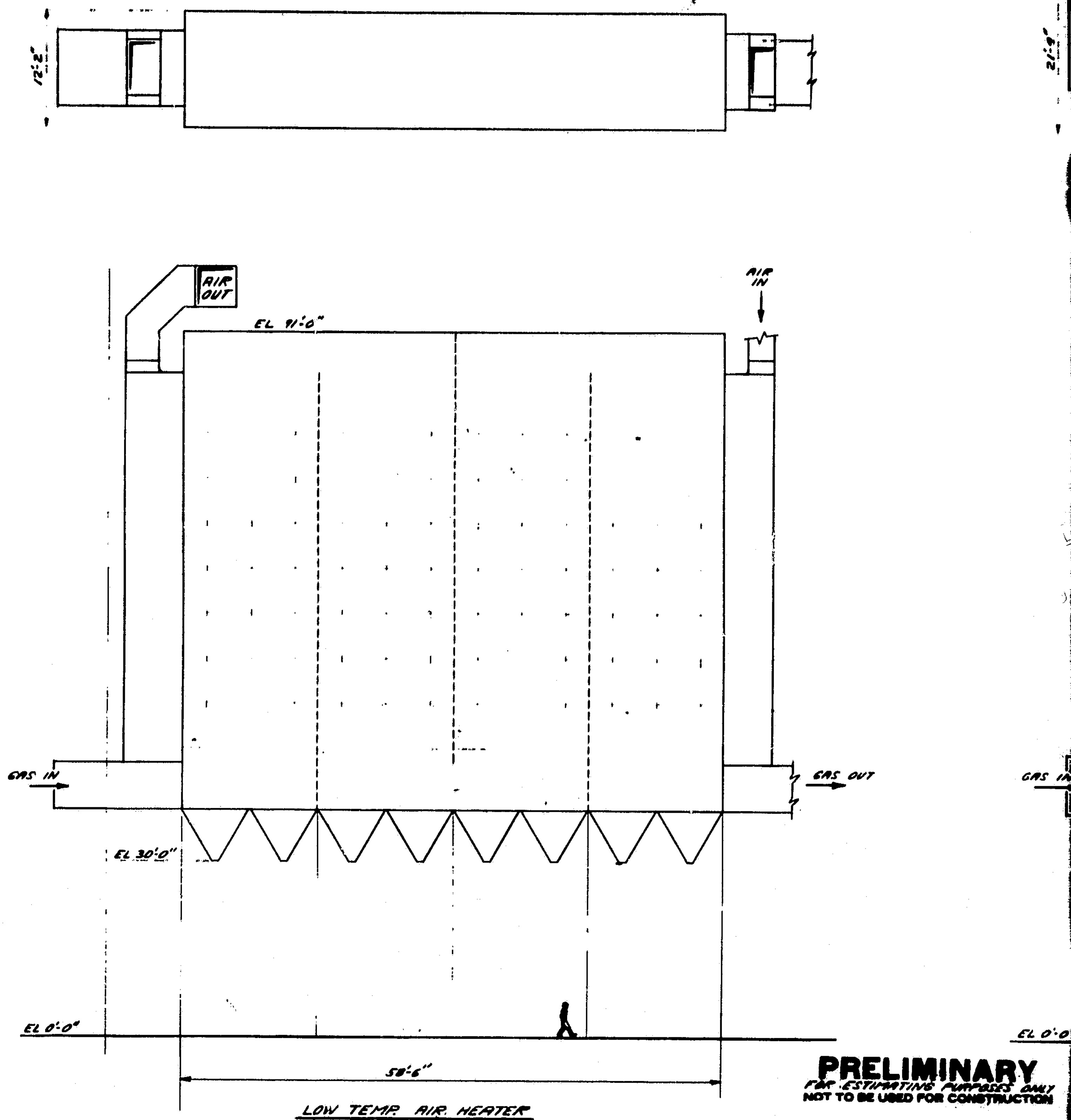

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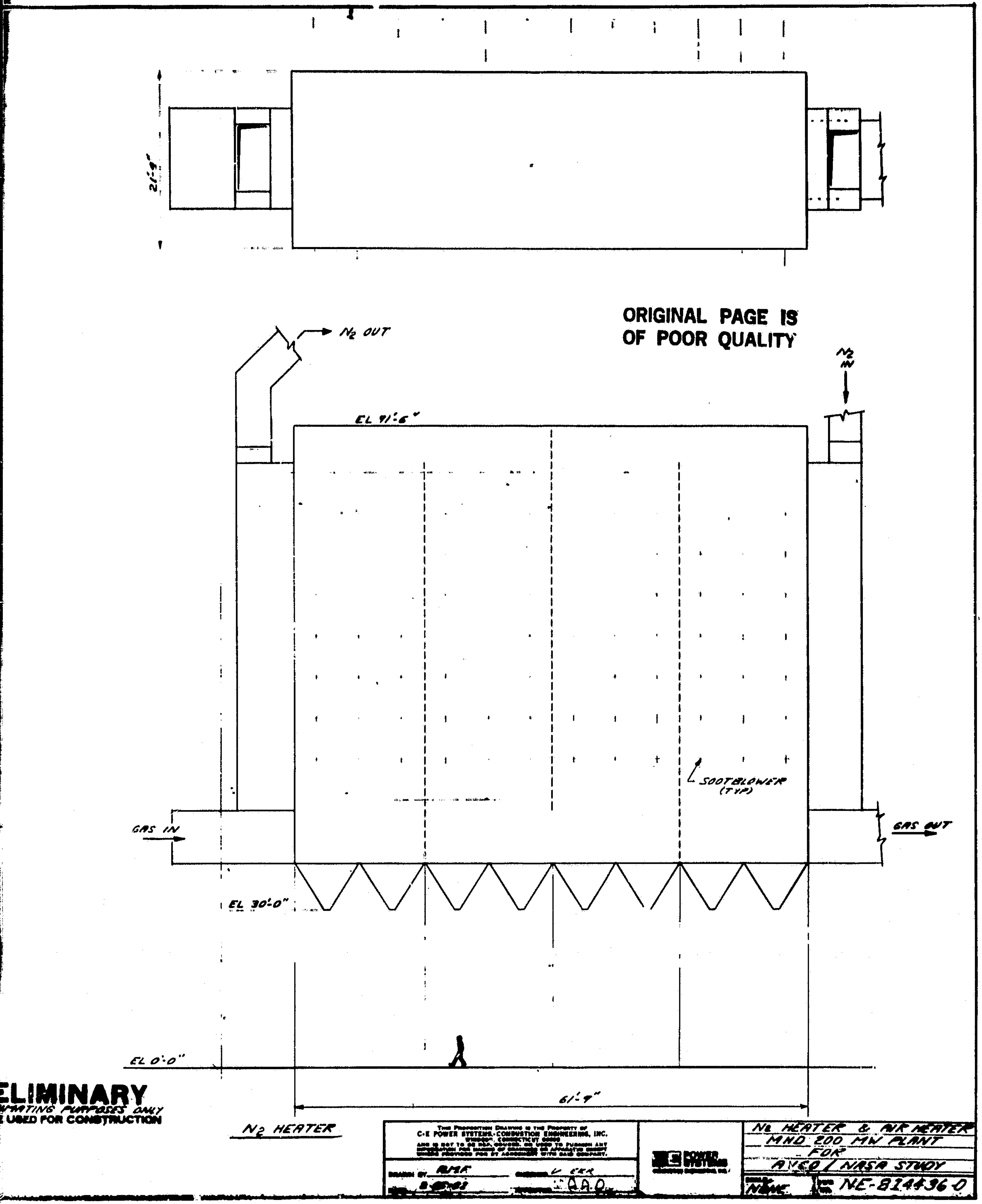
Figure 3-30 N_2 Heater and Air Heate



r and Air Heater for 200 MW_e MHD Plant

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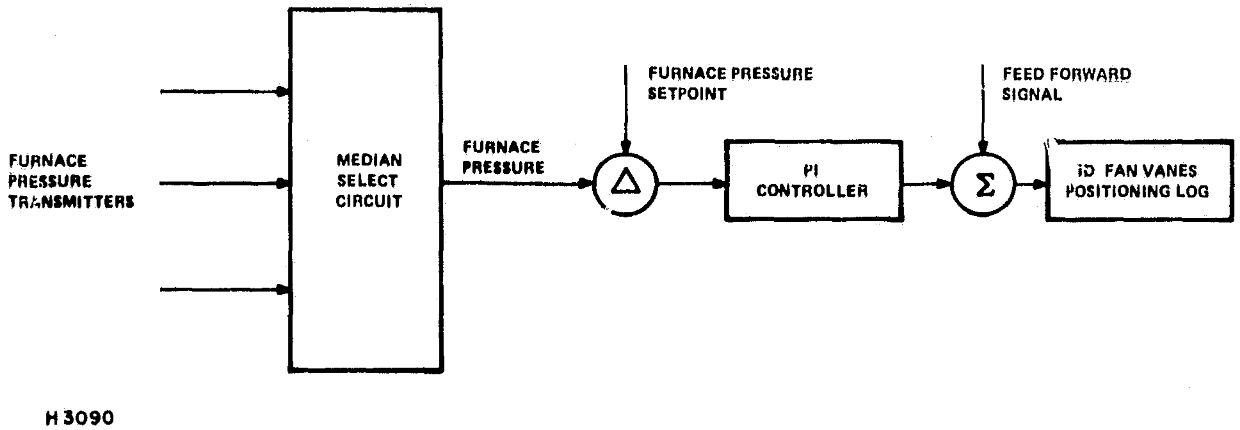

Figure 3-31 Furnace Draft Control

The furnance 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.

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 to the furnace will drop in temperature abruptly. Thus, the 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 3-32.

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 measurement 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.

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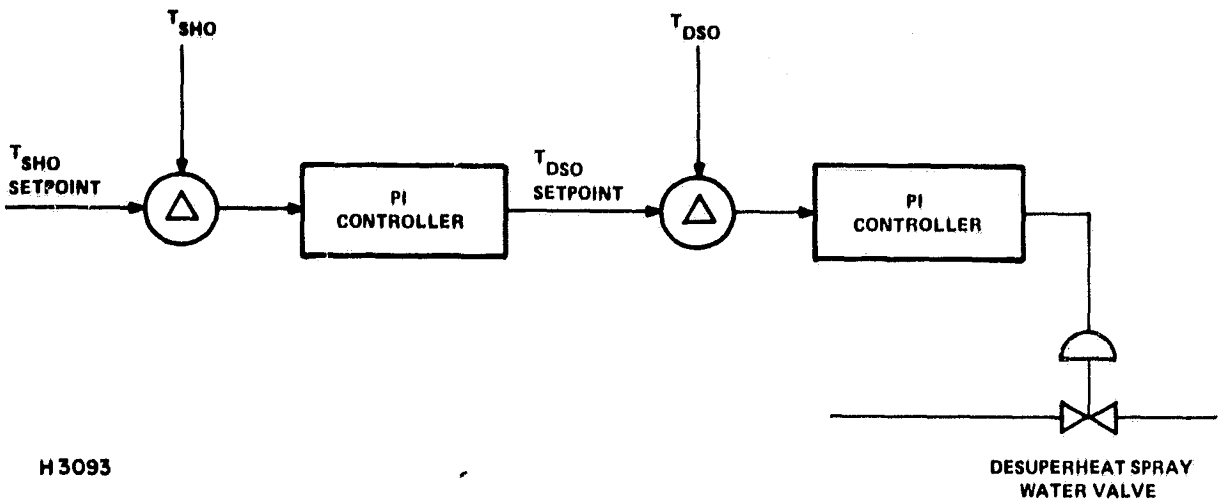

Figure 3-32 Steam Temperature Control

3.6.1.1.16 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.

Four oil guns, located in the walls of the refractory-lined furnace, will be provided to warmup the refractory prior to starting the MHD system. Each gun will be capable of firing 105×10^6 Btu/hr of atomized No. 2 oil for the 200 MW_e design (230×10^6 Btu/hr for the 500 MW_e design). There will be four air atomized ionic flame monitor ignitors and four flame scanners.

Thermocouples will be used to monitor refractory temperatures during the warmup. Warmup will include synchronizing the turbine-generator and carrying up to 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 pulverizer coal being fired in the primary 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 channel, air flow will be trimmed by an O_2 measurement in the exhaust gas.

Figure 3-33 shows conceptually how the combustion control system will operate.

3.6.1.17 Feedwater Controls

The feedwater control system will be a standard three-element feedwater control system. The feedwater flow is adjusted to maintain drum level at setpoint as shown conceptually in the diagram of Figure 3-34.

3.6.2 Stack Gas Cleaning

The particulate removal system was designed such that the total plant particulate emissions would be below the $0.03 lb/10^6$ 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.

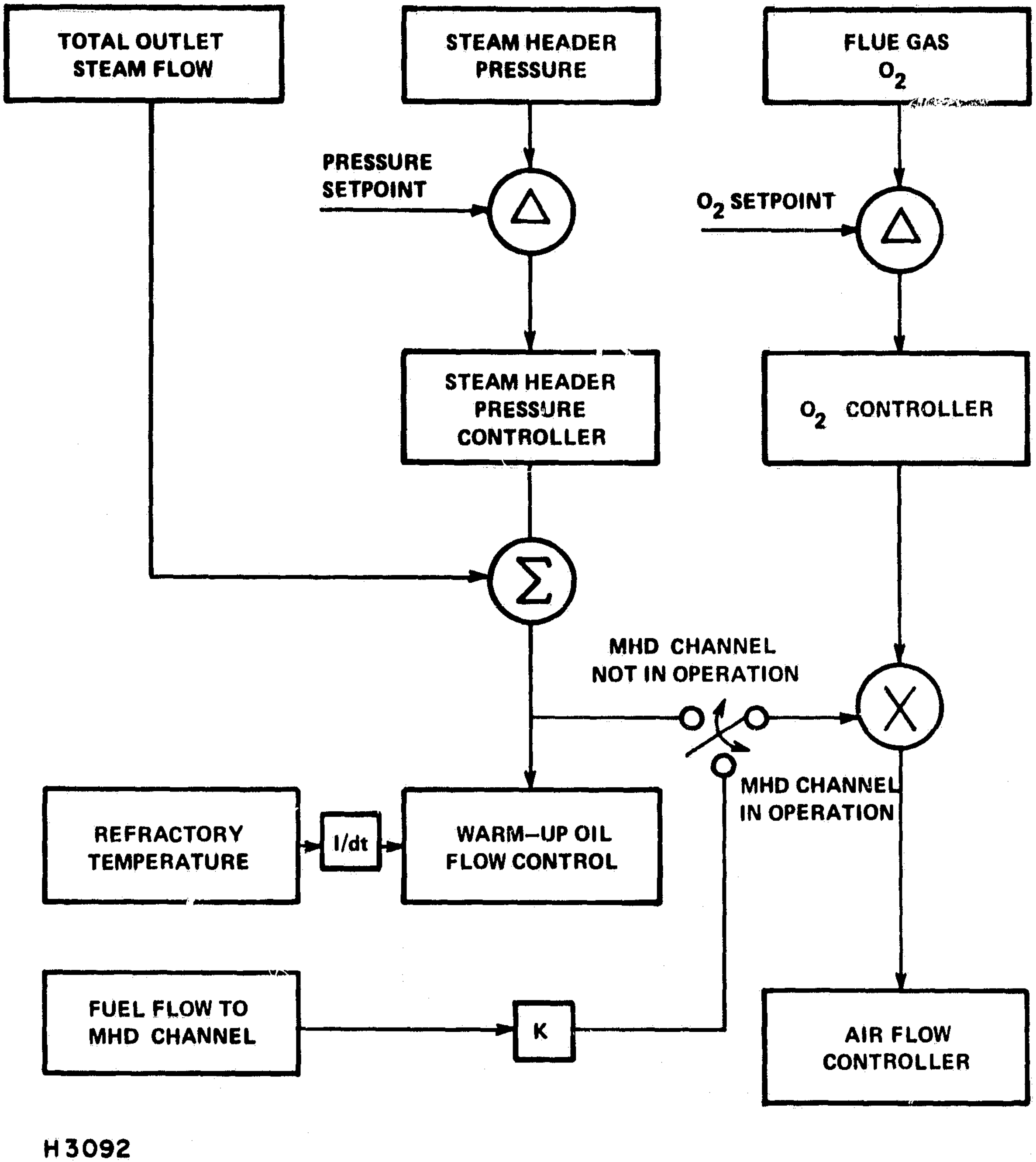

Figure 3-33 Combustion Controls

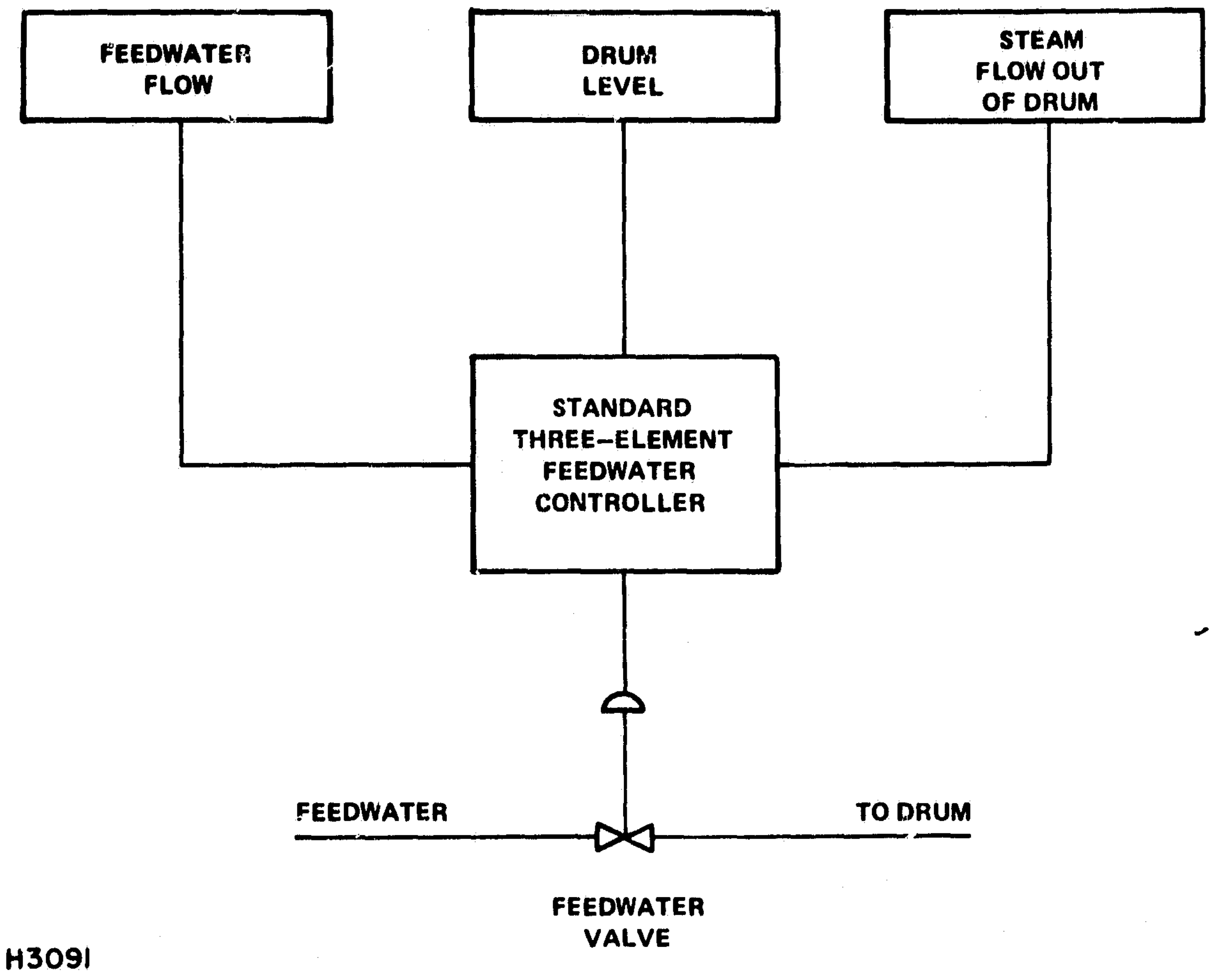

Figure 3-34 Feedwater Controls

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

3.6.2.1 ESP Design

The ESP was designed for a collection efficiency of 99.83% with a gas flow of $\sim 0.36 \times 10^6$ ACFM for the 200 MW_e system and 0.77×10^6 for the 500 MW_e system. A preliminary design for the 200 MW_e system is shown in Figure 3-35. Design details are shown in Table 3-11.

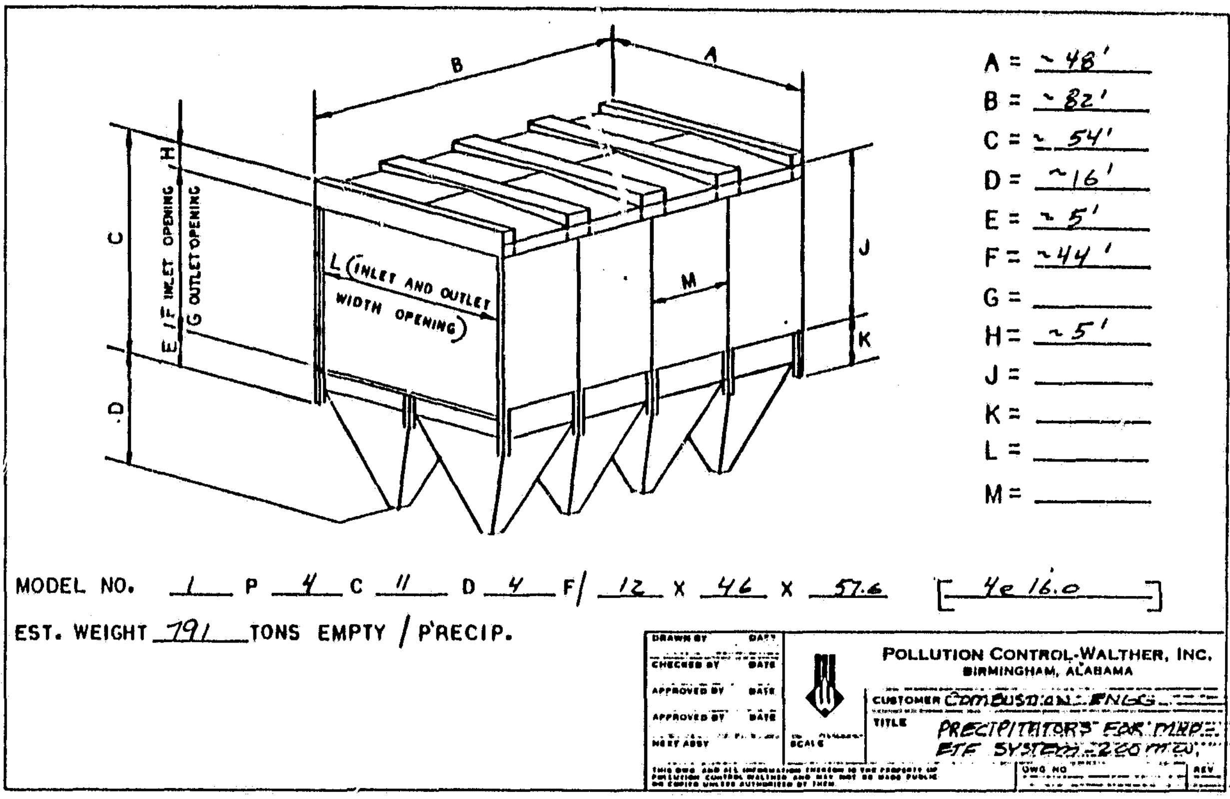

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Figure 3-35 Precipitators for MHD-ETF System 200 MW_e

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TABLE 3-11

ELECTROSTATIC PRECIPITATOR DESIGN DETAILS

Gas Volume	358,300 ACFM @ 250°F
Efficiency	99.83%
Model Number	1P4C11D4F/12 x 46 x 57.6 @ 14.4)
No. of Precipitators	1
No. of Chambers/Precipitator	1
No. of Ducts/Precipitator	44
Duct Spacing	12 in.
No. of Fields	4 @ 14.4 in. each
Total Collecting Plate Area	233,165 ft^2
Total Discharge Electrode Length	137,808 ft
No. of T/Rs	8
SCA	651
Migration Velocity	4.93 cm/sec
Gas Velocity	3.95 ft/sec
Total Expected T/R Power Consumption	363 kW
Total Approximate Precipitator Weight	1,713,000 lb

3.7 STEAM TURBINE-GENERATOR

The steam turbine for the electric generator receives superheated steam from the convective section of the heat recovery steam generator. In the 500 MW_e plant main steam is also supplied to the turbine drivers for the cycle air compressor and the oxygen plan air compressor. In the 200 MW_e plant, the steam supply to these compressor turbine drives is crossover steam taken between the reheat and low-pressure sections of the main steam turbine. The steam turbine-generator is rated at $\sim$ 267 MW_e in the 500 MW_e plant, and $\sim$130 MW_e in the 200 MW_e plant.

The turbine selected is 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 in the 500 MW_e plant has been arranged for six turbine extraction points. Feedwater is heated by extraction steam in the five closed feedwater heaters and one deaerating feedwater heater, and heat is recovered from MHD components and in the high and low-pressure economizers to heat the feedwater to within 50°F of the boiler drum saturation temperature at full load.

The steam cycle in the 200 MW_e plant includes three closed feedwater heaters and one deaerating feedwater heater. Heat is also recovered in the MHD components and the low and high-pressure boiler economizers to raise feedwater temperature to within 50°F of boiler drum saturation temperature at full load.

Steam for the turbine driven boiler feed pump is taken from the crossover between the intermediate and low pressure turbines for both the 500 MW_e and 200 MW_e plants.

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 275°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.

3.8 CYCLE COMPRESSOR AND 'RIVE

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

The air compressor flow rate $\sim$ 1.7 x (10^6) lb/hr for the 500 MW_e plant. The pressure ratio is 7.70, and the power required to drive the compressor is 57.7 MW. The compressor is a multistage axial flow machine without intercooling.

The air compressor flow rate is $\sim$ 0.80 x 10^6 lb/hr for the 200 MW_e plant. The pressure ratio is 5.56, and the power required to drive the compressor is 22 MW. Similar to the 500 MW plant, the compressor for the 200 MW_e plant will be an axial flow machine without intercooling.

Manufacturers have indicated that due to the high work per stage, blades other than what are now standard will be required for these machines. In addition, the downstream portion of the compressor casing will be steel rather than cast iron to accommodate the higher discharge temperature.

For both the 500 MW_e and 200 MW_e plants, 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 $\sim$ 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 low 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 backpressure of 2 in. HgA. The turbine throttle conditions are 2400 psig, 1000°F for the 500 MW_e plant. For the 200 MW_e plant, steam to the compressor turbine drive comes from the crossover between the intermediate pressure and low pressure sections of the main turbine. Throttle conditions are 150 psig, 710°F at full load.

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3.9 COAL DRYING, PULVERIZING, AND FEEDING

The coal drying, pulverizing, and feeding system will be required to handle nearly 200,000 pph of Montana Rosebud sub-bituminous coal for the 200 MW_e system (445,000 pph for the 500 MW_e system). A typical equipment arrangement schematic is shown in Figure 3-36.

The coal will be thermally dried from the as-received condition of 23% moisture to 5% moisture using preheated nitrogen 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 C-E supplied bowl mills (963 RP bowl mills with 600 HP/900 rpm motors for the 200 MW_e design; #1003 RP bowl mills with 600 HP/900 rpm motors for the 500 MW_e design) 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 cylcone 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 full load running to provide for temporary outages or overload operation.

For operation of the MHD combustor, the coal must be delivered against a pressure of ~ 5.25 atm for the 200 MW_e design and 7.25 atm for the 500 MW_e design. To accomplish this, the Petrocarb Lockhopper 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.

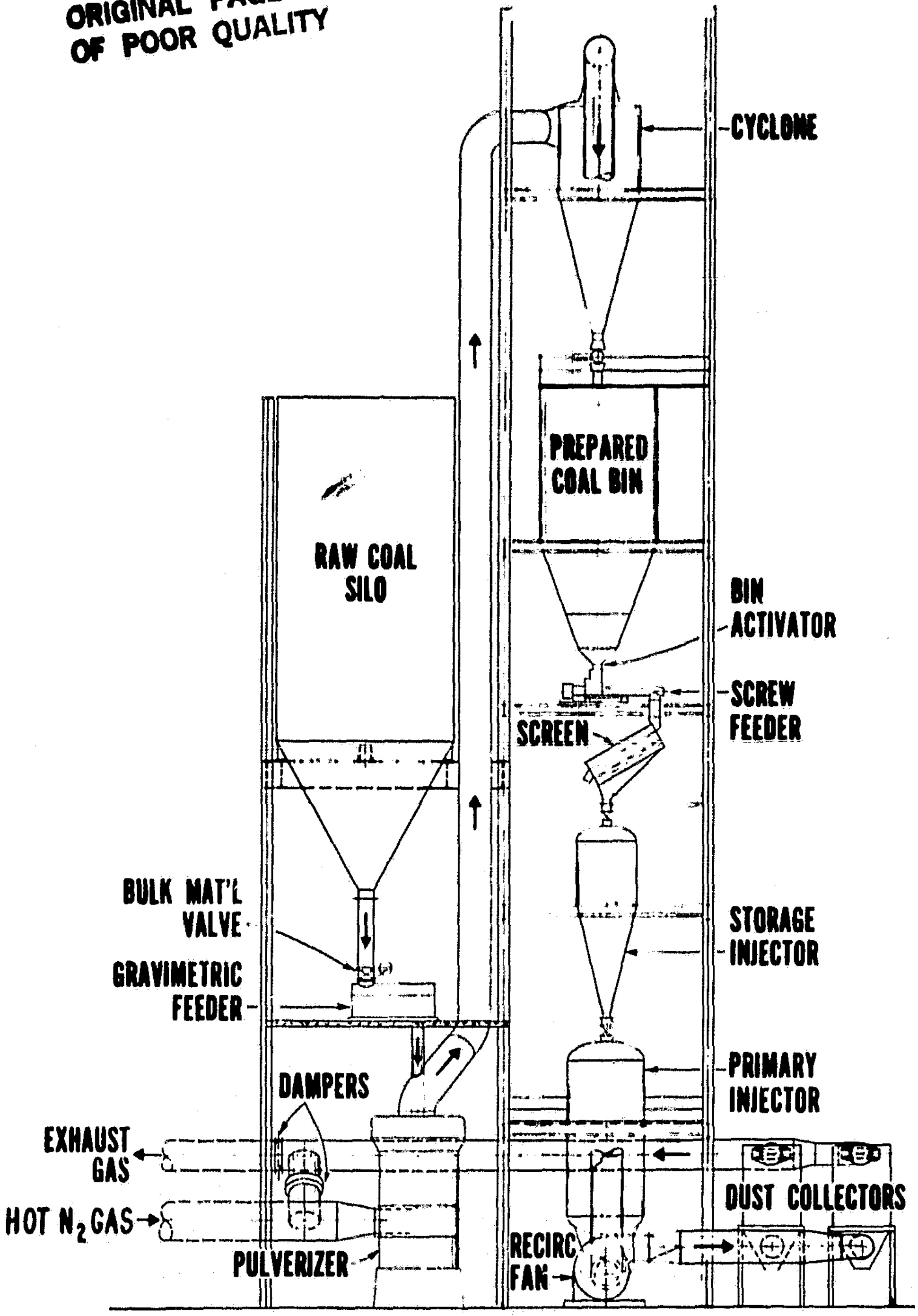

Figure 3-36 Arrangement of Coal Processing Equipment

The 200 MW_e system consists of two bowl mills (plus one spare) feeding into two pressurized feed trains. The 500 MW_e system consists of four bowl mills (plus one spare) feeding into two pressurized feed trains. The drying gas will be passed through a baghouse filter prior to being sent to the stack.

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3.10 SEED MANAGEMENT AND PROCESSING

3.10.1 Seed Management

Seed recovery and management were incorporated as part of plant and equipment design in a similar manner as in the Task II plant design. For a general description of this, reference is made to Subsection 3.10.1 of the Task II Report (Reference 2). 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 for both plant sizes considered here.

Table 3-12 lists data of seed and sulfur mass flow rates for 70% sulfur removal. The seed regeneration process considered is the formate process (see Subsection 3.10.2), which is the same as shown in previous Task I and Task II plant designs.

Pertinent seed and ash flow rates in the system for 70% (NSPS) sulfur removal are listed in Table 3-13. For 70% sulfur removal about one-third of the recovered seed is processed. The remaining two-third of the recovered seed with its ash impurities is considered recycled directly without processing. Seed losses and makeup requirements are presented in Table 3-14. The calculated loss of potassium seed in liquid slag removed from primary radiant boiler furnace is based upon 15% K_2O dissolved in this slag. For the remaining ash 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.[6] 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.

One percent loss has been assumed for the amount of seed processed for 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 adds up to 5.5% 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

TABLE 3-12

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

Plant Size		500 MW_e	200 MW_e
Coal:			
Coal Flow Rate (5% Moisture)	pph	361,871	161,939
Sulfur in Coal	pph	3,780	1,692
Sulfur Required Removed	pph	2,646	1,184
Sulfur Input	lb SO_2/MBtu	1,905	1,905
Seed:			
Potassium Seed Flow Rate (1%K)	pph	20,390	9,566
All Seed as K_2SO_4	pph	45,435	21,315
K Required for S-Removal	pph	6,453	2,887
KCO_2H Produced for Recycle	pph	13,883	6,212
K_2SO_4 Recycled	pph	31,055	14,880
Sulfur in Stack Gas(s)	pph	1,134	508
SO_2 in Stack Gas	pph	2,266	1,016
SO_x Emission	lb SO_2/MBtu	0.57	0.57

TABLE 3-13

SEED AND ASH MASS BALANCES FOR HRSR SYSTEM
FOR 500 MW_e AND 200 MW_e PLANT SIZES

Sulfur Removal (NSPS)	%	500 MW_e 70	200 MW_e 70
Raw coal feed rate to MHD burner	pph	361,870	161,939
Ash contained in MHD burner coal feed	pph	38,690	17,315
Seed feed rate (as K_2SO_4)	pph	45,435	21,315
MHD coal combustor ash removal	%	80	80
Total amount of ash to bottoming plant*	pph	12,770	5,715
Slag removed in primary boiler furnace (40%)	pph	5,110	2,285
Seed loss in slag from primary boiler furnace (maximum):**			
as K_2O	pph	770	345
converted to K_2SO_4	pph	1,425	638
as percent of total	%	3.1	3.0
Seed and ash removed in balance of boiler: (30%)			
Seed as K_2SO_4	pph	13,200	6,200
Ash	pph	2,300	1,060
Seed and ash removed in ESP: (99.83%) eff.)			
Seed	pph	30,758	14,952
Ash	pph	5,350	2,470
Particulates in stack gas with 99.83% ESP eff.:	pph	62	29
as lb/MBtu coal input to MHD combustor		0.016	0.016
Seed loss in stack gas with 99.83% ESP eff.:			
as K_2SO_4	pph	52	25
as percent of total	%	0.11	0.12

*Includes ash impurities contained in recycled seed.

**Based on 15% K_2O in slag.

TABLE 3-14

SEED LOSS AND MAKEUP REQUIREMENTS

Basis: 70% Sulfur Removal (NSPS)

	Percent of Total Seed
Seed loss with slag (15% K_2O in slag)	3.1
Seed loss with fly-ash (17% K_2O in fly-ash)	2.1
Seed loss in seed regeneration process (99% eff.)	0.3
	5.5
Seed supplied with coal ash (0.55% K_2O in ash)	0.5
Makeup Required	5.0
Contingency ($\sim$1/3 additional makeup)	1.6
Total makeup assumed	6.6

Makeup Requirement:

500 MW_e Plant Size: 3000 pph as K_2SO_4

200 MW_e Plant Size: 1405 pph as K_2SO_4

some makeup. Deducting this smaller amount, the total remaining seed makeup requirement is 5.0%. A contingency loss of about 30% of makeup requirements has been added which results in a total assumed makeup requirement of 6.6% or 3000 pph as K_2SO_4 for the 500 MW_e plant and 1405 pph as K_2SO_4 for the 200 MW_e plant. This corresponds to a total seed makeup cost of 0.30 mills/kWhr and 0.33 mills/kWhr for the two plants, respectively based on seed cost of $102/T K_2SO_4.

3.10.2 Seed Reprocessing

As in Task II of this study series, sufficient recovered seed (K_2SO_4) must be continuously reprocessed in a seed regeneration plant to a sulfur-free form for recycle into the combustion gas stream to meet sulfur removal requirements defined by air quality control regulations.

3.10.2.1 Design Criteria

3.10.2.1.1 Seed Flow Rates and Sulfur Removal

The coal feed rate to the MHD combustor is defined as 361,870 pph of Montana Rosebud Subbituminous at 5% moisture content for the 500 MW_e plant and 161,939 pph for the 200 MW_e plant. To meet current (NSPS) for sulfur dioxide (SO_2) emission, 70% of the sulfur introduced by the coal feed must be removed from the combustion gas stream. The stoichiometric equivalent quantity of recovered seed must be reprocessed. The conceptual design of the seed regeneration plant for both the 500 MW_e and 200 MW_e cases is based on this requirement.* Table 3-15 shows sulfur flow rates and resulting seed reprocessing requirements for both the 200 MW_e and the 500 MW_e units.

3.10.2.1.2 Seed Regeneration Process

The Formate Process developed in the ETF Conceptual Design Study is assumed for the Task III study, as generally described in the ETF Reference Systems Design Report and as specifically described in the Task II Report. In this process, reaction in an aqueous medium of potassium sulfate with lime and carbon monoxide is carried out at ~ 30 bar and 392°F to produce solubilized potassium formate and insoluable gypsum. The latter is removed by filtration and water is removed from the former by evaporation. Moisture-free potassium formate is stored in molten form for recycle to the MHD combustor.

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*For this study the sulfur dioxide emitted by the seed regeneration plant coal gasifier is not included in the requirements for the seed regeneration plant size.

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TABLE 3-15

SULFUR FLOW AND SEED REPROCESSING REQUIREMENTS

Basis: Montana Rosebud Subbituminous Coal (5% H_2O) 70% Sulfur Removal

500 MW_e

	pph	lb mol/hr	% Of Feed To Combustor	% Of Recovered Seed
Coal flow to combustor	361,870	-	100	-
Sulfur flow to combustor	3,780	117.90	100	-
Sulfur removal required	2,646	82.53	70	-
Seed flow to combustor				
computed as K	20,390	521.51	100	100
computed as K_2SO_4	45,435	260.72	100	100
Seed reprocessing flow				
computed as K	6,454	165.06	32	32
computed as K_2SO_4	14,383	82.53	32	32
computed as KCO_2H	13,885	165.06	-	-

200 MW_e

	pph	lb mol/hr	% of Feed To Combustor	% Of Recovered Seed
Coal flow to combustor	161,939	-	100	100
Sulfur flow to combustor	1,692	52.78	100	-
Sulfur removal required	1,184	36.93	70	-
Seed flow to combustor				
computed as K	9,566	244.67	100	100
computed as K_2SO_4	21,315	122.31	100	100
Seed reprocessing flow				
computed as K	2,888	73.86	32	32
computed as K_2SO_4	6,436	36.93	32	32
computed as KCO_2H	6,213	73.86	-	-

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3.10.2.2 Methodology

The process and equipment concepts devloped in the Phase II 900 MW_e conceptual design study (70% sulfur removal case) were applied directly. All mass and energy balance data, cost and space allocation estimates were obtained by scaling. It is assumed that commercial equipment can be obtained or built for all process requirements, including the coal gasification step.

3.10.2.3 Conceptual Design

3.10.2.3.1 Process Flow Diagrams

Figure 3-37 represents the basic flow diagram for the seed reprocessing system. Mass flows, enthalpies and states for the individual process streams are shown in Table 3-16 for the 500 MW_e plant, and Table 3-17 for the 200 MW_e plant. As in the Task II case, 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/slurrying to prepare the reactor solution,

4. reaction to produce the KCO_2H product,

5. filtration to separate the $CaSO_4 \cdot 2H_2O$ byproduct, and

6. drying to remove water from the KCO_2H product.

3.10.2.3.2 Overall Energy Requirements

The enthalpies of individual process streams are shown in the data which accompany Tables 3-16 and 3-17 for the 500 MW_e and 200 MW_e plants, respectively. A tabulation of the overall energy inputs and outputs for the process as a whole is shown in Table 3-18. As in the case of the Task II study, waste heat can be recovered from the waste heat boiler steam discharge (in excess of that required by the seed reprocessing plant) and from combustibles in the reactor off-gas.

For the 500 MW_e case these are 6.32×10^6 Btu/hr and 14.59×10^6 Btu/hr, respectively, or a total of 20.91×10^6 Btu/hr. For the 200 MW_e case these are 2.84×10^6 Btu/hr and 6.50×10^6 Btu/hr, respectively, or a total of 9.38×10^6 Btu/hr. Power requirements are ~ 3.9 MW_e and 1.8 MW_e for the 500 MW_e and 200 MW_e plants, respectively.

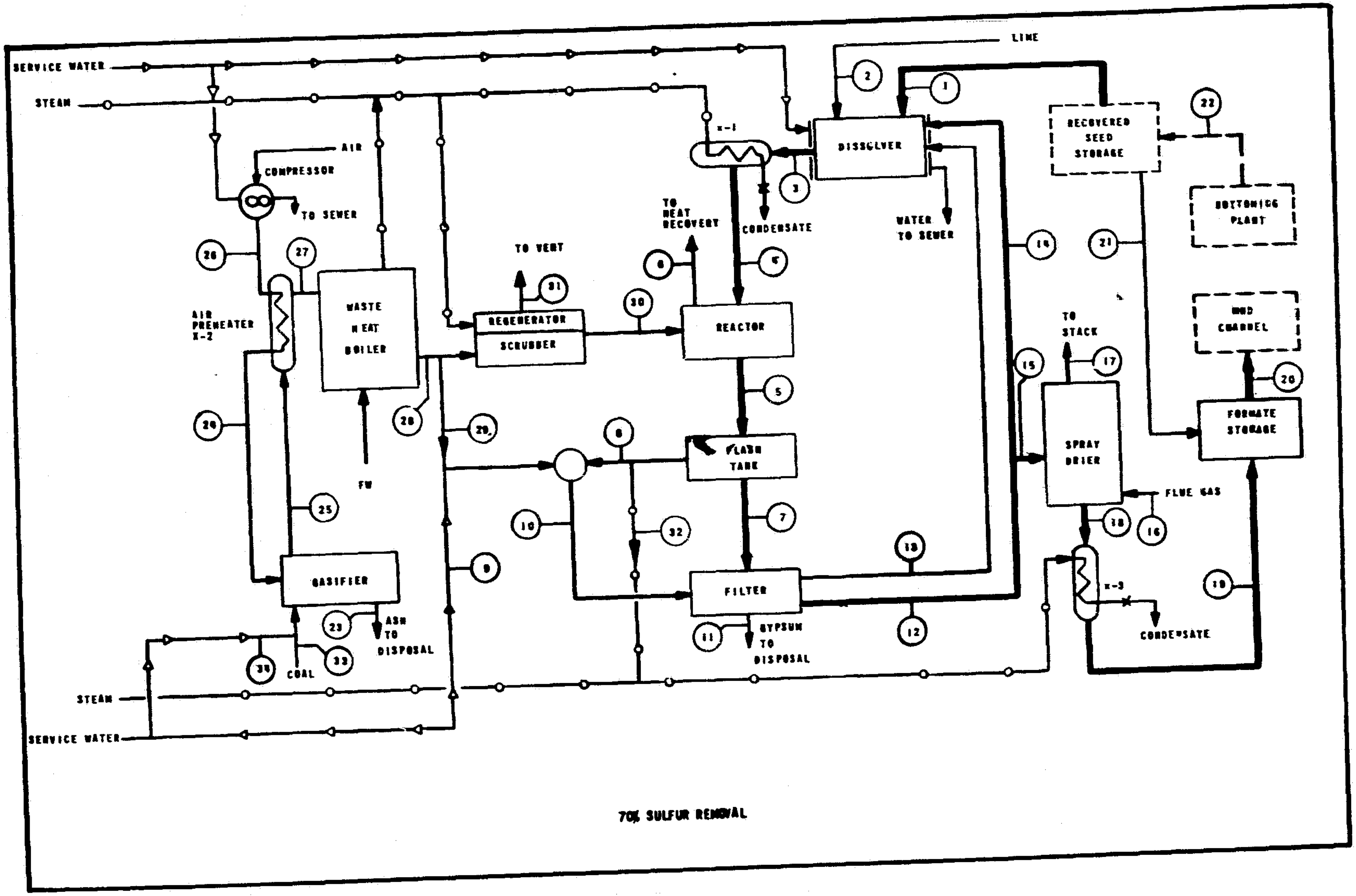

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Figure 3-37 Process Flow Diagram for Seed Regeneration System for 70% Sulfur Removal

TABLE 3-16

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						282												
ASH																		
CaO		4,633																
$Ca(OH)_2$			6,120	6,120														
$CaSO_4 \cdot 2H_2O$					14,223		14,223				14,223							
CO						687												
CO_2																		
COAL*																		
FLUE GAS																1,353,925	1,353,925	
H_2						225												
H_2O_l			57,536	57,536	48,921		39,530		49,268	58,651	3,556	37,102	57,524	1,501	35,601			
H_2O_g						5,638		6,851									35,601	
KCO_2H			1,394	1,394	15,292		15,292					14,483	808	586	13,898			13,898
K_2SO_4	17,175		17,454	17,454	3,059		3,059					2,897	162	117	2,779			2,779
$MISC._g$																		
N_2						16,335												

STREAM NO.:	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
AIR						21,585		21,585								
Ar							282		282	282		282				
ASH					459											
CaO																
$CaSO_4 \cdot 2H_2O$																
CO							5,314		5,314	5,314		5,314				
CO_2							3,289		3,289	3,289			3,289			
COAL*															4,596	
FLUE GAS																
H_2							225		225	225		225				
H_2O_l														2,540		2,441
H_2O_g							2,441		2,441	2,441	2,441					
KCO_2H	13,898	13,898														
K_2SO_4	2,779	30,099	27,320	44,495												
$MISC._g$							225		225	225		225				
N_2							16,335		16,335	16,335		16,335				

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	392	392	212	212	70	206	205	200	200	205	205	252	150	150	334	334	70	70
Press.-ATM	1	1	30	30	30	30	1	1	5	5	5	1	1	1	1	1	1	1	1	8	1	1
Enthalpy-(10^6Btu/hr)	0	[illegible]	7.71	16.11	13.97	8.20	6.16	7.62	0	7.62	13.77	4.83	7.48	0.19	4.63	61.33	85.66	0.29	0.94	0.94	0	0

STREAM NO.:	23	24	25	26	27	28	29	30	31	32	33	34
Temp. °F	2,450	800	2,450	500	2,246	392	392	392	212	212	70	70
Press.-ATM	1	30	30	30	30	30	30	30	1	1	1	5
Enthalpy-(10^6 Btu/hr)	0.23	4.09	22.26	2.41	20.58	5.21	2.90	2.04	0.254	3.21	0	0

SEED REPROCESSING - FORMATE PROCESS
MASS FLOW/TEMPERATURE/PRESSURE/ENTHALPY
PLANT SIZE - 500 MW_e
70% SULFUR REMOVAL

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TABLE 3-17

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						126												
ASH																		
CaO		2,075																
$Ca(OH)_2$			2,741	2,741														
$CaSO_4 \cdot 2H_2O$					6,371		6,371				6,371							
CO						308												
CO_2																		
COAL*																		
FLUE GAS																606,498	606,498	
H_2						101												
H_2O_l			25,774	25,774	21,915		17,708		22,070	26,273	1,593	16,620	25,768	672	15,947			
H_2O_g						2,525		3,088										15,947
KCO_2H			624	624	6,850		6,850					6,488	382	282	6,226			6,226
K_2SO_4	7,693		7,819	7,819	1,370		1,370					1,298	73	53	1,245			1,245
MISC.$_l$																		
N_2						7,317												

STREAM NO.:	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
AIR						9,669		9,669								
Ar							126		126	126		126				
ASH					206											
CaO																
$CaSO_4 \cdot 2H_2O$																
CO							2,380		2,380	2,380		2,380				
CO_2							1,473		1,473	1,473			1,473			
COAL*															2,059	
FLUE GAS																
H_2							101		101	101		101				
H_2O_l														1,138		1,093
H_2O_g							1,093		1,093	1,093	1,093					
KCO_2H	6,226	6,226														
K_2SO_4	1,245	13,483	12,238	19,932												
MISC.$_g$							101		101	101		101				
N_2							7,317		7,317	7,317		7,317				

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 ^oF	70	70	200	342	392	392	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	5	1	1	1	1	1	1	1	1	8+	1	1
Enthalpy– (10^6Btu/hr)	0	0	3.46	7.22	6.26	3.67	2.76	3.42	0	3.42	6.17	2.16	3.35	0.09	2.07	27.47	28.42	0.13	0.42	0.42	0	0

STREAM NO.:	23	24	25	26	27	28	29	30	31	32	33	34
Temp ^oF	2,450	800	2,450	500	2,246	392	392	392	212	212	70	70
Press. –ATM	1	30	30	30	30	30	30	30	1	1	1	5
Enthalpy– (10^6 Btu/hr)	0.10	1.83	9.97	1.08	9.22	2.33	1.30	0.92	0.11+	1.44	0	0

SEED REPROCESSING – FORMATE PROCESS
MASS FLOW/TEMPERATURE/PRESSURE/ENTHALPY
PLANT SIZE – 200 MW_e
70% SULFUR REMOVAL
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NOTES TO TABLES 3-16 and 3-17

		10^6 Btu/hr	
		500 MW_e	200 MW_e
1.	Steam to x-1	8.40	3.76
2.	Steam from waste heat recovery system	15.38	6.89
3.	Steam from 32	3.21	1.44
4.	Cooling water to dissolver	1.31	0.59
5.	Steam from 6	6.55	2.94
6.	CO in 6 - heat of combustion	2.99	1.34
7.	H_2 in 6 - heat of combustion	11.60	5.20
8.	Steam to x-3	0.66	0.29
9.	Coal* input in 33 - heat of combustion	56.86	25.47
10.	Steam in 29	2.90	1.30
11.	Cooling water from compressor	5.88	2.63
12.	Exothermal reaction for conversion of K_2SO_4 to KCO_2H	1.04	0.47
13.	Air from compressor	2.41	1.08

*Illinois No. 6 - moisture-free basis.

**Includes 5% moisture in coal and moisture in air to gasifier plus 2199 lb/hr slurry water.

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TABLE 3-18

OVERALL ENERGY REQUIREMENTS

Thermal Input (10^6 Btu/hr):	500 MW_e	200 MW_e
x-1 (steam)	8.40*	3.76*
x-3 (steam)	0.66*	0.29*
Lime hydration 2	-2.47*	1.11*
K_2SO_4 heat of solution	-1.12	-0.50
Flue gas 16	61.33	27.47
Coal 33	2.41*	1.08*
Compressed air	2.41	1.08
Formate reaction	1.04	0.47
Total	132.05	59.15
Thermal Output (10^6) Btu/hr):		
Waste heat boiler (steam)	15.38**	6.89**
Flash Steam 32	3.21**	1.44**
Reactor discharge (gas) 6		
Steam	6.55**	2.94**
CO (heat of combustion)	2.99**	1.34**
H_2 (heat of combustion)	11.60**	5.20**
Sensible heat	1.67**	0.75**
Gasifier discharge (steam) 29	2.90	1.30
Gypsum discharge 11	13.77	6.12
Formate discharge 19	0.94	0.42
Ash discharge 23	0.23	0.10
Dissolver cooling water	1.31	0.59
Spray drier discharge	65.68	29.42
x-1 plus x-3 condensate	1.29	0.58
Scrubber discharge	0.25	0.11
Balance error	4.28	1.95
Total	132.05	59.15
Electrical Input:		
Auxiliary Motors	3.92 MW_e (5258 HP)	1.76 MW_e (2355 HP)
Compressor cooling water (thermal output)	5.88 x 10^6 Btu/hr	2.63 x 10^6 Btu/hr

*System debit.

**System credit.

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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_2CO_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 3-38 shows a conceptual design for injecting the seed into 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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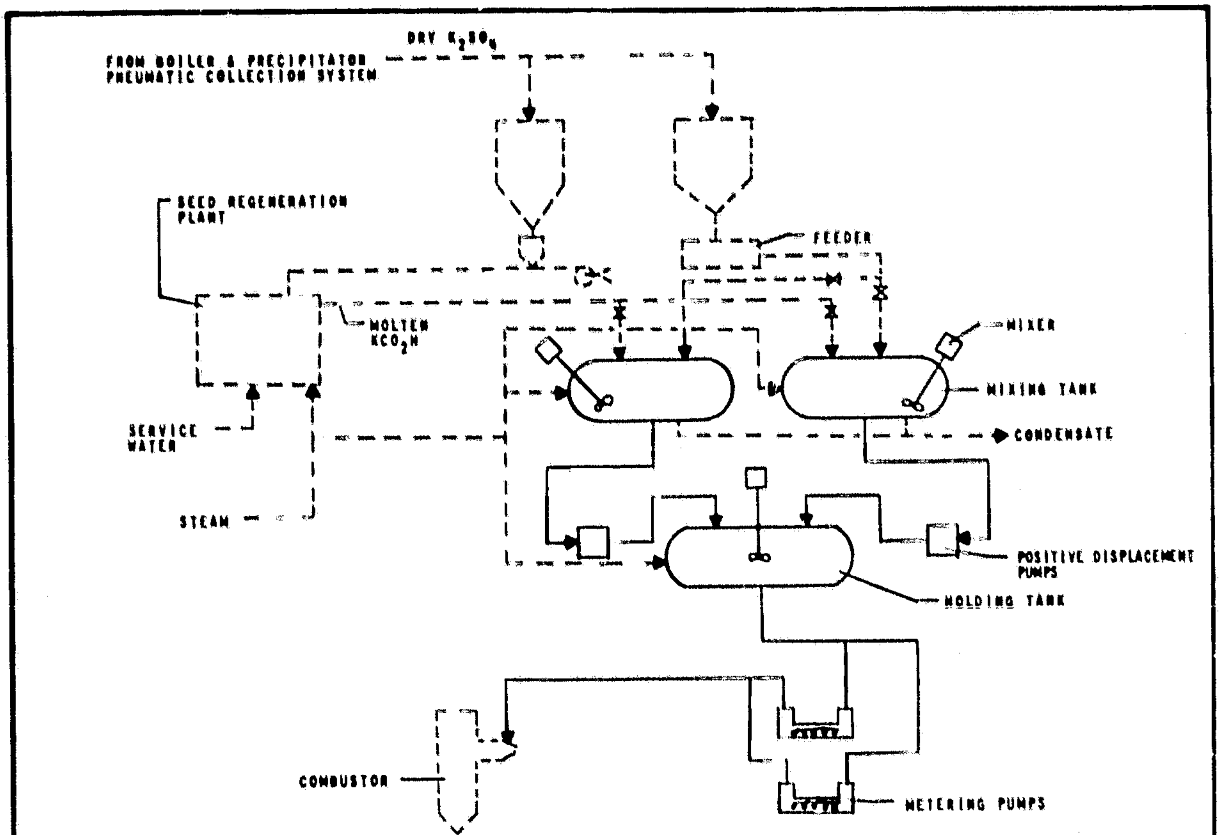

FIGURE 3.10.5-1

SEED FEED SYSTEM

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Figure 3-38 Schematic Diagram of Seed Feed System

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3.11 INVERTER SYSTEM

3.11.1 Introduction

This section describes the conceptual design of the static line commutated inverters for the two ratings of commercial scale, first generation coal fired MHD/Steam power plants derived from the conceptual design of the most attractive plant identified in the previous parametric studies, which was 950 MW_e with an MHD/Inverter rated power of 526 MW_e.

The present plants are 200 and 500 MW_e with corresponding MHD/Inverter powers of 96 and 261 MW_e, respectively.

In all major respects the design for these inverter systems follows the basic concepts already detailed in the Engineering Test Facility (ETF) Report[6], as did the design for the 950 MW_e plant.[2] It also incorporates the modifications or innovations proposed for the 950 MW_e inverter. Appropriate references will therefore be made here to both these earlier reports.

3.11.2 Inverter Bridges

The present MHD channels both utilize diagonal external connections of the loads-inparallel type, so that the required number of inverters each have one of their terminals common with the upstream channel anode tap, and the other terminals to selected channel tappings between anode and cathode. This was likewise the configuration for the 950 MW_e plant inverter system, which utilized a five-terminal parallel connection. Here the load is divided into three inverter groups for the 200 MW_e plant and four for the 500 MW_e plant.

As pointed out in the ETF report and again in the 950 MW_e plant report, this parallel load connection (ETF Figure 2-167 or 2-169) happens to coincide with that favored by the inverter system, in contrast to an independent load connection (ETF Figure 2-166 or 2-168). This is so from the viewpoints of simplicity of equipment configuration and minimized quantities of the major components, less complexity of controls, better electrical efficiency, and overall economics. The fundamental reason is that the parallel connection processes the output at reasonably large ratios of MW_e to current and these ratios which are the voltages of the inverters, are largest for the largest blocks of power (REF: 950 MWe report, pg 3-124).

The extraction points or consolidated frame electrodes along the channel give the following inverter ratings shown in Table 3-19 for both plants.

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TABLE 3-19

200 MW_e PLANT

THREE - TERMINAL PARALLEL CONNECTION

kv	kA	MW_e
5.6	2.8	16
12.1	1.7	21
18.5	3.3	60
		97

500 MW_e PLANT

FOUR - TERMINAL PARALLEL CONNECTION

kV	kA	MW_e
4.8	4.5	22
9.5	3.9	37
15.2	3.4	51
22.4	6.7	151
		261

The number of bridges and internal thyristor components are indicated in Table 3-20 and are based on the following assumptions or constraints, which at this point in time can take into account some very significant improvements in both the voltage and current ratings of thyristors commercially available for HVdc application from at least one supplier. Moreover, the state of the art of producing reliable high-power thyristors continues to advance.

The table uses current ratings (3-phase, 6-pulse bridge rating) up to 4600 A, and a peak inverse voltage (PIV) withstand of 3500 V. In a final detail design, this PIV could possibly be matched optimally with a given current capability, and may be a little higher for some. Here it is taken conservatively the same for all current ratings.

These values contrast with the ratings used for the 950 MW_e plant inverters which were 2500 A and 3000 V.

The current ratings allow sufficient overload capacity both continuous and emergency, to permit MHD channel output above baseload.

One favorable result is that only one pair of bridges requires two strings of thristors in parallel in the six legs of the bridges, and no groups need be paralleled for the given loads. (A group consists of two bridges in series on the dc side and in parallel on the ac side, giving 12-pulse operation instead of the less desirable 6-pulse conversion of one bridge.)

The referenced ETF report (subsection 2.16.1.2) detailed the normal voltage and overvoltage considerations entering into the required peak inverse voltage withstand for the bridges, both as transient surge non-repetitive blocking voltages, and repetitive steady-state blocking voltage, inclusive of MHD channel operation at elevated levels. It was taken in that report, and for the 950 MW_e plant, as 3.5 times the rated dc bridge voltage. It was also pointed out that this is one of those inverter requirements which have to be tailored to the particular ac system with which the inverter interfaces.

It now appears that surge arresters which limit the ac and dc side overvoltages, i.e., coordinate the insulation strengths of the systems with the inverter components, have now improved due to the introduction of metal oxide arresters, specifically zinc oxide. This material has exceptional nonlinear voltage-vs-current characteristics, such that normally it practically does not conduct, but upon the occurrence of an overvoltage will pass current of an amount to limit (cutoff) the overvoltage at a specified designed level.

TABLE 3-20

200 MW_e PLANT

THREE - 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
2.8	2.8	1	1 X 3000 A	48	8.0
1.7	6.1	1	1 X 2000 A	84	10.5
3.3	9.3	1	1 X 3500 A	120	30.0
7.8		3 Groups (6 Bridges)		252	

500 MW_e PLANT

FOUR - TERMINAL PARALLEL CONNECTION

4.5 kA	2.4 kV	1	1 X 4600 A	48	11.0 MW_e
3.9	4.8	1	1 X 4000 A	72	18.5
3.4	7.6	1	1 X 3500 A	96	25.5
6.7	11.2	1	2 X 3500 A	264	75.5
18.5		4 Groups (8 Bridges)		480	

These new arresters are replacing the current limiting gap arresters in ac system application, and are being considered in current dc applications. Taking advantage of their lower protective levels, the bridge overvoltage withstand requirement is lowered here from 3.5 to three times the rated voltage. Combined with the increased PIV of the individual thristor components, this allows a significant reduction in the number of thyristors in series in each of the six legs of the bridges, with the result as in Table 3-20.

The numbers of thyristors shown there include an excess for redundancy, i.e., such that failure of one, or two in some instances, does not require shutdown of the inverter, and their replacement can wait for scheduled maintenance outages. The failure mode for thyristors is invariably to short circuit. Their failure rate in HVdc installations as been very low from the beginning, and keeps improving, being only a small fraction of a percent of the total large number in high-voltage, high-power dc terminals.

3.11.3 Converter Transformers

From the ETF report (subsection 2.16.1.4.2), the required line-to-line voltages on the inverter side of the transformers are calculated according to the thyristor extinction angle and control firing angles meeting the MHD load output voltage-current characteristics. Similarly, the transformer MVA ratings to allow for the reactive power consumption of the inverters, are based on the analysis in the ETF report (subsection 2.16.1.4.3).

The required line-to-line transformer winding voltages on the inverter connected side (secondary side) are 0.86 of the rated dc voltage per bridge; and the MVA are 1.19 times the MW. As shown in Table 3-21, converter transformers are given both as three-winding single phase units, or alternately as three-phase units. In the former case one bridge of a 12-pulse group would output to a wye-connected secondary, the other bridge to a delta-connected secondary, with the third or primary winding connecting of course to the ac side. For three-phase units, each would be dedicated to a single bridge, two transformers per group, one wye-wye and the other delta-wye. In either case the thirty degree transformation shift between the two secondaries gives the 12-pulse dc to ac conversion so that the lowest normal harmonics injected into the ac side would be the 11th followed by the 13th, then the 23rd and 25th, etc.

The MVA ratings in Table 3-21 are self-cooled (OA). Overload capacity for channel loadings above baseload is taken by suitable forced air (FA) ratings of 120 or 125%. Note also that no taps are required on the converter transformers. Compensation for deviations in the ac voltage and assistance to the inverter

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TABLE 3-21

CONVERTER TRANSFORMER RATINGS

200 MW_e PLANT

THREE-TERMINAL PARALLEL CONNECTION

kV Per Bridge of 12-p Group	MW_e Bridge	No. of Groups In Parallel	3-Winding, 1-ph kV sec/kV	2-Winding, 3-ph kV sec/ kV
2.8	8.0	1	1-2.4 kV, 20 MVA	2-2.4 kV, 10 MVA
6.1	10.5	1	1-5.2 kV, 25 MVA	2-5.2 kV, 15 MVA
9.3	30.0	1	1-8 kV, 70 MVA	2-8 kV, 35 MVA
		Total Installed MVA	115	120
		Ratio: MVA/Baseload MW	1.19	1.24

500 MW_e PLANT

FOUR-TERMINAL PARALLEL CONNECTION

kV Per Bridge of 12-p Group	MW_e Bridge	No. of Groups In Parallel	3-Winding, 1-ph kV sec/kV	2-Winding, 3-ph kV sec/ kV
2.4	11.0	1	1-2.1 kV, 25 MVA	2-2.1 kV, 15 MVA
4.8	18.5	1	1-4.1 kV, 45 MVA	2-4.1 kV, 25 MVA
7.6	25.5	1	1-6.5 kV, 60 MVA	2-6.5 kV, 30 MVA
11.2	75.5	1	1-9.6 kV, 180 MVA	2-9.6 kV, 90 MVA
		Total Installed MVA	310	320
		Ratio: MVA/Baseload MW	1.19	1.23

controls to maintain optimum power factor during off-baseload operation is common to all inverters, and can therefore be made by standard plus and minus 10% on-load-tap-changer of the main inverter transformer.

The voltage of the primary windings of the converter transformers is that of the intermediate bus, i.e., the same voltage as for the bottoming plant generator. However the transformer primary bus is not normally connected to the generator bus; although provision may be made so that outage of one of the two main step-up transformers (inverter and generator to high side ac grid voltage) may allow MHD operation without the bottoming plant, or of both at reduced load.

Conversion of the MHD power in two steps is still considered advantageous for the same reasons advanced in the ETF report. In addition to providing an important buffer reactance between the ac system and MHD-inverter dynamics, it obviates the need for synchronized individual tap changers on each of the inverter transformers. The rating of the main step-up transformer need not include the mvar requirements of the inverter inasmuch as this reactive compensation and the filtering of ac harmonics can be accomplished at the lower voltage intermediate bus. This is another point in favor of such a bus, allowing significant economies in the design of the filters and reactive compensation equipment.

The main inverter transformer can be 100/120 MVA, OA/FA for the 200 MW_e plant; and 250/300 MVA for the 500 MW_e plant.

3.11.4 Water-Cooled Thyristor Bridges

The possibility of using water-cooled thyristor bridges was advanced for serious consideration in connection with the inverter of the 950 MW_e plant. It can now be reinforced because more successful experience has been accumulated with water-cooled, air insulated thyristor bridges. Utilizing them, ongoing design improvements for HVdc terminals appears to progress toward more compaction of the bridge structures.

With regard to refrigerant gas cooled, SF6 compressed gas insulated thyristors, nothing more positive can be said since the 950 MW_e report. It remains to be assessed at such time as an MHD plant is to become reality. However, apart from increased cost, it would appear likely to prove attractive for the larger sized plants only. The inverter bridges for a 200 MW_e plant would not really gain by an SF6 enclosure.

3.11.5 Harmonic Filters

The conventional provisions for the necessary filtering of the ac harmonics injected into the ac system by converter operation, have been sharply tuned, high Q-filters for the first two characteristic harmonics (11th and 13th in 12-pulse groups), and a high-pass filter for the harmonics of higher order.

The inverter section of the 950 MW_e plant report called attention to the renewed possibility that good filtering could be obtained with a high-pass, broadband, low Q-filter to screen all harmonics. An advantage from their use would eliminate the problems sometimes encountered due to detuning of the conventional filters principally because of temperature variations of their capacitor elements. This can be troublesome not only from the standpoint of poorer filtering of the converter generated harmonics, but also because electrical resonances may arise between the filters and the ac system impedance at frequencies other than the tuned filter frequencies. It is recalled that this is another aspect of dc terminal design which makes a converter terminal unique to the particular part of an ac grid with which it connects.

The earlier report noted that such a new type broadband filter had been designed for an HVdc high-power transmission line. However its experience is not known yet. The device therefore remains an option to be evaluated at the time a real MHD plant will be built.

3.11.6 Reactive Compensation

At the ac bus, the inverter appears as a generator operating at leading power factor. Taking control modes into account, the power factor is about 0.84. That is, for the 200 MW_e inverter the 97 MW_e baseload active power is 0.84 of the MVA, reactive power about 0.54 of the MVA, or 0.64 of the active power - 0.64 x 97 = 62 MVAR.

Similarly for the 500 MW_e plant inverter the reactive power requirement is 0.64 x 261 MW = 167 MVAR at baseload.

These MVAR needs vary approximately directly with the load. About one-half of the full load MVAR is normally supplied by the capacitors in the ac filters, and is available as a fixed compensation amount at all loads. The excess needs have to be supplied by additional sources. These excess MVAR are:

	200 MW_e Plant	500 MW_e Plant
75% Load	15 MVAR	40 MVAR
Full Load	30	80
125% Load	45	120

The ETF report detailed the considerations and relative merits of supplying the excess reactive requirements in whole or in part from the bottoming plant ac generator, a synchronous condenser at the plant or nearby on the ac system, or by banks of switched capacitors conventional to HVdc transmission terminals.

The 950 MW_e plant report repeated these factors with particular impact to that larger size, and added the possibility of a new device, the static var compensator. This would in great degree combine the desirable features of continuously adjustable var supply as provided by rotating machines, with the fast transient voltage support possible from capacitor banks.

Since that writing such devices have begun to be used on ac systems for similar functions, and are being actively considered for ongoing ac transmission projects. Also, they are being evaluated for projected HVdc terminals, as was forseen in the 950 MW_e report.

All alternatives should be considered in a real MHD plant design. It may be that the static var compensator (which also uses thyristor control) will prove optimal for the larger 500 MW_e plant, while conventional switched capacitor banks may serve the smaller 200 MW_e plant inverter.

As in the case of filters, and inverter bridge insulation requirements, this is another aspect where the ac system characteristics must be carefully assessed case-by-case.

3.11.7 Inverter Controls

Another innovation over the earlier ETF inverter design was advanced for the 950 MW_e commercial plant, and is likewise advanced here. It is worth some brief explanation.

In the ETF analysis to establish control principles for the MHD channel-inverter interface (subsections 2.16.1.6.1 thru 2.16.1.6.5 and Figure 2-171), it was noted that setting a dc voltage operating level on the inverter as a reference could force the channel to operate at its optimum efficiency for a given power output. This was in addition to the constant extinction angle and constant current controls, which are those conventional to HVdc

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converters but were unconventionally applied to match inverter with MHD machine characteristics.

It still appears as it did for the 950 MW_e inverter, that this additional control mode is not only desirable for more efficient operation, but is essential for stable operation, or more stable than is possible with the other two modes alone. Indeed it would be the dominant mode in steady or quasi-steady state, and would be supplemented or overridden by the other two only during transition periods of a disturbed nature.

The reason for the added mode stems from the fundamental fact that the MHD generator cannot control its own voltage, i.e., terminal voltage is current dependent. This means in essence that the inverters are asked to control both current and voltage simultaneously -- an impossible task unless the MHD generator had always a predictable and definite relationship between its current and voltage outputs, which is not the case. Its volt-current characteristics are in reality fairly wide bands rather than defined lines (Figure 2-171 of ETF report).

On constant extinction angle control the inverter countervoltage is itself not constant, but also depends on the magnitude of the dc current. Therefore while tending to compensate for MHD current output deviations, the new equilibrium operating point is determined not by the inverter but by the internal emf of the channel after the deviation.

On current control, the stabilizing influence of the inverter is somewhat better; but again the new operating point following MHD fluctuation is determined by the channel internal emf.

In other words, in both of these control modes the inverter can only try to stabilize current by changing its voltage in a sense opposite to that of the channel until the MHD internal dynamics settle inside the dead bands of generator and inverter regulators. The inverter is constantly after a moving target. In the HVdc transmission line rectifier-inverter coordination, the inverter when in current control mode (abnormal for an HVdc line) can always work against a fixed voltage held by the rectifier. The situation in the MHD case is analogous to the HVdc case if one attempted to control the power flow by simultaneously allowing both inverter and rectifier on current control - which can be shown to be an unstable mode.

Since voltage is the ultimate variable in the MHD channel operation, the inverter ought to be given a constant voltage characteristic also, i.e., a voltage reference setting against which the actual voltage of the channel output is constantly measured. Any deviaton produces an error signal which after suitable time lag, advances or retards firing angles to restore the set voltage by forcing it to be the inverter counter-voltage as derived from the ac system voltage.

If this set voltage reference can also be calculated for optimum efficiency of the channel at the operating power level, as was discussed in the ETF report, so much the better.

On the representation of the combined MHD-inverter characteristics of Figure 2-171 of the ETF report, the new characteristic would be a horizontal line always below the constant extinction angle line, and extending from zero current to the current control "vertical" line. For current less than some reference value, operation would be at the intersection of the MHD characteristic with the new voltage reference, and the current regulator is inoperative. When large transient current changes take place, then the current error signal automatically assumes control, and, of course, the CEA control is always in readiness to override when the firing angle has to be determined by the need not to encroach into the safe extinction angle (prevention of commutation failure).

3.11.8 Inverter and MHD Channel Protection

These were treated at length in the ETF report, establishing principles, components and function logic (subsections 2.16.1.7.1 thru 2.16.1.7.4).

They apply here as well, along with the dc smoothing reactor which is an integral part of the inverter bridges, and together with the firing control, helps to maintain uninterrupted operation in the event of external ac system disturbances with recovery of the bridge after the disturbance is cleared.

Also, the bypass switch remains to short-circuit the MHD generator and inverters in the event of severe or prolonged malfunctions for which the inverters cannot recover.

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 inches 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. The 500 MW_e plant has a condenser heat load of 1.71 (10^9) Btu/hr resulting in a multiple cell cooling tower with a total fan power of 1,282 kW and a circulating water flow of 121,550 gpm. The 200 MW_e plant has a condenser heat load of .79 (10^9) Btu/hr. This also results in a multiple cell cooling tower with a total fan power of 632 kW and a circulating water flow of 59,935 gpm.

Since ~ 75% of the heat load is removed by evaporative cooling, it is necessary to blow down 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 $\sim 0.4\%$ 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 ~ 7.25 atm for the 500 MW_e plant and 5.25 atm for the 200 MW_e plant and both at $4700^{\circ}/F$. 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 3-39.

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 overflow line 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.

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 3-39. 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.

<u>Boiler Slag</u> - 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.

<u>Boiler and ESP Seed and Ash</u> - 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.

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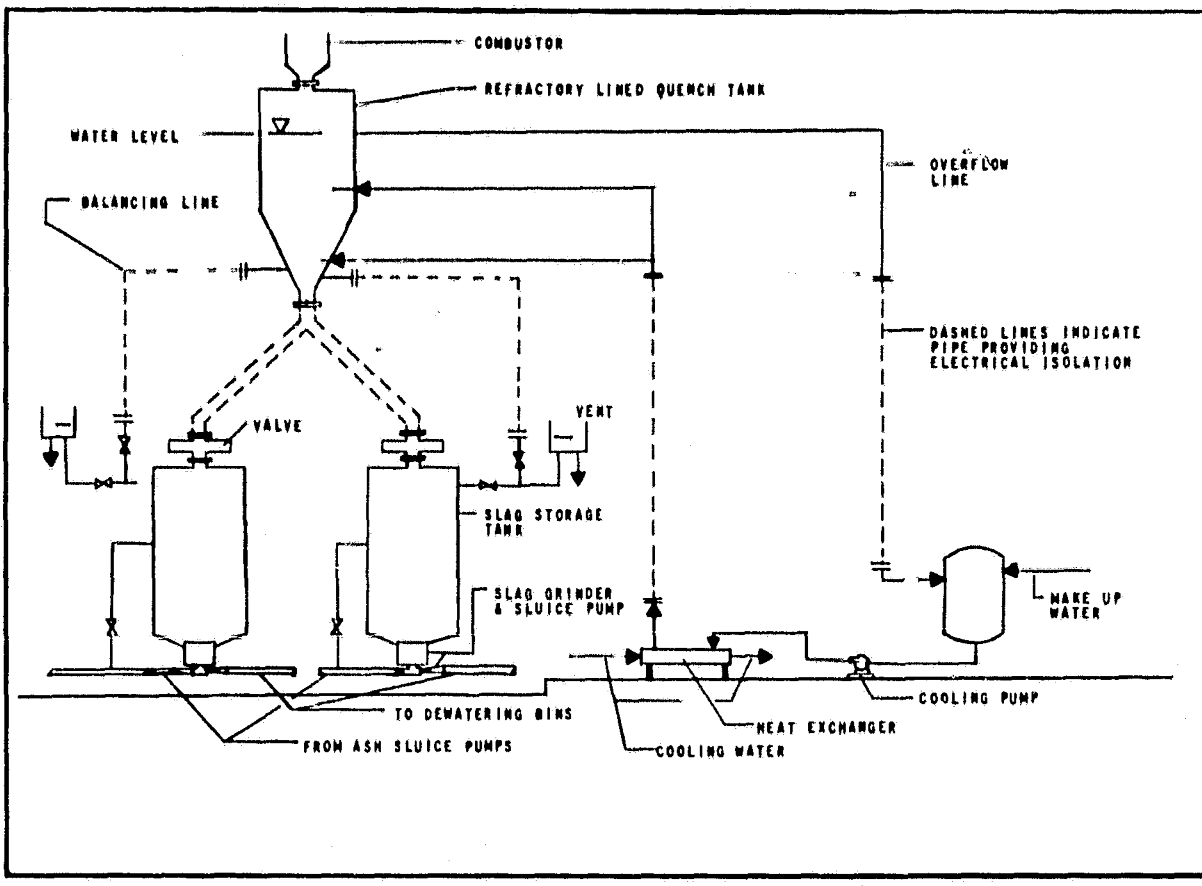

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Figure 3-39 Diagram of Combustor Slag Collection System

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 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 444,730 lb/hr (22.7% moisture) for the 500 MW_e plant and 199,020 lb/hr (22.7% moisture) for the 200 MW_e plant. Coal is assumed to be delivered by unit train.

The coal handling system is shown in Figures 4-1 and 4-4 for the 500 MW_e and 200 MW_e plants, respectively. 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 storage silos above the pulverizers. The 500 MW_e plant will have 5 silos, 4 of which will have adequate capacity to provide 24 hr of storage at full load. The 200 MW_e plant will have three silos, 2 of which will have adequate capacity for 24 hr storage at full load. 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 feedwater and condensate systems for both the 500 MW_e and 200 MW_e plants include closed feedwater heaters, one open deaerating feedwater heater, a high- and low-pressure economizer, and the MHD channel and combustor. There are two half capacity motor-driven condensate pumps, one full-size turbine driven boiler feed pump and one 25% startup, motor-driven boiler feed pump. These components are arranged in the steam cycle so that the heat available from the MHD combustion gases is used in the most efficient manner. The channel is cooled using condensate where the temperature is compatible with state-of-the-art channel design concepts and materials which have demonstrated long-term operation. The combustor is cooled by the highest temperature feedwater so that the best available use is made of the high combustor temperature. High and low-pressure economizers are also cooled by the warmest feedwater possible, while maintaining a water to gas temperature difference of about 50^{o}F. Feedwater to the boiler is subcooled by 50^{o}F.

The condensate and feedwater cycle for the 500 MW_e plant has six feedwater heaters while the 200 MW_e plant has four feedwater heaters. Air compressors for both the 500 MW_e and 200 MW_e plants are driven by steam turbines. For the 500 MW_e plant, the turbines utilize main steam. For the 200 MW_e plant, the turbines utilize crossover steam. Mechanical drive turbines of the size required for the 200 MW_e plant have not as yet been built to use high-pressure steam. As in the case with the boiler feed pump drive, turbines in this size range typically use crossover steam.

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 boiler feed 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.

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.

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.

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 Cable Engineers Association (ICEA)

Institute of Electrical and Electronics Engineers (IEEE)

National Fire Protection Association (NFPA)

Chapter 70 of NFPA, 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 3R 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. Nonmotor 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 120/208 V 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 economies, 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 continuous 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 annunciator 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 recommendations.

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 ICEA 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 ICEA 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 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. 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 3996 TPD of contained oxygen in the product from the O_2 plant for the 500 MW_e power plant and 1618 TPD for the 200 MW_e power plant. Two cold box units with heat exchangers and necessary valving and auxiliaries arranged in parallel have been assumed for the larger 500 MW_e power plant and two for the smaller 200 MW_e power plant. 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% and 32% oxygen by volume at nominal load for the 500 MW_e and 200 MW_e power plant, respectively. The mixture of air and oxygen is compressed by the cycle compressor and delivered to the MHD combustor for combustion of the coal.

Based upon the information provided by NASA, the cost of the O_2 plant for early commercial MHD power plant application has been assumed to vary linearly with the O_2 plant capacity for capacities above 3000 TPD. For smaller capacities, the O_2 plant cost has been estimated by a scaling method with the use of a scaling exponent factor as shown in Figure 3-40. Accordingly, the estimated cost of the oxygen plant for the 500 MW_e power plant which has a capacity 3996 TPD has been arrived at by linear scaling of the Task II oxygen plant cost which has a capacity of 6957 tons per day. The oxygen plant for the smaller 200 MW_e power plant has a capacity of 1618 TPD. The cost of this oxygen plant was arrived at by applying linear scaling of the Task II oxygen plant cost down to 3000 TPD and an exponential scaling factor of 0.74 for scaling from 3000 TPD to 1618 TPD (see Figure 3-40).

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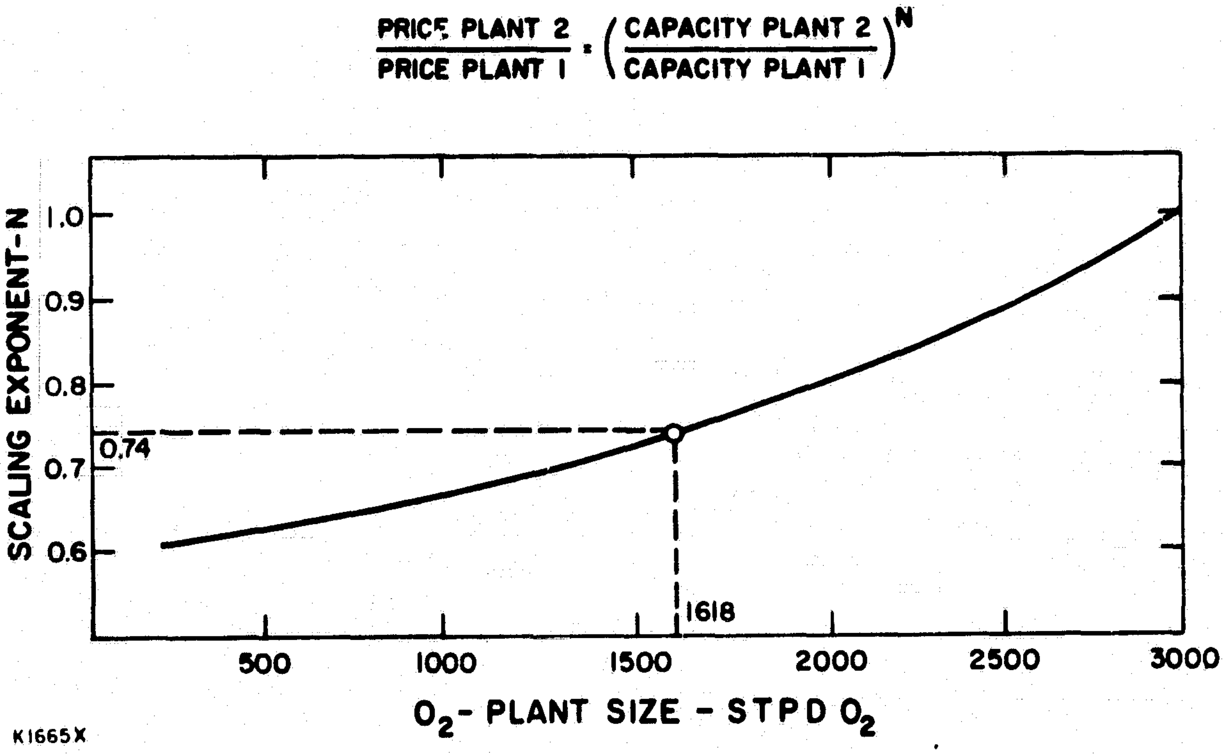

Figure 3-40 Oxygen Plant Scaling Factor

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 for the 500 MW_e plant and Figures 4-4, 4-5 and 4-6 for the 200 MW_e plant.

The Plot Plan shows the entire plant property. The two single items that account for ~ 50% of the total required area are waste disposal and the coal handling and storage facilities. For the 500 MW_e plant waste disposal and coal handling and land requirements account for 30% and 23%, respectively, while for the 200 MW_e plant they require ~ 20% and 28%, respectively.

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 Figures 4-2 and 4-5. 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 G. This space will be considered an unsafe work area when the unit is operating.

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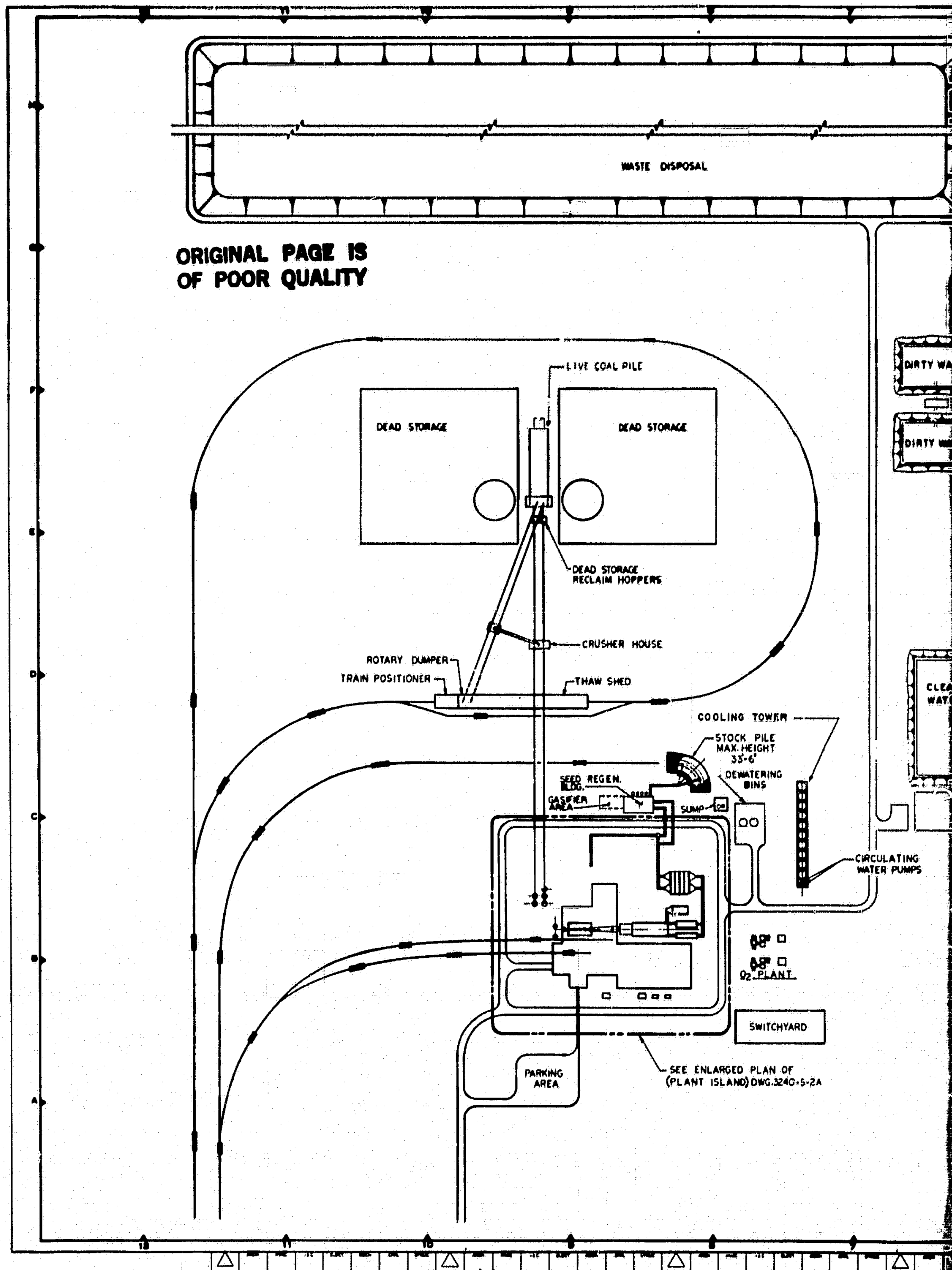

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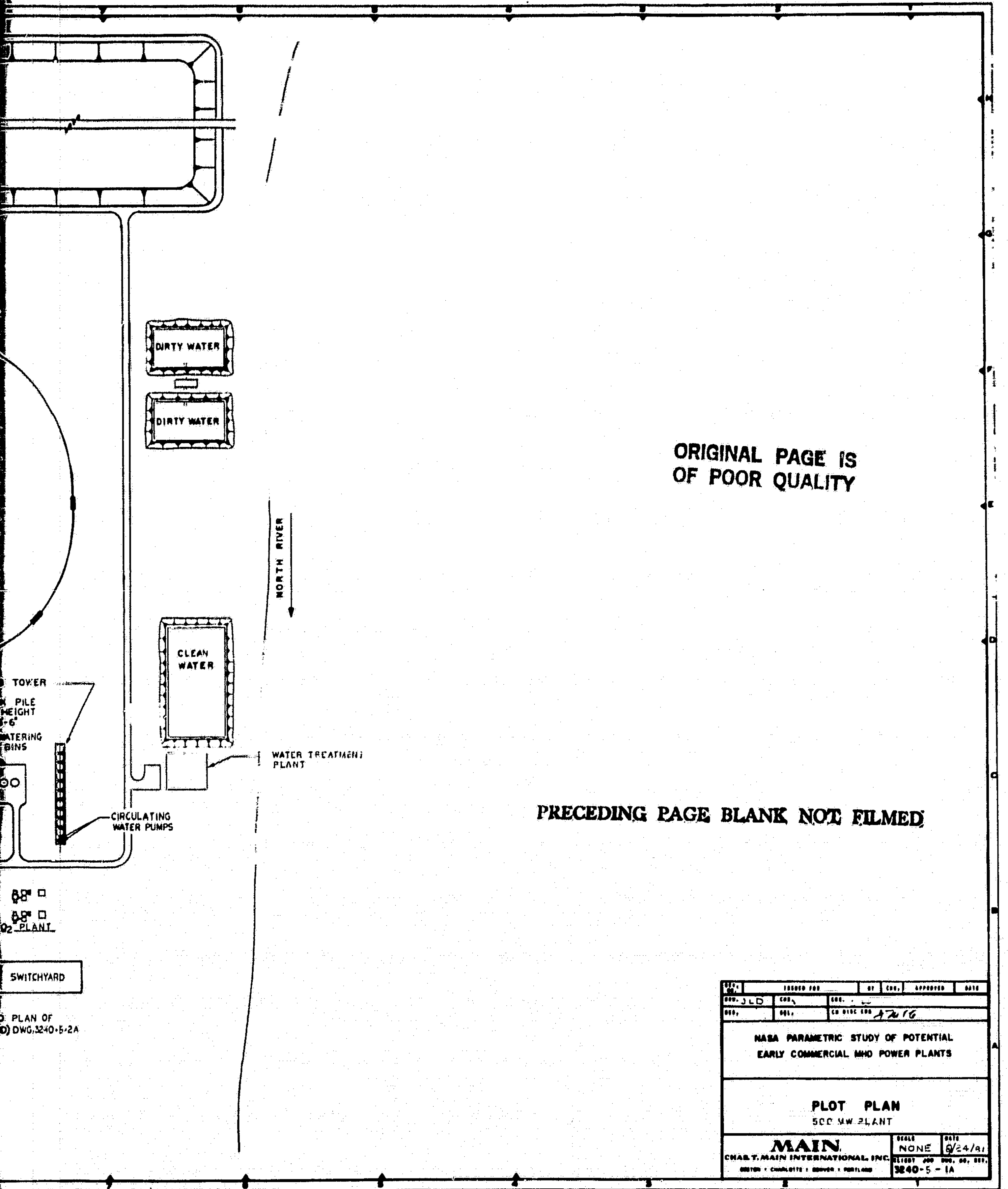
Figure 4-1 Plot Plan



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-1 Plot Plan for 500 MW_e Plant

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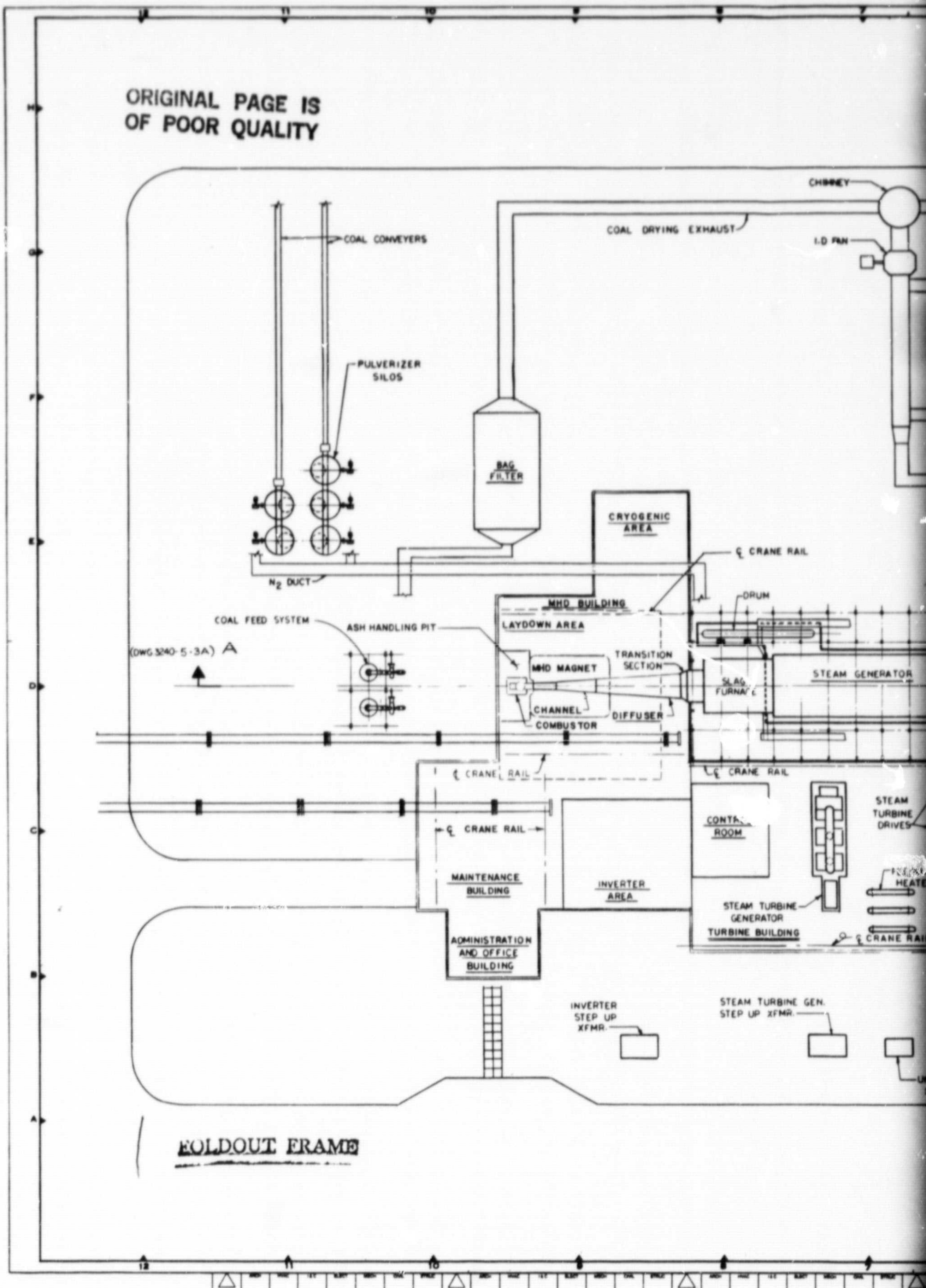

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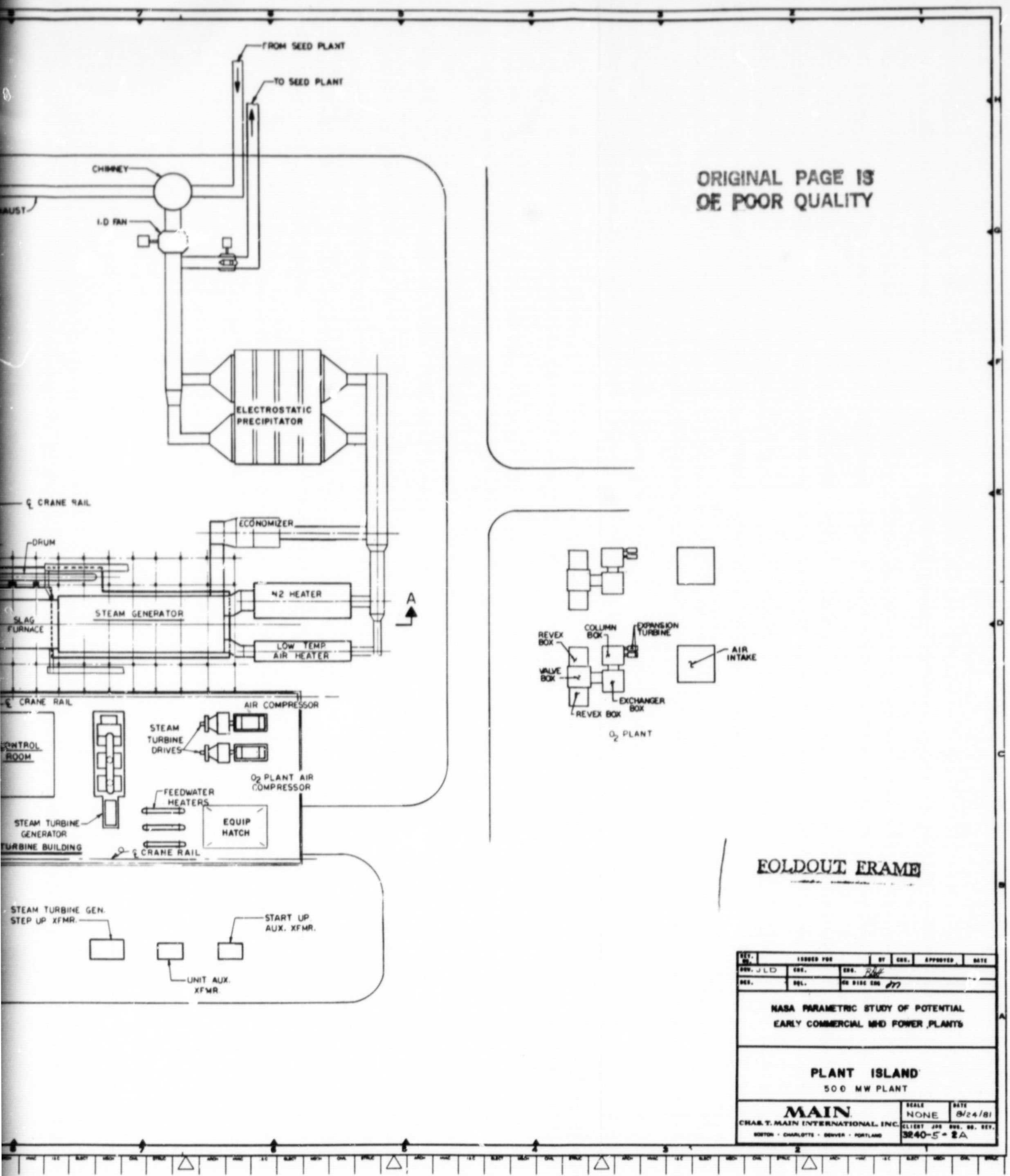
Figure 4-2 Plant Island Arra



ant Island Arrangement for 500 MW_e Plant

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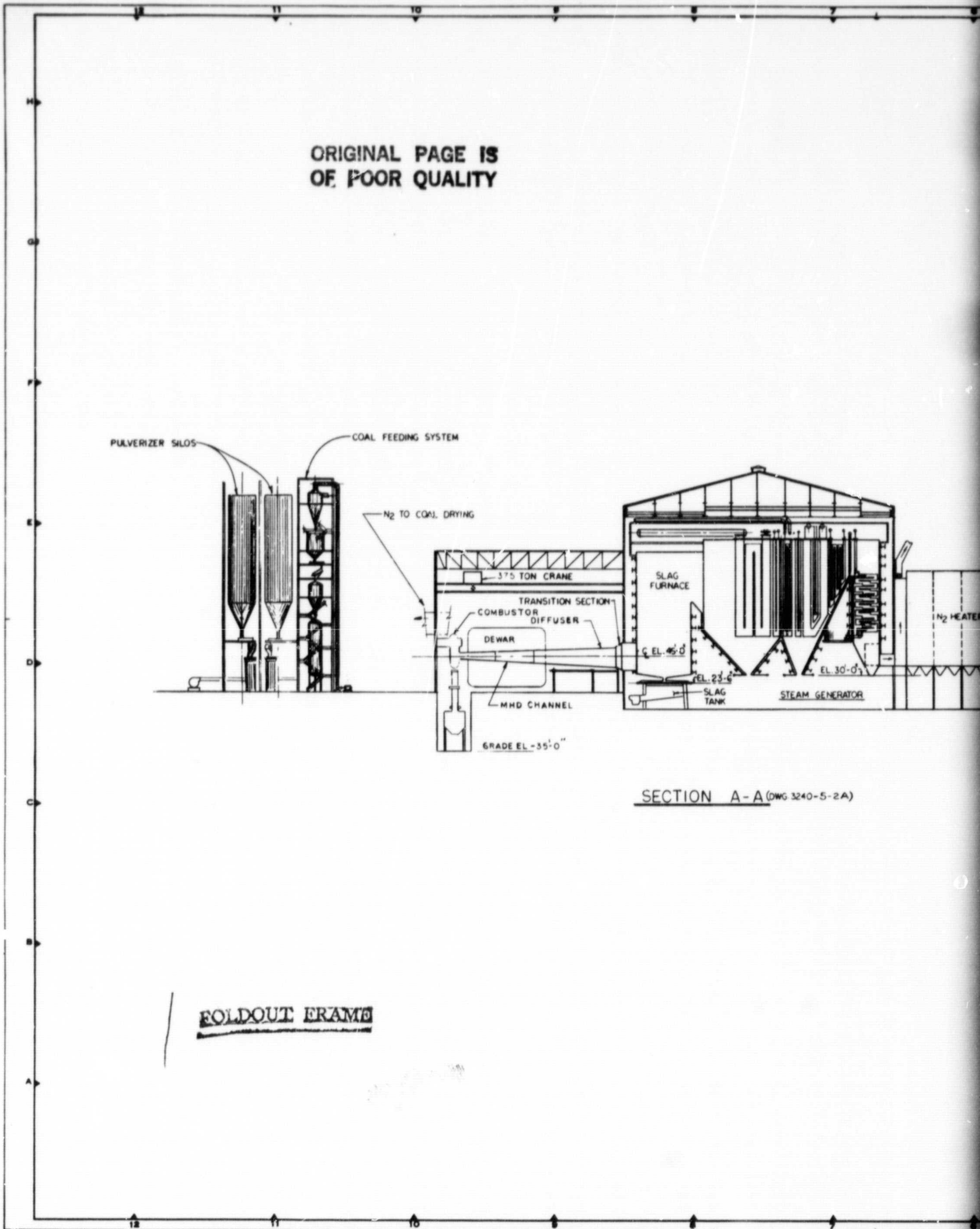

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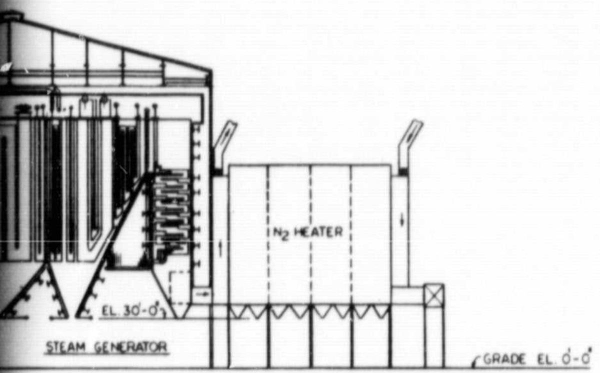
Figure 4-3 Section Through Plant I



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DRN. JLD

NASA PARAMETRIC STUDY OF POTENTIAL EARLY COMMERCIAL MHD POWER PLANTS

PLANT ISLAND
SECTIONS AND DETAILS
500 MW PLANT

MAIN
CHAS. T. MAIN INTERNATIONAL, INC.
BOSTON · CHARLOTTE · DENVER · PORTLAND

SCALE	DATE
NONE	8/24/81
3240-5 - 3A	

on Through Plant Island of 500 MW_e Plant

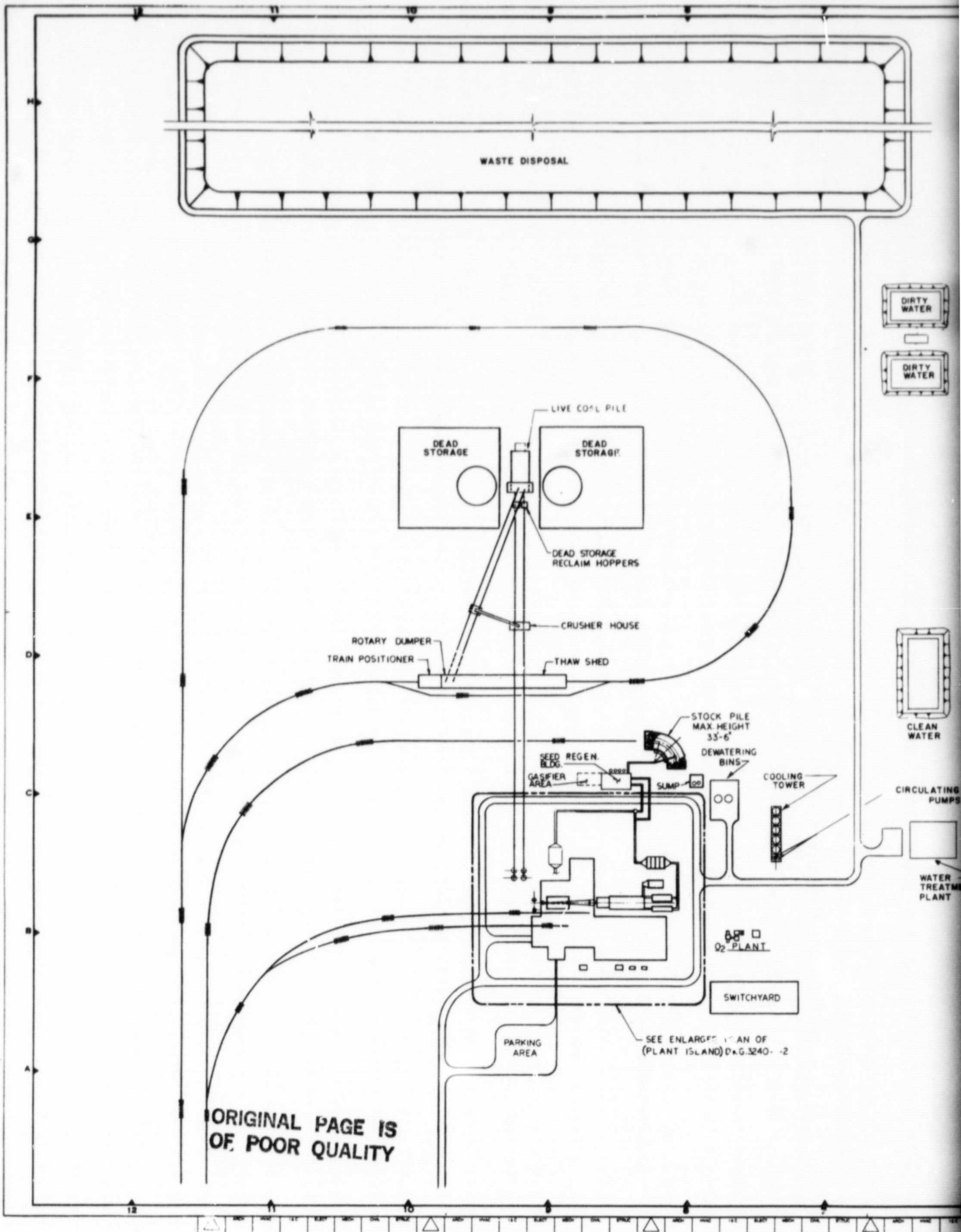

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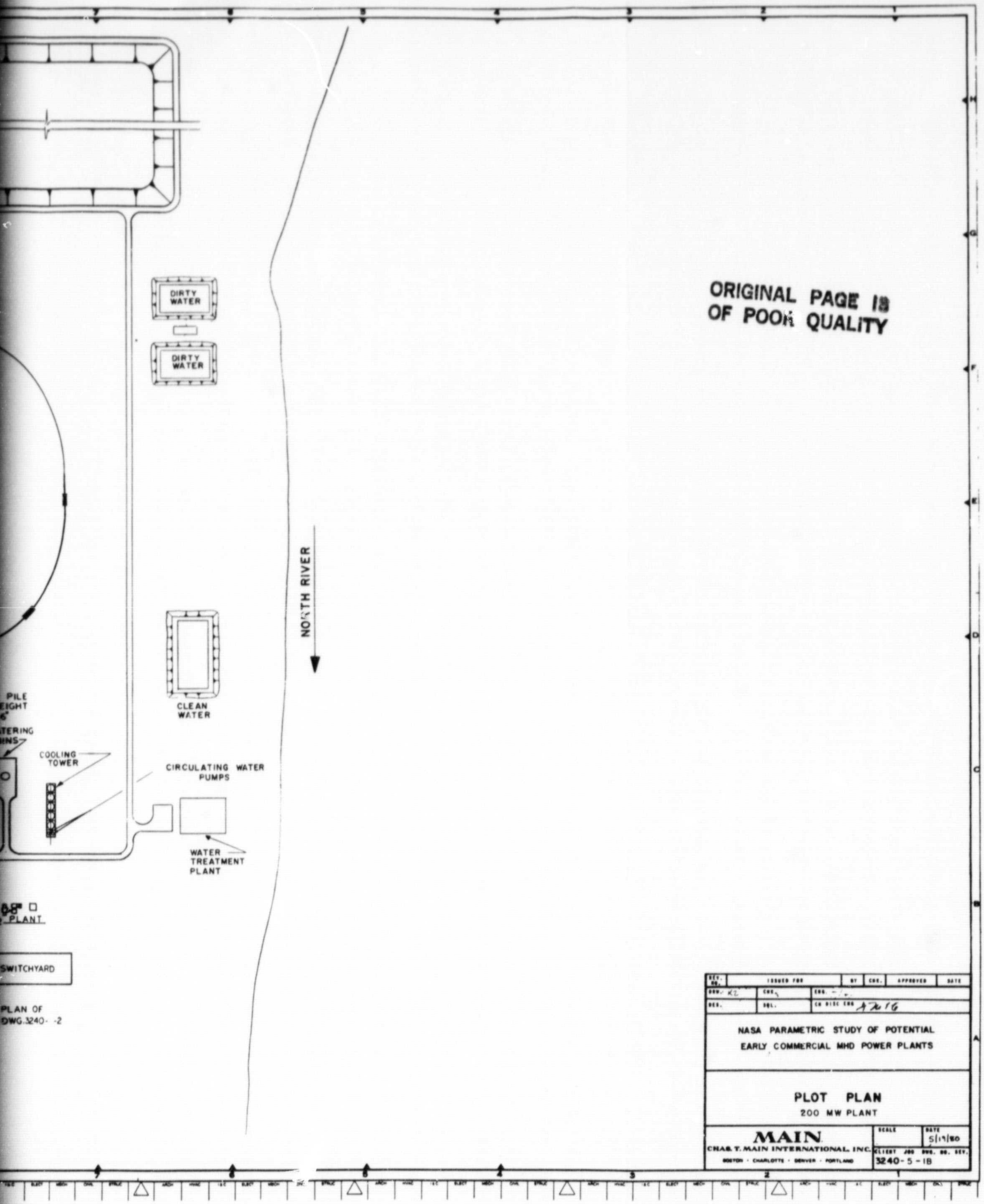
Figure 4-4 Plot Plan for



4 Plot Plan for 200 MW_e Plant

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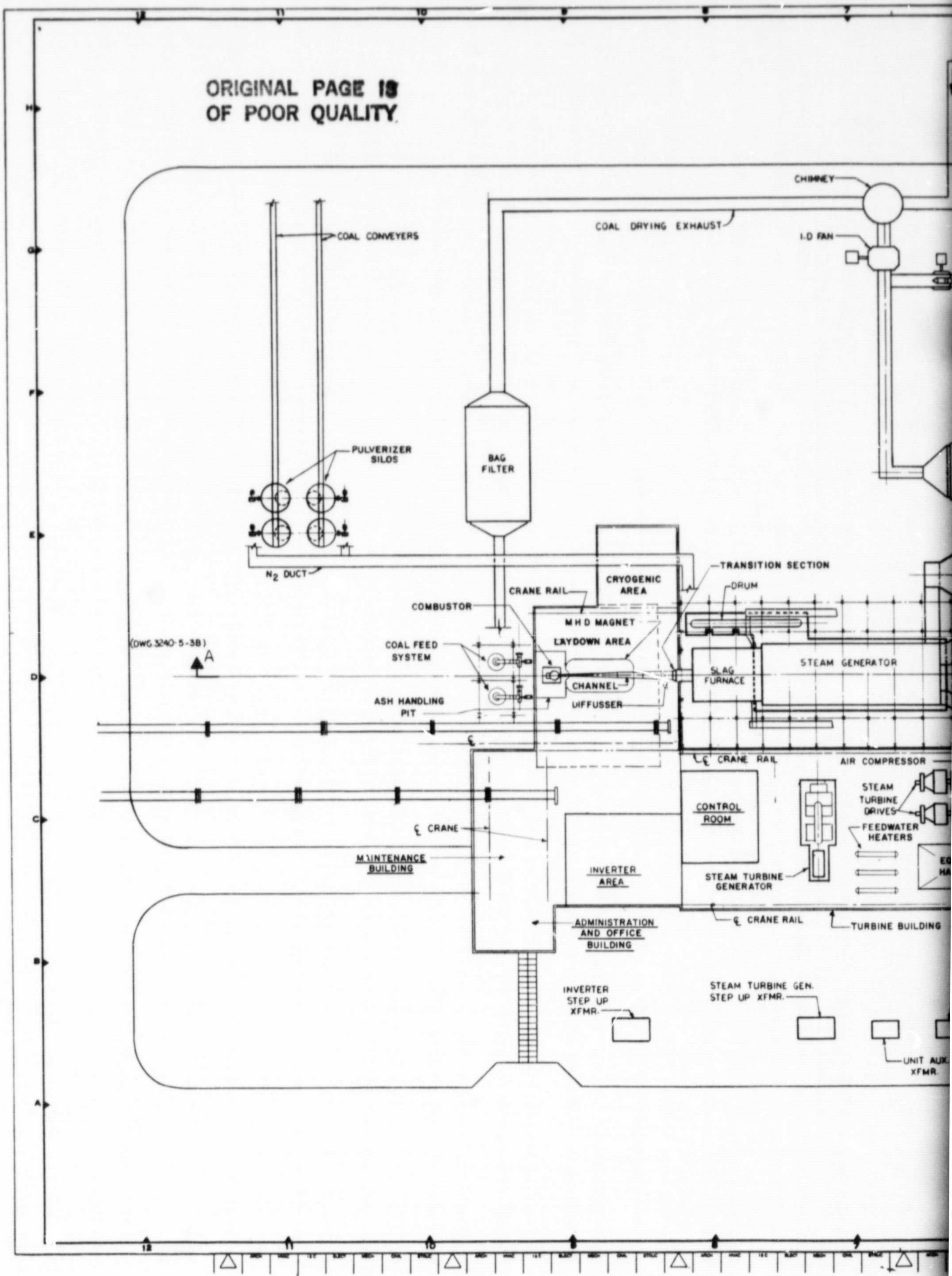

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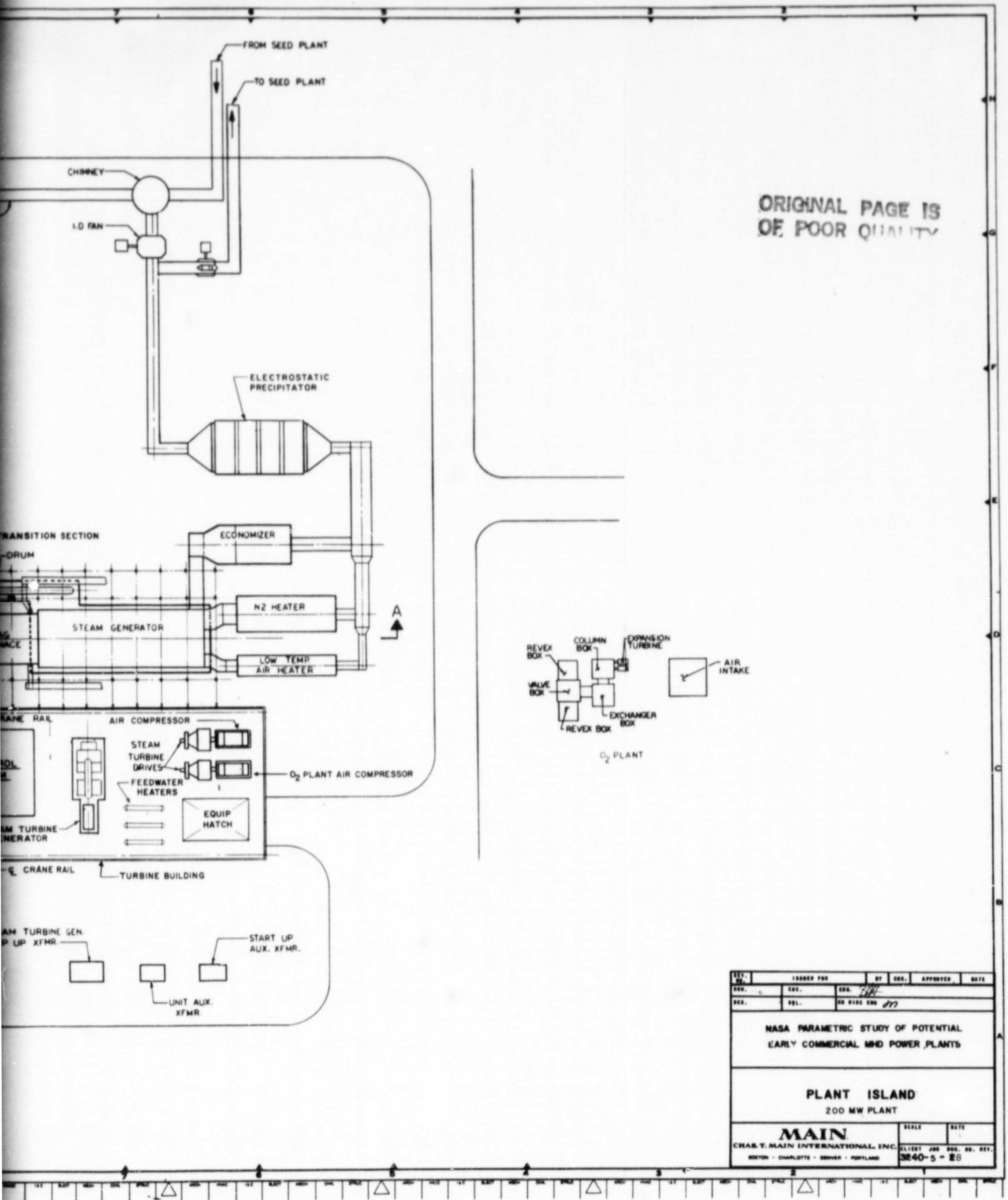
Figure 4-5 Plant Island Arranger



t Island Arrangement for 200 MW_e Plant

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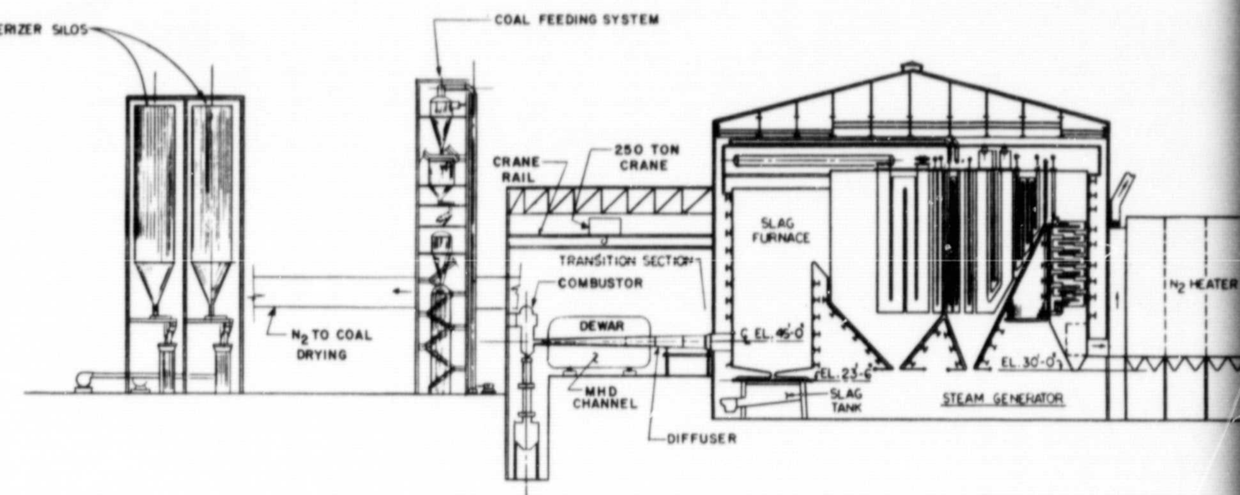

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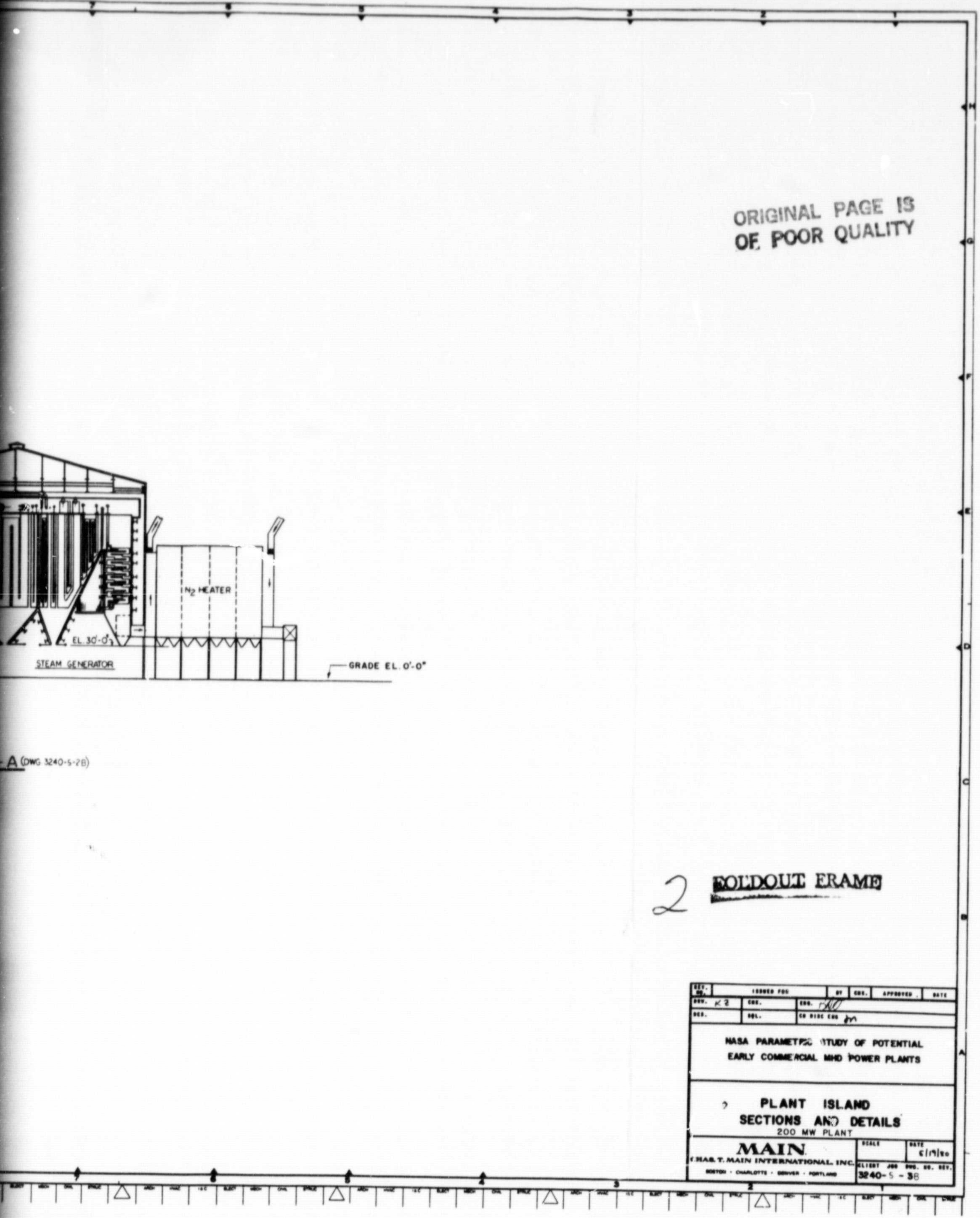
Figure 4-6 Section Through Plant



ion Through Plant Island of 200 MW$_e$ Plant

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

The foundation pit of the combustor slag system, is considered as a high contingency item at this stage of project development. The pit design will provide for membrane waterproofing 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 a 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 Adminstration and Office Building, as shown in Figures 4-2 and 4-5. 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 bridge crane 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 steel frame building covered with insulated metal siding and a built-up roof. A bridge crane located below the roof will facilitate maintenance and erection of equipment. A 375 ton crane will be provided for the 500 MW_e plant, a 250 ton crane for the 200 MW_e plant. The railroad track inside the building will facilitate transportation 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

An 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 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 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 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 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 loations.

Adequate entrance and egress will be provided through service and main 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 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 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. Bridge cranes will be installed in the MHD building, maintenance building and turbine building.

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.

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6.0 ESTIMATED PLANT COSTS AND COST OF ELECTRICITY

6.1 CAPITAL COSTS - 500 MW_e and 200 MW_e PLANTS

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 estimates are shown in Tables 6-1 and 6-2 for the 500 MW_e and the 200 MW_e plants, respectively. 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. Estimates have been prepared for typical 500 MW_e and 200 MW_e plants, and a "first of a kind" 200 MW_e plant.

"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 contractor or general contractor directly to a single estimating account. For conceptual estimates, indirect construction costs are expressed as a percentage of the

TABLE 6-1

500 MW_e PLANT

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				
310.	LAND AND LAND RIGHTS	ACRE	550		825		-0-	83	908
311.	STRUCTURES AND IMPROVEMENTS	L.S.*			15,288	10,530	5,262	2,929	34,009
311.1	Improvements to Site	L.S.			1,385	2,114	1,057	456	5,012
311.2	MHD Building	C.F.*			5,196	2,725	1,363	928	10,212
311.3	Bottoming Plant Building	C.F.			5,473	3,737	1,869	1,108	12,187
311.4	Steam Generator Building (FDN's)	C.Y.*			49	143	72	26	290
311.6	Maint. Serv., Warehouse and Office Buildings	C.F.			1,221	566	278	27	2,092
311.7	Other Buildings	C.F.			326	473	237	104	1,140
311.8	On-site Waste Treatment	L.S.			1,638	772	386	280	3,076
312.	BOILER PLANT EQUIPMENT			47,276	16,961	25,149	12,577	10,195	112,158
312.1	Coal Handling and Processing	TPH*			9,267	3,193	1,597	1,406	15,463
312.11	Unloading and Yard Storage				4,132	2,052	1,026	721	7,931
312.12	Reclaim and Delivery				5,135	1,824	912	787	8,658
312.2	Slag and Ash Handling	TPH			2,418	604	302	332	3,656
312.4	Steam Generator			42,574	1,091	17,566	8,784	7,001	77,016
312.41	Steam Generator	TON		42,574	23	17,098	8,549	6,824	75,068
312.43	Instrumentation and Controls				798	319	160	128	1,405
312.44	Auxiliaries				270	149	75	49	543
312.5	Effluent Control			4,702	312	2,489	1,245	875	9,623
312.51	Precipitator and Breeching	ACFM*		4,702	19	1,939	970	763	8,393
312.52	Chimney			0	293	550	275	112	1,230
312.7	Other Boiler Plant Systems				3,873	1,297	649	581	6,400
312.71	Condensate and Feedwater Systems	MW			2,061	742	371	317	3,491
312.72	Condensate and Feedwater Treatment and Supply System				788	316	158	126	1,388
312.73	Secondary Air System	LS			1,024	239	120	138	1,521

*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 (Continued)

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	–		14,084	7,319	3,941	1,972	2,732	30,048
314.1	Steam Turbine Generator and Aux.	MW		14,084		986	493	1,556	17,119
314.2	Condenser and Auxiliaries	BTU/HR			1,219	693	347	226	2,485
314.3	Circulating Water System				3,479	1,147	574	520	5,720
314.31	Pumps, Valves, Piping & Struct.	GPM			950	304	152	141	1,547
314.32	Cooling Tower	BTU/HR			2,529	843	422	379	4,173
314.4	Steam Piping Systems Main, Hot & Cold Reheat, Extraction, & Aux. Steam Systems	TON			2,070	1,032	516	362	3,980
314.5	Other Turbine Plant & Mech. Equipment	L.S.			551	83	42	68	744
315.	ACCESSORY ELECTRICAL EQUIPMENT				8,646	8,385	4,195	2,122	23,348
315.1	Station and Auxiliary Transf.	EA			711	55	28	79	873
315.2	Miscellaneous Motors	EA			1,092	258	129	148	1,627
315.3	S.G. and MCC's	CUB			1,744	387	194	233	2,558
315.4	Conduit, Tray, Cable and Bus Work	L.S.			2,976	6,343	3,172	1,249	13,740
315.5	Miscellaneous Electrical Equipment	L.S.			286	930	465	168	1,849
315.6	Integrated Control System	L.S.			512	334	167	101	1,114
315.7	Data Acquisition System	L.S.			955	39	20	101	1,115
315.8	Emergency Power Systems	L.S.			370	39	20	43	472
316.	MISC. POWER PLANT EQUIPMENT	L.S.			1,085	298	149	153	1,685

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TABLE 6-1 (Continued)

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

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			100,168	4,376	16,223	8,073	19,274	148,114
317.1	Combustion Equipment			12,793	1,188	3,141	1,571	2,679	21,372
317.11	Coal Drying	TPH		6,107	66	1,338	669	818	8,998
317.12	Coal Injection	TPH		5,852	52	1,634	817	833	9,188
317.13	Combustor	L.B.		780		20	10	81	891
317.14	Slag Coll. System	TPH			1,070	149	75	129	1,423
317.2	MHD Generator			4,502		116	59	936	5,613
317.21	Nozzle	L.B.		121		5	3	26	155
317.22	Channel (3000°F)	L.B.		3,563		81	41	737	4,422
317.23	Diffuser and Transition	L.B.		818		30	15	173	1,036
317.3	Magnet Subsystem	TON		29,022		419	210	5,415	35,066
317.31	Structure			3,928		81	41	405	4,454
317.32	Winding Assembly			14,952		16	8	2,895	17,371
317.33	Dewar			8,116		36	18	1,634	9,793
317.34	Refrigeration System			1,816		26	13	371	2,227
317.35	DC Power Instr. & Control			710		260	130	110	1,210
317.4	Inverters and Electrode Con.	MW		19,188		3,233	1,616	4,807	28,844
317.41	Inverters			16,288		2,808	1,404	4,100	24,600
317.42	Electric Consolidation Circ.			2,900		425	212	707	4,244
317.5	Oxidizer System	lb/hr		4,870	499	597	349	641	7,056
317.51	Air Compressor and Drive			4,870	-0-	487	244	560	6,161
317.52	Comb. Air Piping and Ductwork			-0-	499	210	105	81	895
317.6	Seed Subsystem	lb/hr KCO_2H		8,666	273	3,680	1,840	2,892	17,351
317.61	Seed Regeneration Process			8,666	-0-	3,598	1,799	2,813	16,876
317.62	Seed Injection System			-0-	273	82	41	79	475
317.7	Oxygen Enrichment System	TPH		21,127	2,416	4,937	2,428	1,904	32,812

TABLE 6-1 (Continued)

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				
350.	TRANSMISSION PLANT				3,309	573	287	418	4,587
350.1	Structures and Improvements	L.S.			111	129	65	31	336
350.2	Main Transformers	EA			1,528	80	40	165	1,813
350.3	Switchyard	L.S.			1,670	364	182	222	2,438
	SUBTOTAL - Direct Accounts			161,528	57,809	65,099	32,515	37,906	354,857
	ENGINEERING SERVICES								
	Preliminary Engineering								7,097
	Detailed Design								14,194
	Construction Management								7,097
	OTHER COSTS								7,097
	TOTAL ESTIMATED OVERNIGHT CONSTRUCTION COSTS								390,342
	CONSTRUCTION PERIOD, YEARS								4.83
	*TOTAL ESTIMATED COST (including Interest and Escalation during Construction)								422,350
	*Mid-1978 dollars								

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TABLE 6-2

200 MW_e PLANT TYPICAL

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			675			18	743
311.	STRUCTURES AND IMPROVEMENTS	L.S.			10,955	6,909	3,456	2,132	23,452
311.1	Improvements to Site	L.S.			763	1.165	583	251	2,762
311.2	MHD Building	C.F.			3,565	1,886	943	639	7,033
311.3	Bottoming Plant Building	C.F.			4,133	2,456	1,228	782	8,599
311.4	Steam Generator Building (FDN's)	C.Y.			31	91	46	17	185
311.6	Maint. Serv., Warehouse and Office Buildings	C.F.			1,180	517	259	196	2,152
311.7	Other Buildings	C.F.			250	348	174	77	849
311.8	On-site Waste Treatment	L.S.			1,033	446	223	170	1,872
312.	BOILER PLANT EQUIPMENT			22,124	9,432	14,704	7,353	5,892	59,505
312.1	Coal Handling and Processing	TPH			5,107	1,760	880	775	8,523
312.11	Unloading and Yard Storage				2,277	755	378	341	3,751
312.12	Reclaim and Delivery				2,830	1,005	503	434	4,772
312.2	Slag and Ash Handling	TPH			1,010	252	126	139	1,527
312.4	Steam Generator			20,534	513	10,326	5,163	4,115	40,651
312.41	Steam Generator	TON		20,534	14	10,058	5,029	4,014	39,649
312.43	Instrumentation and Controls				366	178	89	71	704
312.44	Auxiliaries				133	90	45	30	298
312.5	Effluent Control			1,590	225	1,355	678	454	4,302
312.51	Precipitator and Breeching	ACFM		1,590	11	950	475	372	3,398
312.52	Chimney				214	405	203	82	904
312.7	Other Boiler Plant Systems				2,577	1,011	506	409	4,503
312.71	Condensate and Feedwater Systems	MW			1,219	439	220	188	2,066
312.72	Condensate and Feedwater Treatment and Supply System				668	276	138	108	1,190
312.73	Secondary Air System	LS			690	296	148	113	1,247

TABLE 6-2 (Continued)

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	–		10,413	3,973	2,223	1,113	1,772	19,494
314.1	Steam Turbine Generator and Aux.	MW		10,413		729	365	1,100	12,657
314.2	Condenser and Auxiliaries	BTU/HR		-0-	545	224	112	88	969
314.3	Circulating Water System				1,984	656	328	297	3,265
314.31	Pumps, Valves, Piping & Struct.	GPM			590	192	96	88	966
314.32	Cooling Tower	BTU/HR			1,394	464	232	209	2,299
314.4	Steam Piping Systems Main, Hot & Cold Reheat, Extraction, & Aux. Steam Systems	TON			1,141	569	285	200	2,195
314.5	Other Turbine Plant & Mech. Equipment	L.S.			303	45	23	37	408
315.	ACCESSORY ELECTRICAL EQUIPMENT				5,009	4,617	2,310	1,196	13,132
315.1	Station and Auxiliary Transf.	EA			392	36	15	44	481
315.2	Miscellaneous Motors	EA			602	142	71	82	897
315.3	S.G. and MCC's	CUB			1,205	213	107	153	1,678
315.4	Conduit, Tray, Cable and Bus Work	L.S.			1,641	3,486	1,743	687	7,557
315.5	Miscellaneous Electrical Equipment	L.S.			157	520	260	94	1,031
315.6	Integrated Control System	L.S.			282	184	72	56	614
315.7	Data Acquisition System	L.S.			526	21	11	56	619
315.8	Emergency Power Systems	L.S.			204	21	11	24	260
316.	MISC. POWER PLANT EQUIPMENT	L.S.			870	176	88	113	1,247

TABLE 6-2 (Continued)
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				
317.	MHD TOPPING CYCLE			53,379	2,100	8,877	4,407	10,219	78,982
317.1	Combustion Equipment			7,058	736	2,136	1,069	1,239	12,238
317.11	Coal Drying	TPH		3,250	11	1,123	562	563	5,509
317.12	Coal Injection	TPH		3,206	18	898	449	528	5,099
317.13	Combustor	L.B.		602		17	9	63	691
317.14	Slag Coll. System	TPH			707	98	49	85	939
317.2	MHD Generator			2,089		96	49	223	2,457
317.21	Nozzle	L.B.		84		5	3	9	101
317.22	Channel (3000°F)	L.B.		1,631		67	34	173	1,905
317.23	Diffuser and Transition	L.B.		374		24	12	41	451
317.3	Magnet Subsystem	TON		17,547		358	179	3,616	21,700
317.31	Structure			1,683		46	23	350	2,102
317.32	Winding Assembly			8,357		10	5	1,674	10,046
317.33	Dewar			5,437		26	13	1,095	6,571
317.34	Refrigeration System			1,370		20	10	280	1,680
317.35	DC Power Instr. & Control			700		256	128	217	1,301
317.4	Inverters and Electrode Con.	MW		9,196		1,543	772	2,302	13,813
317.41	Inverters			7,913		1,365	683	1,992	11,953
317.42	Electric Consolidation Circ.			1,283		178	89	310	1,860
317.5	Oxidizer System	lb/hr		2,604	66	329	149	315	3,463
317.51	Air Compressor and Drive			2,604		260	115	298	3,277
317.52	Comb. Air Piping and Ductwork				66	68	34	17	186
317.6	Seed Subsystem	lb/hr KCO_2H		4,840	150	2,068	1,035	1,619	9,712
317.61	Seed Regeneration Process			4,840		2.023	1,012	1,575	9,450
317.62	Seed Injection System				150	45	23	44	262
317.7	Oxygen Enrichment System	TPH		10,045	1,148	2,347	1,154	905	15,599

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TABLE 6-2 (Continued)

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				
350.	TRANSMISSION PLANT			-0-	1,823	314	158	383	2,678
350.1	Structures and Improvements	L.S.			61	71	36	17	185
350.2	Main Transformers	EA			842	43	22	91	998
350.3	Switchyard	L.S.			920	200	100	275	1,495
	SUBTOTAL - Direct Accounts			85,916	34,837	37,820	18,885	21,775	199,233
	ENGINEERING SERVICES								
	Preliminary Engineering								3,985
	Detailed Design								7,969
	Construction Management								3,985
	OTHER COSTS								3,985
	TOTAL ESTIMATED OVERNIGHT CONSTRUCTION COSTS								219,157
	CONSTRUCTION PERIOD, YEARS								4.33
	*TOTAL ESTIMATED COST (including Interest and Escalation during Construction)								235,155
	*Mid-1978 dollars								

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.

"Contingency" represents the total contingency that has been applied to each line item. As owner committed 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

Instabilities of material and labor markets

Uncertainties in project timing

Errors and omissions

Weather

Short-term strikes, walkouts, and other labor disputes

Other unforeseeable occurrences and conditions which would delay or other wise increase material and/or installation costs.

For the estimates of the typical 500 MW_e and 200 MW_e plants, a 10% contingency factor has been applied to Balance of Plant (BOP) structures, improvements and well defined mechanical systems. A 20% contingency factor has been applied to the following "higher technology" accounts:

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 and contingency), 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 Subtotal 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 vs plant size for both early MHD power plants and coal-fired steam plants with scrubbers. The graph does not include escalation and interest during construction. Also shown on the graph is the capital cost of the 800 MW_e ECAS Reference Steam Plant. These costs are reported in mid-1978 dollars.

6.2 "FIRST OF ITS KIND" 200 MW_e PLANT COST

A "first of its kind" plant capital costs were developed for the 200 MW_e plant. It does not include the separate research and development costs associated with any components of the power plant. In addition, this "first of its kind" plant cost estimate does not consider the prior design, construction and operation of a test facility, pilot or commercial demonstration plant, now identified as an ETF of about the same thermal capacity as the 200 MW_e commercial power plant considered here. In this "first of its kind" plant cost estimate the costs of "high technology" and prototypical or unusual equipment items were increased. This reflects additional engineering and design work, specific design features or margins incorporated in equipment design, additional

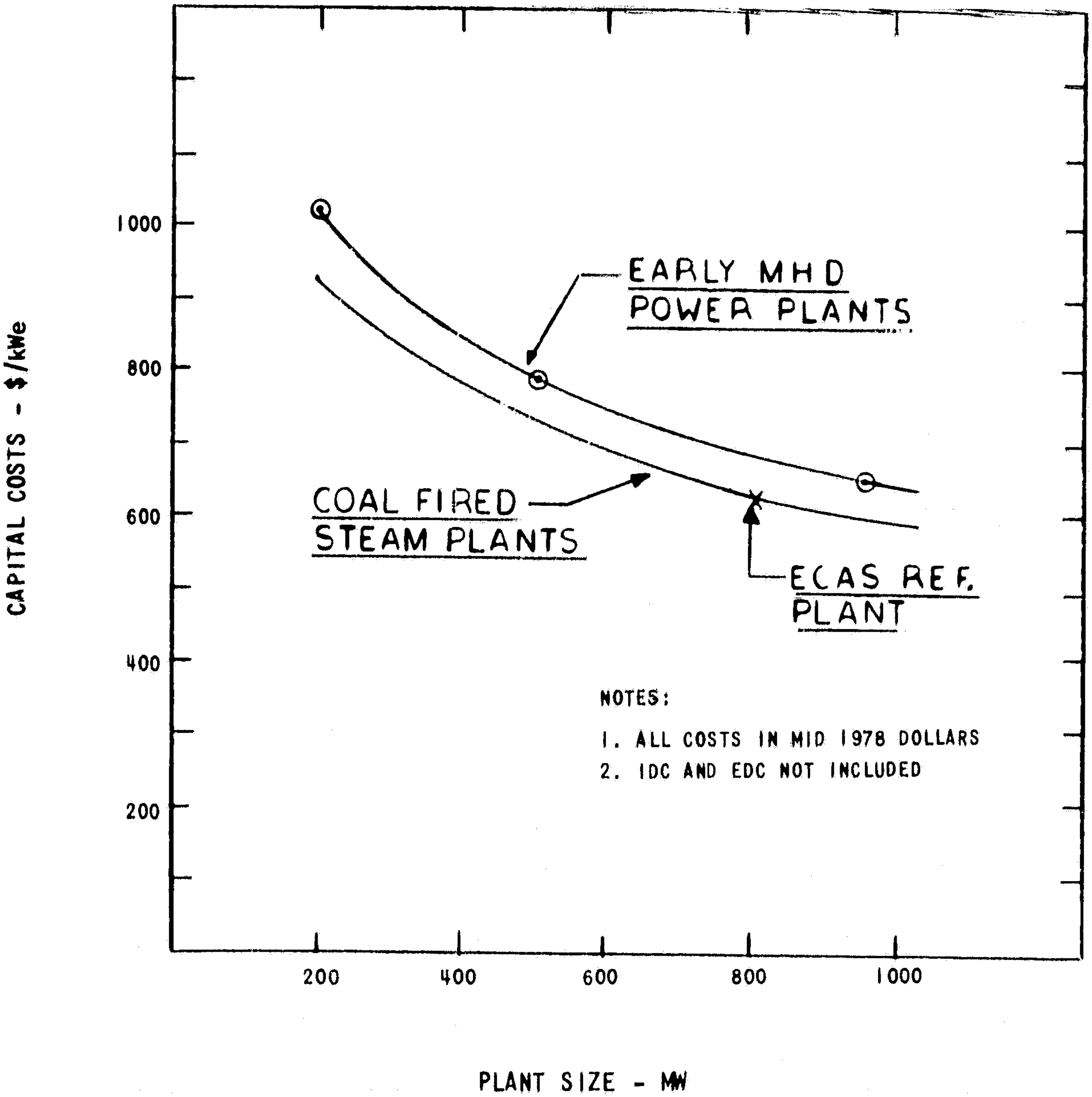

Figure 6-1 Capital Costs vs Plant Size

tests and procedures which are to be expected for producing equipment for "one and first of its kind" commercial plant. In real life, such increased costs for the "first of its kind" may not appear, but rather such additional costs for the "first" unit may be spread out over the expected sales of several subsequent units or simply considered the price for commercial introduction in a competitive market-place.

"First of its kind" cost increases have been estimated for the following "high technology" and prototypical or unusual equipment items:

Account No.	Account Description
312.4	Steam generator
312.51	Precipitator Breeching
317.1	Combustion Equipment
317.21	Nozzle
317.22	Channel
317.23	Diffuser and Transition
317.3	Magnet Subsystem
317.4	Inverters and Electrode Consolidation Circ.
317.61	Seed Regeneration Process

The contingency for each of the above items has been increased to 30% (from 20% in the initial 200 MW_e plant estimate) to reflect the lack of experience associated with "first of its kind" units. Also, the construction time period for the "first of its kind" 200 MW_e plant has been increased to 5 years, which is $\sim$ 8 months longer than for the typical 200 MW_e plant. This reflects the expected additional time required to construct, checkout and startup a plant on which there is no prior experience.

The cost estimate for the 200 MW_e "first of its kind" plant is shown on Table 6-3. Itemized costs are shown only in those accounts where equipment cost or contingency has increased from the typical 200 MW_e plant cost estimate. In those accounts where costs do not change from the typical 200 MW_e plant, only the total cost is shown.

It is mentioned that very limited efforts were allowed for estimating the above costs in these parametric analyses and that the cost estimates presented are considered to be rough.

It is also added that the commercial introduction of MHD power generation is considered to be different from that of nuclear or gas turbines, so that direct analogies with these two technologies are not apparent. In the latter cases the government played a vital role and provided extensive financial support which gave a direct basis for the present commercial nuclear and gas turbine industries.

TABLE 6-3

200 MW_e PLANT - FIRST OF A KIND
PROJECT COST ESTIMATE (DOLLARS X 10^{-3})

ACCOUNT NUMBER	ACCOUNT DESCRIPTION	UNIT	QUANTITY	MATERIAL: MAJOR COMPONENT	MATERIAL: BALANCE OF PLANT COST	INSTALLATION COST	INDIRECT COST	CONTINGENCY	TOTAL COST
310.	LAND AND LAND RIGHTS	ACRE							743
311.	STRUCTURES AND IMPROVEMENTS	L.S.							23,452
311.1	Improvements to Site	L.S.							
311.2	MHD Building	C.F.							
311.3	Bottoming Plant Building	C.F.							
311.4	Steam Generator Building (FDS's)	C.Y.							
311.6	Maint. Serv., Warehouse and Office Buildings	C.F.							
311.7	Other Buildings	C.F.							
311.8	On-site Waste Treatment	L.S.							
312.	BOILER PLANT EQUIPMENT								75,281
312.1	Coal Handling and Processing	[illegible]							8,523
312.11	Unloading and Yard Storage								
312.12	Reclaim and Delivery								
312.2	Slag and Ash Handling	TPH							1,527
312.4	Steam Generator	TON		23,807	581	12,210	6,105	12,811	55,514
312.41	Steam Generator			23,807	16	11,904	5,952	12,504	54,183
312.43	Instrumentation and Controls				432	216	108	227	983
312.44	Auxiliaries				133	90	45	30	344
312.5	Effluent Control	ACFM		1,879	225	1,355	678	1,077	5,214
312.51	Precipitator and Breeching			1,879	11	950	475	995	4,310
312.52	Chimney				219	405	203	82	904
312.7	Other Boiler Plant Systems	MW							4,503
312.71	Condensate and Feedwater Systems								
312.72	Condensate and Feedwater Treatment and Supply System								
312.73	Secondary Air System	LS							

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TABLE 6-3 (Continued)
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	--							10,494
314.1	Steam Turbine Generator and Aux.	MW							
314.2	Condenser and Auxiliaries	BTU/HR							
314.3	Circulating Water System								
314.31	Pumps, Valves, Piping & Struct.	GPM							
314.32	Cooling Tower	BTU/HR							
314.4	Steam Piping Systems Main, Hot & Cold Reheat, Extraction, & Aux. Steam Systems	TON							
314.5	Other Turbine Plant & Mech. Equipment	L.S.							
315.	ACCESSORY ELECTRICAL EQUIPMENT								13,132
315.1	Station and Auxiliary Transf.	EA							
315.2	Miscellaneous Motors	EA							
315.3	S.G. and MCC's	CUB							
315.4	Conduit, Tray, Cable and Bus Work	L.S.							
315.5	Miscellaneous Electrical Equipment	L.S.							
315.6	Integrated Control System	L.S.							
315.7	Data Acquisition System	L.S.							
315.8	Emergency Power Systems	L.S.							
316.	MISC. POWER PLANT EQUIPMENT	L.S.							1,247

C-3

TABLE 6-3 (Continued)
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				
317.	MHD TOPPING CYCLE								100,425
317.1	Combustion Equipment			7,174	735	2,144	1,073	3,328	14,465
317.11	Coal Drying	TPH		3,216	11	1,123	562	1,474	6,386
317.12	Coal Injection	TPH		3,206	18	898	449	1,371	5,942
317.13	Combustor	L.B.		752		25	13	237	1,027
317.14	Slag Coll. System	TPH			707	98	49	256	1,110
317.2	MHD Generator			2,669		142	72	865	3,748
317.21	Nozzle	L.B.		100		7	4	33	144
317.22	Channel (3000°F)	L.B.		2,120		101	51	582	2,554
317.23	Diffuser and Transition	L.B.		449		34	17	150	650
317.3	Magnet Subsystem	TON		21,784		408	204	6,719	29,115
317.31	Structure			2,104		60	30	658	2,852
317.32	Winding Assembly			10,859		18	8	3,265	14,149
317.33	Dewar			6,520		30	15	1,570	8,535
317.34	Refrigeration System			1,500		22	11	460	1,993
317.35	DC Power Instr. & Control			800		280	140	366	1,586
317.4	Inverters and Electrode Con.	MW		12,997		2,193	1,097	3,486	19,683
317.41	Inverters			10,907		1,881	941	2,746	16,475
317.42	Electric Consolidation Circ.			2,090		312	156	740	3,208
317.5	Oxidizer System	lb/hr							6,778
317.51	Air Compressor and Drive								
317.52	Comb. Air Piping and Ductwork								
317.6	Seed Subsystem	lb/hr KCO_2H		5,090	150	2,172	1,087	2,528	11,027
317.61	Seed Regeneration Process			5,090		2,127	1,064	2,484	10,765
317.62	Seed Injection System				150	45	23	44	262
317.7	Oxygen Enrichment System	TPH							15,599

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TABLE 6-3 (Continued)
PROJECT COST ESTIMATE (DOLLARS X 10^{-3})

ACCOUNT NUMBER	ACCOUNT DESCRIPTION	UNIT	QUANTITY	MATERIAL: MAJOR COMPONENT	MATERIAL: BALANCE OF PLANT COST	INSTALLATION COST	INDIRECT COST	CONTINGENCY	TOTAL COST
350.	TRANSMISSION PLANT								2,678
350.1	Structures and Improvements	L.S.							
350.2	Main Transformers	EA							
350.3	Switchyard	L.S.							
	SUBTOTAL - Direct Accounts								236,442
	ENGINEERING SERVICES								
	Preliminary Engineering								4,729
	Detailed Design								9,458
	Construction Management								4,729
	OTHER COSTS								4,729
	TOTAL ESTIMATED OVERNIGHT CONSTRUCTION COSTS								260,087
	CONSTRUCTION PERIOD, YEARS								5.0
	*TOTAL ESTIMATED COST (including Interest and Escalation during Construction)								282,294
	*Mid-1978 dollars								

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6.3 COST OF ELECTRICITY - 500 MW_e and 200 MW_e PLANTS

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 6-4. Escalation and interest cost factors are given in Table 6-5. Items 1 through 3 and 5 through 14 of Table 6-4 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/hr. 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 contractor's costs adders.

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 Tables 6-1, 6-2 and 6-3 for the base labor rate of $14.20/hr. The production costs consists of fuel costs and O&M costs. Fuel costs are developed from the plant efficiency discussed in Section 2.2.

Figure 6-2 shows the levelized COE vs plant size for the coal-fired steam plants considered in Figue 6-1, and the early MHD plants. Also shown is the levelized COE for the 800 MW_e ECAS Reference Steam Plant. As can be seen from the graph the levelized COE for the MHD plants in the 200 MW_e to 950 MW_e size range are below those for comparable coal-fired steam plants.

As specified by DOE a sensitivity analysis was conducted to determine the effects of varying labor rate, fuel cost and real fuel escalation on COE. Three values of labor rate and fuel costs and four values of real fuel escalation have been considered. Tables 6-6 and 6-7 present arrays of levelized COE for the various combinations of these variables for the 500 MW_e and 200 MW_e plants, respectively.

6.4 OPERATING AND MAINTENANCE COSTS - TASK II (950 MW_e PLANT)

6.4.1 Introduction and Summary

Non-fuel operating and maintenance costs were calculated in more depth for the larger 950 MW_e plant studied in ("Conceptual Design Study of Potential Early Commercial MHD Power Plant"). A search of the literature was conducted to determine the best method to perform these calculations. Most, if not all, methods report O&M costs in mills/kWhr or in fixed non-fuel O&M costs in $/kW/MO and variable O&M costs in mills/kWhr. In all cases, labor and material are lumped together with no apparent convenient method of separting the two. In addition, the utilities practice great latitude in how the various components are reported.

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TABLE 6-4

ECONOMIC PARAMETERS

Plant Size	500 MW_e	200 MW_e	200 MW_e
1. Plant Life, Years	30	30	30
2. Plant Site		Middletown, USA	
3. Capacity Factor	65%	65%	65%
4. Construction Time	4.83	4.33	5.0
5. Fixed Charge Rate	18%	18%	18%
6. Escalation During Construction	6.5%	6.5%	6.5%
7. Interest During Construction	10%	10%	10%
8. Percent Expenditure vs Time	Specified "S" curve (see Table 6-3)		
9. Economic Base Year		Mid - 1978	
10. Fuel Cost (coal) ¢/M Btu	105	105	105
Fuel Cost Range ¢/M Btu	105-150	105-150	
11. Labor Rate (1), $/hr	14.20	14.20	14.20
Labor Rate Range $/hr	14.20-17.04	14.20-17.04	
12 Plant Performance for COE	Full load heat rate		
13. Fuel & O&M Levelizing Factor	2.004 (for real fuel esc. rate = 0)		
14. Real Fuel Escalation (2)	0 to 3%/year		

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

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

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TABLE 6-5

ESCALATION AND INTEREST COST FACTORS

[Escalation + Interst = Total. Annual rates; escalation, 6.5%; interest 10%]

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 Figure 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.

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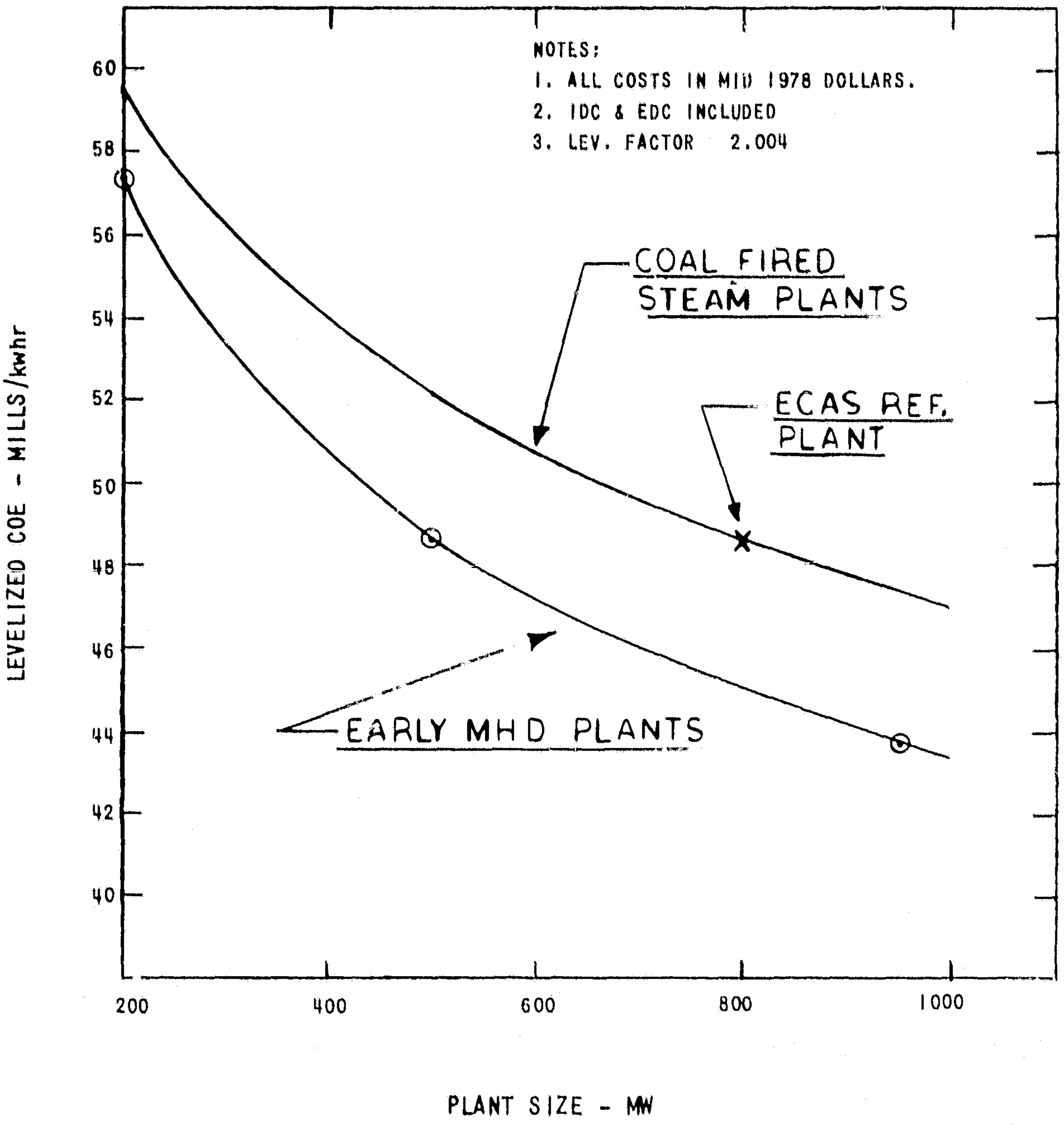

Figure 6-2 Levelized COE vs Plant Size

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TABLE 6-6

LEVELIZED COE FOR VARIOUS PARAMETERS

500 MW_e PLANT

Real Fuel Escalation	0	0.01	0.02	0.03
Levelizing Factor	2.004	2.292	2.636	3.049
		Levelized COE = mills/kWhr		
Fuel = 105¢/10^6 Btu				
Labor Rate $/hr				
20.59 (14.20)	48.50	51.68	55.45	59.98
22.65 (15.62)	51.15	54.33	58.10	62.63
24.71 (17.04)	53.80	56.98	60.75	65.28
Fuel = 125¢/10^6 Btu				
Labor Rate $/hr				
20.59 (14.20)	51.69	55.34	59.65	64.84
22.65 (15.62)	54.34	57.99	62.30	67.49
24.71 (17.04)	56.99	60.64	64.95	70.14
Fuel = 150¢/10^6 Btu				
Labor Rate $/hr				
20.59 (14.20)	55.68	59.90	64.90	70.91
22.65 (15.62)	58.33	62.55	67.55	73.56
24.71 (17.04)	60.98	65.20	70.20	76.21

TABLE 6-7

LEVELIZED COE FOR VARIOUS PARAMETERS

200 MW_e PLANT

Real Fuel Escalation	0	0.01	0.02	0.03
Levelizing Factor	2.004	2.292	2.636	3.049
	Levelized COE = mills/kWhr			
Fuel = 105¢/10^6 Btu				
Labor Rate $/hr				
20.59 (14.20)	57.49	60.80	64.75	69.51
22.65 (15.62)	58.59	61.90	65.85	70.61
24.71 (17.04)	59.69	63.00	66.95	71.71
Fuel = 125¢/10^6 Btu				
Labor Rate $/hr				
20.59 (14.20)	60.83	64.62	69.14	74.59
22.65 (15.62)	61.93	65.72	70.24	75.69
24.71 (17.04)	63.03	66.82	71.34	76.79
Fuel = 150¢/10^6 Btu				
Labor Rate $/hr				
20.59 (14.20)	65.01	69.39	74.64	80.95
22.65 (15.62)	66.11	70.49	75.74	81.05
24.71 (17.04)	67.21	71.59	76.84	82.15

In this estimate a Plant staff was developed including Supervision, Office, Clerical, Sercurity, Operations and Maintenance Personnel. Operations and Maintenance material costs were estimated for the major components that normally would be included in a conventional power plant. Additional costs for the MHD cycle components including the channel, combustor, nozzle, diffuser and transition section, the Seed Plant and the Oxygen Plant were developed. The maintenance costs for rebuilding the channel includes both labor and material. It was assumed tht the channel will be repaired at the manufacturer's facilities. As mentioned in Section 6.1 of Task II report (Reference 2) the channel maintenance costs equals the estimated costs for the initial channel after 10,000 hr of operation has been accumulated, but that channel maintenance can occur at shorter time intervals than 10,000 hr. The operating and maintenance costs for the O_2-plant were based on information provided by NASA (LOTEPRO). The total estimated O&M cost has been divided into fixed non-fuel O&M cost in $/kW/year and variable O&M costs in mills/kWhr. The rationale for the division into the above two costs was derived from a national Electric Reliability Study, Reference 8.

The total estimated levelized O&M cost for the plant is $26,714,600 in mid-1978 dollars or 4.94 mills/kWhr. The total costs has been divided into fixed non-fuel O&M costs in $/kW/year and variable O&M costs in mills/kWhr based on the assumed 65% capacity factor. In order to obtain these two costs the ratio between the total dollars and each of the two components was calculated from the National Electric Reliability Study, Reference 8, and used to calculate the fixed and variable O&M costs for the Early Entry MHD Plant. The results indicate that the fixed non-fuel O&M costs is 16.33 $/kW/year. The variable O&M cost is 2.08 mills/kWhr. A summary of this calculation is shown in Table 6-8.

6.4.2 Operating and Maintenance Costs

The operating and maintenance costs shown in Table 6-9, have been broken down in three major categories as specified for the Phase II 900 MW_e Plant, namely:

1. Labor and materials required for plant operation - Labor and materials have been listed separately. The operations labor includes management, administrative engineering and laboratory, instrument technicians and plant security including coal handling and the Seed Plant.

2. Labor and materials required for continuing plant maintenance or repair functions.

3. Labor and materials required for interim replacement or rehabilitation of major components such as MHD Generator, Combustor, Oxygen Plant, etc.

TABLE 6-8

O&M COST SUMMARY

CATEGORY	LABOR	MATERIAL
Plant Operation	$1,966,550	$1,043,800
Plant Maintenance	1,501,200	4,994,800*
Seed Plant	147,800	3,376,500
Oxygen Plant	120,000	180,000**
	$3,735,550	$9,595,100
		$3,735,550
Total O&M		$13,330,650

* Includes Labor for Channel Repair at Manufacturer's Facility
** Includes operation and maintenance labor for O_2 Plant

Levelization Factor for 30 years/ NASA = 2.004

$13,330,650 x 2.004 = $26,714,600

mills/kWhr @ 0.65 Cap. Factor $= \dfrac{26.714,600 \times 1000}{8760 \times 0.65 \times 949,000}$

= 4.94 mills/kWhr

Assume DOE Report[2] Ratio for fixed Non-Fuel O&M Cost and Variable O&M Cost

Fixed Non-Fuel O&M = 58%

Variable O&M = 42%

Early Entry Fixed Non-Fuel O&M Cost = $15,494,500

Early Entry Variable O&M Cost = $11,200,100

Fixed Non-Fuel O&M Cost = 16.33 $/kW/year

Variable O&M Cost = 2.08 mills/kWhr

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TABLE 6-9

OPERATION AND MAINTENANCE COSTS

1. PLANT OEPRATION

Labor		Material	
Administration	451,600	Wast Handling	336,700
Plant Operation	817,300	Make Up Water	400,000
Plant Eng.	687,650	Fuel Oil	114,800
		Insrumentation	50,000
		Station Supplies	142,300
Seed Plant	147,000	Seed	3,154,800
	$2,114,350		$4,198,600
			$2,114,350
Total Operation			$6,312,950

2. PLANT MAINTENANCE

Labor		Material	
Main. Labor Includ. Superv.	1,351,200	Water Treat	50,000
		Piping/Valves, ect.	90,000
Contract. Maint.	150,000	Aux. Rot. Equip.	10,000
		Boiler Maint.	700,000
		Channel Maint.	3,522,300
		Combuster	100,000
		Nozzle	2,500
		Diffuser and Trans.	20,000
		Turbine	500,000
Oxygen Plant	120,000		180,000
Seed Plant	*		221,700
	$1,621,200		$5,396,500
			$1,621,200
Total Maintenance			$7,017,700

Operation	$ 6,312,950
Maint.	$ 7,017,700
PLANT TOTAL	$13,330,650

*Seed Plant Labor included in Maintenance Labor

TABLE 6-9 (Continued)

3. IDENTIFED MAJOR MAINTENANCE ITEMS

MHD Channel	3,522,300
Combuster	100,000
Diffuser and Transtion	20,000
*Pulverizer Main.	94,000-378,561
Oxygen Plant	275,500
Seed Plant	221,700

*Estimates range from 5¢ to 20¢/ton

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It should be noted that the items listed in Item 3 should not be summed with Items 1 and 2. Labor and materials in Item 3 are included in the first 2 categories, but were broken out since they are major maintenance items.

The detailed breakdown for these various costs have been determined from a variety of sources including estimates by the Contractors for which no actual operating and/or maintenance data is available.

An attempt has been made to break these costs down into fixed non-fuel O&M costs in $/kW/year and a variable cost in mills/kWhr. This breakdown is not conveniently arrived at due to the various methods used by utilities and power pools. These types of costs will vary depending on how the costs are allocated in the utilities rate base and those costs that can be recovered in the sale or exchange of power between utilities and/or within power pools.

The National Electric Reliability Study, Reference 8, arrived at an allocation for non-fuel fied O&M costs in $/kW/MO and variable O&M costs in mills/kWhr. It determined that 58% represents the fixed O&M costs and 42% represents the variable costs for this size plant.

It is not possible in this study to accurately determine all the maintenance and operting expenses. Much of this expense will vary widely between plants of a given utility as well as different utilities. Much of the cost will depend on the preventative maintenance programs practiced by a specific plant and how each operating group performs their function of inspecting operating equipment and to make changes as required before extensive damage is incurred.

6.4.3 500 and 200 MW_e Plants

The total costs for the 500 MW_e Plant was calculated to be 5.25 mills/kWhr and for the 200 MW_e Plant 5.5 mills/kWhr.

7.0 NATURAL RESOURCE REQUIREMENTS AND ENVIRONMENTAL INTRUSION

Tables 7-1 and 7-2 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 7-1 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 7-2 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 ~ 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.

TABLE 7-1

ENVIRONMENT INTRUSION

	500 MW_e Plant		200 MW_e Plant	
Wastes	lb/hr	lb/kWhr	lb/hr	lb/kWhr
Ash	38,690	0.077	17,315	0.080
Gypsum	14,223	0.028	6,371	0.030
Heat Rejected	Btu/hr	Btu/kWhr	Btu/hr	Btu/kWhr
Cooling Tower	1.71 (10^9)	3,392	0.79 (10^9)	3,661
Chimney and Losses	4.1 (10^8)	813	1.9 (10^8)	880
Emissions	lb/hr	lb/10^6 Btu	lb/hr	lb/10^6 Btu
SO_x	2,268	0.57	1,015	0.57
NO_x	1,983	0.5	888	0.5
Particulate	63	0.016	28	0.016
Net Plant Output - MW	504.1		215.8	

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TABLE 7-2

NATURAL RESOURCE REQUIREMENTS

	500 MW_e Plant		200 MW_e Plant	
	lb/hr	lb/kWhr	lb/hr	lb/kWhr
Coal (22.7% Moisture)	444,730	0.882	199,020	0.922
K_2SO_4 - Seed Makeup	2,999	0.0059	1,407	0.0065
Unslaked Lime	6,120	0.012	2,075	0.0096
Watercooling Tower	GPM	gal/kWhr	GPM	gal/kWhr
Evaporation	2,565	0.305	1,110	0.309
Blowdown	855	0.102	370	0.103
Land	Acres	Acres/100 MW_e	Acres	Acres/100 MW_e
Waste Disposal	170	33.7	90	39.8
Plant Facilities	380	75.4	360	159.3
Total	550	109.1	450	199
Net Plant Output - MW	504.1		215.8	

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8.0 SUMMARY AND CONCLUSIONS

The plant performance analyses have shown that a relatively high net plant efficiency can be maintained for early commercial baseload MHD power plants in the size range 200 MW_e - 1000 MW_e. The calculated net plant efficiencies are 41.0% and 42.9%, respectively, for nominal plant capacities of 200 MW_e and 500 MW_e, which is 2.9 and 1.0 percentage points lower than the calculated efficiency of 43.9% for the larger 950 MW_e Task II power plant. All of these MHD plant efficiencies are significantly higher than the efficiency of 34.3% given for the reference steam plant with 175°F stack gas temperatures (Reference 7). (It is mentioned that this reference steam plant efficiency is based on supercritical steam conditions. Subcritical steam conditions as used for the steam bottoming plant in the early MHD power plant designs would reduce the conventional reference steam plant efficiency to about 33%). The calculated MHD power plant efficiencies in Task II and Task III are plotted in Figure 8-1. The curve in this figure shows the resulting variation in net plant efficiency versus MHD power plant size.

The calculated levelized costs of electricity for the two MHD power plants studied in Task III with nominal capacities of 200 MW_e and 500 MW_e and for the larger 950 MW_e studies in previous Task II are shown on the bar chart diagram in Figure 8-2. The contributions to total electricity costs of capital charges which are based on 18% fixed charge rate and 65% capacity factor, fuel costs which are based on 105¢/MBtu, and Operating and Maintenance (O&M) costs are indicated by the subdivisions of the bars in this figure. Comparable estimated electricity generating costs for conventional coal burning steam power plants of the same capacities as the MHD power plants are also shown on Figure 8-2. These are based on the capital cost curve for conventional steam power plants shown in Figure 6-1 in previous Section 6.1. In addition cost data for the modified ECAS reference steam power plant with 175°F stack gas temperature which has a nominal capacity of 800 MW_e is included in Figure 8-2. For all steam power plants the fuel costs have been based on the modified ECAS reference steam plant efficiency of 34.3%. For all the MHD power plants the electricity costs are found to be lower than for a conventional steam power plant of corresponding size. The projected reductions in electricity generating costs from the use of MHD compared to conventional steam technology are calculated to be 4.0 mills/kWhr for the 950 MW_e plant, 3.7 mills/kWhr for a 500 MW_e plant and 2.1 mills/kWhr for a 200 MW_e plant. The savings becomes less and less as the plant becomes smaller, as expected. However, the

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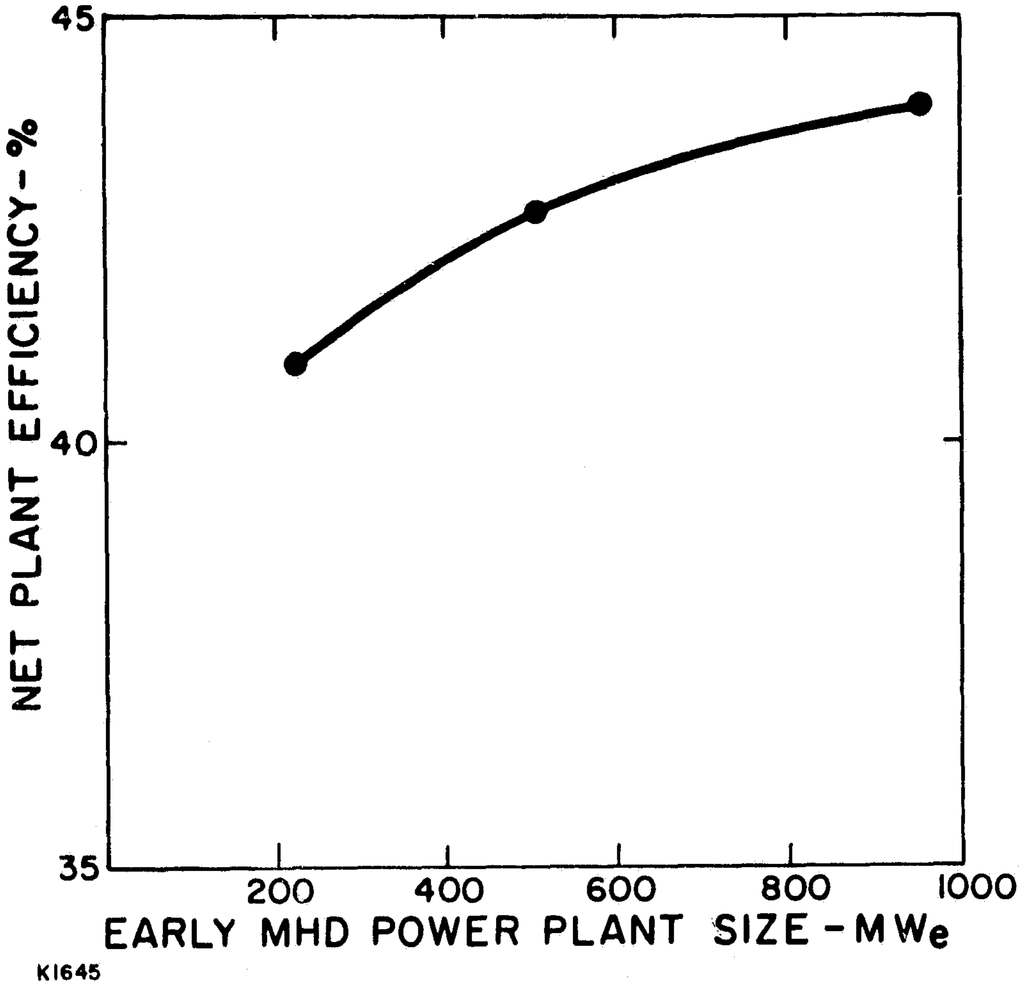

Figure 8-1 Net Plant Efficiency vs Plant Size

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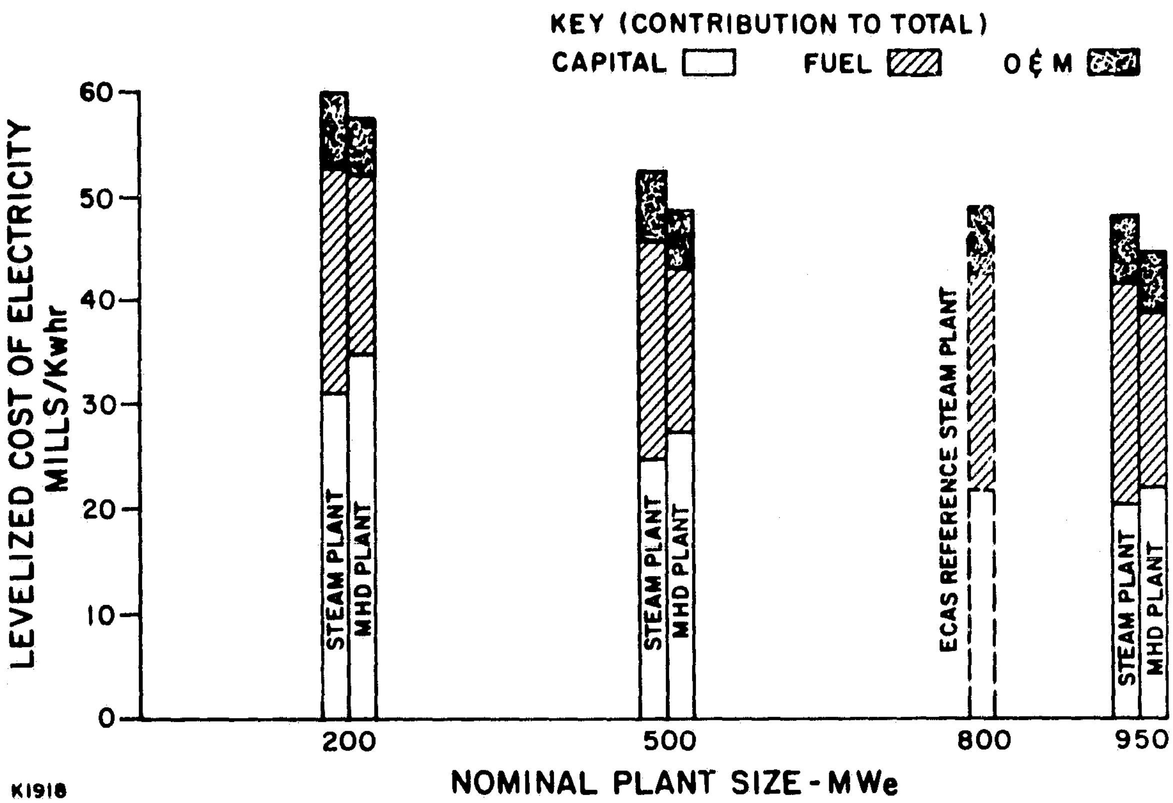

Figure 8-2 Comparative Levelized Costs of Electricity for Early MHD Power Plants and Conventional Steam Plants

electricity generating costs for even the smallest plant of 200 MW_e capacity is considered to be attractive compared to a corresponding conventional steam power plant. The above comparison is based upon a fuel cost of 105¢/MBtu. Higher fuel costs would increase the attractiveness of the use of MHD because of its much more efficient use of the fuel.

The MHD power plant designs presented here were based on the use of subsonic channel operation along with the use of a relatively high magnetic field (6 T). It results in a relatively high MHD generator performance without excessive electrical stress levels of the channnel.

Supersonic channel operation accompanied with the use of a lower magnetic field ($\sim$ 4.5 T) is considered to offer an important potential alternative to subsonic channel operation for early MHD power plants. For supersonic operation a relatively small reduction in plant performance can be expected for a significant reduction in magnetic field. This would reduce the magnet cost and risks substantially which might make supersonic channel operation very attractive, particularly for the <u>first</u> commercial plant. Therefore, further investigations and trade-off analysis between subsonic and supersonic MHD generator operation are recommended. It is considered prudent to emphasize low risk, cost and high reliability for the <u>first</u> commercial plant even though this may result in some penalty in performance.

In summary MHD power plants based on "moderate technology" design assumptions for early commercial use are attractive for baseload applications in all plant unit sizes from 200 MW_e and above.

The use of MHD power generation for the intermediate load range was not studied here. However, the results of this study indicates the potential use of MHD power generation also for this application because of its attractiveness even at the lower size range for baseload operation. Studies of MHD power generation for the intermediate and peaking load range are strongly urged. Intermediate and peaking load power plants with their lower capacity factors and smaller capital investments offer distinct advantages for the commercial introduction of any new energy conversion technology as was also experienced by the gas turbine.

9.0 REFERENCES

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APPENDIX A

COAL AND ASH ANALYSIS OF MONTANA SUBBITUMINOUS (ROSEBUD) COAL

Proximate Analysis, Coal
As Received, Percent

Moisture	22.7
Volatile Matter	29.4
Fixed Carbon	39.2
Ash	8.7

Ultimate Analysis, Percent

Hydrogen	6.0
Carbon	52.1
Nitrogen	0.79
Oxygen	31.5
Sulfur	0.85
Heating Value, Wet, Btu/lb	8920
Heating Value, Dry, Btu/lb	11539
Coal Rank	Subbit B

Ash Analysis, Percent

SiO_2	37.6
Al_2O_3	17.3
Fe_2O_3	5.1
TiO_2	0.7
P_2O_5	0.4
CaO	11.0
MgO	4.0
Na_2O	3.1
K_2O	0.5
SO_3	17.5
Initial Deformation Temp ^{o}F	2190 $\pm$ 230
Softening Temp ^{o}F	2230 $\pm$ 240
Fluid Temp ^{o}F	2280 $\pm$ 240

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APPENDIX B

SUMMARY OF AUXILIARY POWER REQUIREMENTS (kW)

	500 MW_e Plant	200 MW_e Plant
Superconducting Magnet		
Cryogenic System	400	240
Coal Handling and Proc.		
Feeders, Conveyors etc	724	326
Pulverizers and Blowers	2678	1183
Nitrogen Blowers	693	348
Coal Feeding		
Petrocarb System Comp.	1004	325
Steam Generator		
Boiler Circ. Pumps	2360	1060
Condensate Pumps	619	317
ID Fans and Sec. Air Blowers	1686	795
Electrostatic Precipitator	500	363
Seed Regeneration System		
Seed Regeneration Plant	4385	1973
Seed Feed System	14	6
Balance of Plant		
Circ. and Cooling Water Pumps	1884	935
Cooling Tower FAns	1282	632
Ash Handling System	216	109
Miscellaneous	82	34
Station Services		
HVAC, Lighting, Control Power, etc.	1000	500
TOTAL	19,527	9,146

APPENDIX C

NEW STATIONARY SOURCES PERFORMANCE STANDARDS FOR ELECTRIC STEAM GENERATING UNITS

JUNE 1979

<u>Emission Limits/10^6 Btu Heat Input</u>

<u>SO_2</u>

1.2 lbs maximum

90% reduction if > 0.60 lb/MBtu

70% reduction if < 0.60 lb/MBtu

<u>NO_x</u>

0.60 lbs for bituminous coal

0.50 lbs for subbituminous coal

<u>Particulates</u>

0.03 lbs