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ENGINEERING TEST FACILITY CONCEPTUAL DESIGN

Final Report: Part 2

June 1978

MASTER

Work Performed Under Contract No. EF-77-C-01-2614

Avco Everett Research Laboratory, Inc.
a Subsidiary of Avco Corporation
Everett, Massachusetts

U. S. DEPARTMENT OF ENERGY

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2.13 STEAM PLANT

2.13.1 Steam Generator

2.13.1.1 Performance and Tradeoff Analysis

The conceptual steam generator design represents a significant departure from conventional boiler practice. This design evolved from consideration of a number of problem areas which are peculiar to the MHD application and drew heavily from both utility and industrial recovery boiler state-of-the-art.

The steam generator is of multi-chamber design and divided into:

- Primary radiant slag furnace
- Secondary seed recovery furnace
- Afterburner and subsequent third chamber which includes air and gas tubular heaters
- Economizer

The most important factors influencing the steam generator design are discussed below.

NO_x Control - Due to the very high combustion temperature associated with MHD power generation, emission control of nitrogen oxides has been of concern throughout the design process. A further discussion of this particular pollution problem is contained in the following Section 2.12.2 entitled, "NO_x Emission Control." Design features are incorporated for solving this problem. They are based on experimental and analytical work and involve:

- a. Substoichiometric combustion in the primary MHD combustor.
- b. Controlled cooling of the slightly fuel rich high temperature MHD generator exhaust gases with provision for extended residence time of these above gas temperatures of 2900°F. This will allow the NO_x compounds to decay toward their equilibrium concentrations and below current EPA standards.

A gas residence time of ~ 2 sec is provided by reducing the gas velocity in the initial boiler chamber (primary radiant furnace). The furnace chamber walls are lined with refractory in order to reduce heat transfer and the gas cooling rate.

Results from analytical calculations described in the following section show that the NO_x level in the gas can be reduced to below EPA standards with the above design features of the radiant primary furnace and proper substoichiometric gas mixture. Complete oxidation of the combustion gases are attained by afterburning at a lower temperature of about 1900°F in the subsequent part of the boiler.

Seed Recovery - Efficient recovery of K_2SO_4 seed is essential for economic operation of the open cycle MHD system. Therefore, careful consideration was given to this important problem in the design of the steam bottoming plant.

Condensation and solidification temperatures for K_2SO_4 are roughly 2250°F and 1970°F , respectively. By maintaining the temperature leaving the primary boiler (slag) chamber at roughly 2900°F , the amount of seed lost in that chamber is minimized. The second boiler (seed recovery) chamber is designed to cool the gas from 2900°F to about 1900°F . During this cooling the gas seed will condense and then pass from the liquid phase to the solid phase. Some of the seed, along with some of the remaining ash, will be collected in a hopper at the bottom of the chamber. There will be no pockets where the seed/slag might be trapped. Similar hoppers will be provided in the third boiler chamber which includes air and gas tubular heaters and the Rear Convective (Economizer) pass. Essentially, all of the solids remaining in the gas stream after passing over the convective surfaces will be removed in the gas cleanup device (ESP) before the gas is sent to the stack. Material collected in the hoppers and in the ESP will be processed as necessary for seed reclamation.

Materials Problems - Because high metal temperatures are expected in the Low Temperature Air and Gas Heaters and finishing Superheater, SA 213-304 and -310 stainless steels will be used in these sections.

Waterwall tubes in the Slag and Seed Recovery furnace chamber will be made of carbon steel. The walls in the Slag furnace chamber will be covered with high magnesia refractory to control the rate of heat transfer. Because these chambers will be exposed to a reducing atmosphere, and to protect against corrosion from molten seed, the tubes will be aluminized. This will provide added protection in the Slag Chamber, in the event that cracks develop in the refractory.

Circulation - The waterwall circuitry is necessarily complex for this multi-chambered steam generator design. This factor dictated the use of Controlled Circulation (i.e., pumped circulation with orifices) to assure positive circulation in the required amounts under all operating conditions.

Steam Conditions - The design was based on steam conditions of 1250 psi/950°F to match the steam turbine equipment originally selected. The selection of alternate steam conditions have been discussed in Section 1.4.2.4.3.

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 which address this (anticipated) critical problem.

- The gas is cooled below the potassium sulfate melting point (1970°F) before entering any closely spaced tube assemblies.
- The convective pass is designed for low gas velocities and SH assemblies are vertically oriented (recovery boiler design practice for sodium sulfate laden gases employs these approaches).
- Numerous rotary sootblowers are provided in the convective section to permit periodic cleaning of the assemblies.

2.13.1.2 Primary Radiant Slag Furnace Design

The Steam Generator consists of a multi-section unit with pressurized water-cooled walls. The MHD diffuser will discharge $\sim 517 \times 10^3$ lb/hr gas flow at a temperature of 3700°F into the Primary Radiant Slag Furnace chamber. This chamber, 67' high with a 21.5' by 20.8' plan area, will be wet-bottomed and lined with a high magnesia ram refractory mix (from 1" to 4" thick). The gas will enter horizontally through a single opening near the bottom of the chamber and move upward at a velocity of ~ 30 ft/sec. The average uniform gas cooling rate will be about 400 F/sec which provides a gas dwell time above 2900°F of about 2 sec to ensure NO_x emission control. The flue gas exits the Primary Radiant Furnace chamber at about 2900°F.

Cooling will be by SA 210C fusion welded 1-1/4" OD carbon steel tubes with aluminizing on the furnace side for corrosion protection.

A single air nozzle, located 16' from the top of the chamber, will be provided to introduce secondary air for afterburning of the gas at reduced load. During normal load, secondary air for afterburning is injected and

mixed with the gas at a later point and just prior to leaving the secondary seed recovery furnace. However, at reduced loads the gas temperatures entering the normal burnout zone are not expected to be high enough to ensure complete oxidation of the gas. Therefore, under these operating conditions it becomes necessary to introduce secondary air for afterburning at the top of the primary furnace where the gas temperature always remains sufficiently high for afterburning of the gas.

Six oil guns (rated at 34×10^6 Btu/hr each) will be located in the lower region of the slag furnace chamber. These guns will be used to provide sufficient heat input to the chamber during startup and shutdown to prevent excessive temperature gradients in the refractory.

2.13.1.3 Secondary Seed Recovery Furnace Design

The flue gas will enter near the top of the Seed Recovery Furnace chamber at 2900°F and will be cooled to about 1900°F in the chamber. The chamber will be dry bottomed, 67' high by 20.8' by 20.8'. The waterwall surface consists of aluminized 1-1/4" OD carbon steel tubes, fusion welded on 1-3/4" centers.

The finishing Superheater panels will be located in this section. As the gas is cooled in this chamber, the seed component (K_2SO_4) will pass through both the condensation and solidification points (2250°F and 1970°F , respectively). The critical zone in the gas path will, therefore, be in the upper portion of the chamber where molten seed is formed and deposited on the panels and upper waterwalls. Molten seed is expected to be highly corrosive. As the seed enters the cooler lower portion of the chamber, it will solidify. Some of the condensed seed material, along with some of the remaining ash, will be collected in the dry hopper at the bottom of the chamber. The remaining seed, will be carried with the gas to the subsequent third chamber.

Just prior to leaving the seed recovery chamber, the gas under normal load operating conditions will be mixed with preheated air (54×10^3 lbs/hr at about 500°F) for afterburning of the gas. The gas temperature at the bottom of the chamber will then be about 1900°F which is sufficiently high for relative rapid oxidation of CO to CO_2 . The air will be introduced through 6 auxiliary air registers at the inlet to the transition passage between the second seed

recovery furnace and subsequent third chamber. The final flue gas composition will contain ~ 5% excess air. Wall blowers will be provided in the lower portion of the chamber to prevent excessive accumulation of seed/slag material in this region.

2.13.1.4 Third Chamber (Air Heater Chamber)

The third chamber in the Steam Generator is referred to as the Air Heater Chamber. In addition to carrying out the balance of the evaporation duty and first steam superheating it contains the heaters for heating of air and recycle gas for the high temperature preheater to 1100°F. The lower cavity of this chamber is also used to complete the burnout of the substoichiometric flue gas mixture initiated in the transition section from the upstream Seed Recovery Chamber.

The concurrent heat absorption in the walls of the transition passage and the lower part of the Air Heater Chamber during burnout will result in a gas temperature of about 1770°F approaching the heater surfaces.

The Low Temperature Air and Recycle Gas Heater panels and the initial and intermediate Superheater sections will be located in the upper portion of this chamber. The overall chamber height will be located in the upper portion of this chamber. The overall chamber height will be 67'. The plan of the lower chamber will be 20.8' by 20.8'. Additional seed and slag will be collected in the dry bottom hopper to be recycled to the primary MHD combustor.

The rear pass of the steam generator will contain the Economizer sections. Flue gas will enter this pass at ~ 800°F and will be cooled to the cleanup inlet temperature of 275°F. This section will also include a dry bottom hopper for the collection of seed and slag. The collected material will be recycled to the primary MHD combustor.

Wall blowers will be provided in the lower portion of this chamber to prevent excessive accumulation of seed/slag material in this region. Fully retractable soot blowers will be provided in the upper Air Heater Chamber to prevent solids accumulation on the Low Temperature Air Heater and Superheater convective surfaces.

2.13.1.5 Low Temperature Air and Gas Heaters

The Low Temperature Air and Gas Heaters, located in the third chamber, will be divided into 2 major sections, each consisting of multiple

panels of tangentially welded 1-7/8" OD chromium-molybdenum or stainless steel tubes. The heater sections will be used to heat the combustion air and recycle gas for the High Temperature Air Heater to the required inlet temperature. All heater tubes will be vertically oriented to prevent gas side plugging.

One of the two heater sections will consist of 10 panels, 7' by 41.3', with 22-1/2" transverse spacing for minimum blockage due to slag/seed buildup. HTAH combustion air will enter at the top of this section at ~ 510°F and flow downward through the panels, discharging at 1100°F. A single pass design was incorporated to minimize air-side pressure drop.

The other LTAH section will consist of a total of 16 panels, 6.25' by 45.8', with 14-3/4" spacing for low blockage due to gas side buildup. HTAH combustion air will flow through 10 panels, entering at ~ 510°F and exiting at 1100°F. HTAH recycle gas will flow through the remaining 6 panels, entering at ~ 320°F and exiting at 1100°F.

The air and gas will enter through separate inlet manifolds at the top and flow downward in a single pass, exiting into separate manifolds located between the Air Heater Chamber and the Rear (Economizer) Convective Pass.

2.13.1.6 Superheater Design

Saturated steam leaves the drum and flows through the roof tubes of the third chamber. The steam then proceeds to the convective pass walls before entering the initial superheat convective assembly. The Superheater will be divided into 2 major sections. The primary section consisting of 5 banks of 2" OD tubing will be located in the convective pass. Longitudinal tube spacing will be 4.5" for all banks. Transverse tube spacing will be 6.75" for the first and final banks and 4.5" for the remaining 3 banks. Intermediate Superheater assemblies will be vertically oriented to minimize fouling.

The second (finishing) Superheater section will be located in the Seed Recovery furnace chamber. This section will consist of 6 U-shaped panels of 2" OD tangentially welded stainless steel tubes. The panels will be 9.4' by 47.2' with 5.2' spacing between panels. Steam from the primary Superheat section will enter 3 of the finishing panels at the top, flow through the U-shaped path, and exit at the top. Two spray desuperheaters will be provided between these first three and the final three Superheater panels for temperature control.

The desuperheaters will be sized to provide up to 75°F temperature control at design point conditions. The steam will then flow through the final 3 panels, exiting at a final condition of 1345 psia and 955°F.

2.13.1.7 Economizer Design

The Economizer will consist of 11 banks of 2" OD SA 178A tubes located in the rear pass of the third chamber. The tubes will be oriented horizontally, since particle loadings and temperatures are expected to be low enough to preclude disposition problems. Longitudinal and transverse tube spacing will be 4.0" and 6.0", respectively.

Water conditions entering the Economizer will be ~ 1600 psia and 230°F. The water will leave the Economizer at ~ 350°F and 1570 psia. The flue gas will make several turns as it flows through the rear pass, entering at ~ 800°F and exiting at 275°F.

Multiple-nozzle rotary sootblowers spanning the width of the gas pass will provide for the periodic cleaning of the Economizer assemblies.

2.13.1.8 Summary Data

Data for the heat absorbing surfaces of the steam generator including air and recycle gas heaters are summarized in Table 2-52 and assembly details for these are presented in Table 2-53. The arrangement of the heat recovery steam generator with air and recycle gas heaters and economizer and subsequent electrostatic precipitator is shown in Figure 2-140.

Test program details for the steam generator are presented in Appendix B.

2.13.1.9 Instrumentation and Controls

The steam generator to be supplied to the MHD ETF is a balanced draft, controlled circulation, nonreheat unit. The steam generator recovers waste 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 electrical load will be shared between the MHD channel and the turbine generator and the load must fluctuate in unison.

Steam generator instrumentation is summarized in Tables 2-54, 2-55, and 2-56.

TABLE 2-52
STEAM GENERATOR HEAT ABSORBING SURFACES SUMMARY

<u>Section</u>	<u>Installed Surface (ft²)</u>	<u>Material</u>
Superheater	37, 545 (Developed)	SA-213 TP 304-H, SA-209 T-1, SA-210 A-1, SA-178 A
Air and Recycle Gas Heaters	15, 500 (Projected)	SA-213 TP 310, TP 304-H, T-9, T-22
Economizer	41, 054 (Developed)	SA-178 A
Evaporator	19, 700 (Projected)	SA-210 C (About 2/3 Aluminized)

TABLE 2-53

STEAM GENERATOR ASSEMBLY DETAILS

<u>Section</u>	<u>*Location</u>	<u>Tube OD</u>	<u>Transverse Spacing</u>	<u>Longitudinal Spacing</u>	<u>Comments</u>
LTAH-Air I	TC	1-7/8"	22.5"	1-7/8"	10 Panels
LTAH-Air II	TC	1-7/8"	14.75"	1-7/8"	8 Panels
LTAH-Recycle Gas	TC	1-7/8"	14.75"	1-7/8"	8 Panels
SH-Finishing	SRF	2.0"	5.2'	2.0"	6 Panels
SH-Pendant, Front	TC	2.0"	6.75"	4.5"	----
SH-Intermediate	TC	2.0"	4.5"	4.5"	----
SH-Low Temp.	TC	2.0"	6.75"	4.5"	----
Economizer	RP	2.0"	6.0"	4.0"	11 Banks
Waterwalls	PSF, SRF, TC	1-1/4"	1-3/4"	---	Fusion Welded Walls

* PSF - Primary Slag Furnace
 SRF - Seed Recovery
 TC - Third Chamber
 RP - Rear Pass

TABLE 2-54

MHD-ETF STEAM GENERATOR INSTRUMENTATION LIST

<u>Flows</u>	<u>Instrument or Method</u>	<u>Number</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Equivalent Range</u>
<u>Steam and Water</u>				
Feedwater	Differential Pressure Transducer	1	Feedwater Flow Nozzle	0-1500 gpm
Superheater Desuperheat	Calculated	1	Heat Balance	
Circulating Water	Water Manometer	2	Downcomer Pitot Tubes	
Waterwall Absorption Test Loops	Differential Pressure Transducer		Flow Nozzles; Slag Furnace and Seed Recovery Furnace Calorimeters	
<u>Air and Gas</u>				
Total Flue Gas	Pitot Traverse	1	Duct to ESP	0-150,000 scfm
Air to MHD Combustor	Laser Spectrophotometer to Measure CO/CO ₂	1	Diffuse Exit	
Total Air	Calculated		From Fuel Flow and Composition Plus Oxygen Meas.	
Burnout Air	Differential Pressure Transducer	1	Venturi Meter	
Burnout Air	Calculated		O ₂ Measurement of Gas at Economizer Outlet	

TABLE 2-54

MHD-ETF STEAM GENERATOR INSTRUMENTATION LIST (Cont.)

<u>Flows</u>	<u>Instrument or Method</u>	<u>Number</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Equivalent Range</u>
Coal Fan Air Flow	Differential Pressure	1	Venturi Meter	0-50, 000 cfm
Flue Gas Flow Distri- bution	Pitot Traverse		Sections in Steam Gen- erator Convective Pass	
<u>Solids</u>				
Slag to Ash Pit	Load Cell	1	Ash Bins	0-7000 pph
Solids from Hoppers	Load Cell	3	Ash Bins	0-5000 pph
Coal to Combustor	Calibration of Petrocarb ΔP	1	Primary Combustor/ Combustor ΔP	0-70, 000 pph
Coal to Pulverizer Coal Bin		1	Coal Feeder RPM	0-90, 000 pph

TABLE 2-54

MHD-ETF STEAM GENERATOR INSTRUMENTATION LIST (Cont.)

<u>Temperatures</u>	<u>Instrument or Method</u>	<u>Number</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Range (°F)</u>
Steam and Water	Calibrated CR-C Well Thermocouples	1	Economizer Inlet	0 - 500
		1	Economizer Outlet	0 - 500
		1	Superheater Outlet	0 - 1000
		1	Superheater Desuperheater Inlet	0 - 1500
		1	Superheater Desuperheater Outlet	0 - 1000
		1	Superheater Desuperheater Spray Water	0 - 500
		1	Transition Outlet	0 - 1000
		2	Downcomers	0 - 1000
			Furnace Calorimeters	
Metal	Calibrated Stainless Steel Sheathed CR-C Chordal Thermocouples	200	Furnace Waterwall Tubes - Slag Furnace; Vertical Strips, 20 each x 4 walls; Horizontal Strips, 10 each 4 2 alls x 3 elevations.	0 - 1000
		10	LTAH Panels - 3rd Chamber	0 - 2000
		20	Superheater Sections - 2nd and 3rd Chambers	0 - 2000
Air and Gas	CR-C Thermocouples	1	LTAH Inlet (Air and Re- cycle Gas)	0 - 1000
		1	LTAH Outlet (Air and Re- cycle Gas)	0 - 1500
		1	Economizer Inlet (gas)	0 - 1000

TABLE 2-54

MHD-ETF STEAM GENERATOR INSTRUMENTATION LIST (Cont.)

<u>Temperatures</u>	<u>Instrument or Method</u>	<u>Number</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Range (°F)</u>
Air and Gas	Shielded Aspirated Water Cooled Probes with Appropriate TC's (e.g., Platinum/ Platinum 10% Rhodium)	14	Slag Furnace Outlet, Finishing Superheater Out- let, LTAH Inlet/Outlet, Intermediate SH Points	0 - 3000
	Radiation Pyrometer	3	Intermediate Points in Primary Radiant Furnace	0 - 4000
	CR-C Thermocouples	1 1	Gas Entering Mill Gas to Baghouse	0 - 1000 0 - 500
Refractory (Absorp- tion)	Calibrated Stainless Steel Sheathed C-A Thermocouples		Slag Furnace	0 - 2000
Refractory (Moni- toring)	Calibrated Stainless Steel Sheathed Thermo- couples	40	Slag Furnace, Vertical Strips, 10 each	0 - 2000

TABLE 2-54

MHD-ETF STEAM GENERATOR INSTRUMENTATION LIST (Cont.)

<u>Pressures</u>	<u>Instrument or Method</u>	<u>Number</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Range psig</u>
Steam and Water	Calibrated Bourbon	1	Economizer Inlet	0 - 2000
	Gauges and Strain	1	Economizer Outlet	0 - 2000
	Gauge Pressure	1	Drum	0 - 2000
	Transmitters	1	Superheater Outlet	0 - 2000
		1	Superheater Spray Water	0 - 2000
Air and Gas	Water Manometers and Pressure Transmitters	3	Furnace	-10" to 10" H ₂ O
		1	Economizer Inlet (Gas)	-10" to 10" H ₂ O
		1	Economizer Outlet (Gas)	-10" to 10" H ₂ O
		1	Precipitator Outlet	-10" to 10" H ₂ O
		2	HTAH Blower Outlet (Air and Recycle Gas)	0 - 10
		2	LTAH Inlet (Air and Recycle Gas)	0 - 10
		2	LTAH Outlet (Air and Recycle Gas)	0 - 10
		3	Superheater Sections (Gas)	-10" to 10" H ₂ O
	Magnehelics	3	Across all Chambers	0 to 10" H ₂ O
	Strain Gauge Pressure Transmitters	1	Coal Storage Injector	0 - 200
		1	Coal Primary Injector	0 - 200
		1	Flue Gas to Mill	-10" to 0" H ₂ O
		1	Flue Gas from Mill	-20" to 0" H ₂ O
		1	Flue Gas to Cyclone	-20" to 0" H ₂ O
		1	Flue Gas to Coal Fan	-30" to 0" H ₂ O
		1	Flue Gas from Coal Fan	-10" to 0" H ₂ O
		1	Flue Gas from Baghouse	0" to 10" H ₂ O

TABLE 2-54

MHD-ETF STEAM GENERATOR INSTRUMENTATION LIST (Cont.)

<u>Flue Gas Constituents</u>	<u>Instrument or Method</u>	<u>Number</u>	<u>Location of Measurement or Calculation Procedure</u>
Nitrogen Oxides - NO _x	Chemiluminescence Analyzer	2	Economizer gas outlet and stack monitor.
		3	1st Radiant furnace chamber at inlet, 1/2 elevation and at transition to 2nd radiant furnace chamber.
Carbon Monoxide - CO	Infrared Analyzer	1	Economizer gas outlet and stack.
		1	Gas leaving finishing superheater.
		1	Gas to LTAH.
Total Hydrocarbons - THC	Flame Ionization Analyzer	2	Economizer gas outlet and stack.
Oxygen - O ₂	Paramagnetic Analyzer	1	Economizer gas outlet.
Sulfur Dioxide - SO ₂	Wet Chemistry	2	Economizer gas outlet and stack.
Carbon Dioxide - CO ₂	Calculated	2	Economizer gas outlet and stack.
Particulates	ASME Dust Collector	2	Economizer gas outlet and stack.
		1	ESP outlet.
Solids Levels	Load Cells	1	Pulverized coal storage bin.
		1	Coal storage injector bin.
		1	Coal primary injector bin.
Slag Deposits	Visual Observation		Slag furnace.

TABLE 2-55

FSSS PRIMARY ELEMENTS

<u>Device</u>	<u>No.</u>	<u>Measuring</u>
Pressure Switch	1	Primary Air Pressure Very Low
Pressure Switch	1	Primary Air Pressure Low
Pressure Switch	3	High Furnance Vacuum Trip
Pressure Switch	1	High Furnace Vacuum Alarm
Pressure Switch	1	High Furnace Pressure Alarm
Pressure Switch	3	High Furnace Pressure Trip
Pressure Switch	1	Ign. Atom. Air Pressure Low
Pressure Switch	1	Ign. Atom. Air Pressure Normal
Pressure Switch	1	Warmup Oil Atom. Air Pressure Low
Pressure Switch	1	Warmup Oil Header Pressure Low
Pressure Switch	1	Warmup Oil Supply Pressure Normal
Delta P Switch & Transmitter	1	Windbox/Furnance Delta P
Delta P Swtich	1	Purge Air > 30%
Delta P Switch	1	Scanner Duct/Furnance Delta P
Delta P Switch	3	Atom. Air/Oil Delta P High
Delta P Switch	3	Atom. Air/Oil Delta P Low
Level Switch	2	Drum Level High
Level Switch	2	Drum Level Low
Level Switch	2	Drum Level Low-Low-Trip
Flow Switch	1	Warmup Oil Flow Adequate
Pressure Switch	1	Ign. Oil Header Pressure Low
Pressure Switch	1	Ign. Oil Header Pressure Normal
Pressure Switch	1	Ign. Oil Header Pressure High

Three elevations of C-E ultraviolet self-checking flame scanners, including scanner air fan and air piping, will monitor the warmup firing.

TABLE 2-56
STEAM GENERATOR INSTRUMENTATION

<u>Device</u>	<u>No.</u>	<u>Measuring</u>
Pressure Transmitters	3	Furnance Pressure
Pressure Transmitter	2	Drum Pressure
Pressure Transmitter	1	Feedwater Pressure
Temperature Transmitter	1	Combustion Air Temperature
Temperature Transmitters	4	Desuperheat Outlet Temperature Superheater Outlet Temperature
Temperature Transmitter	1	Feedwater Temperature
Temperature Transmitter	5	Refractory Temperature
Flow Transmitter	1	Feedwater Flow
Flow Transmitter	1	Drum Outlet Steam Flow
Flow Transmitter	1	Oil Flow
O ₂ Transmitter	3	O ₂
Drum Level Transmitters	2	Drum Level
Temperature Transmitter	2	Mil Gas Outlet Temperature
Air Flow Transmitters	2	Combustion Air
Pressure Transmitter	1	S. H. O. Steam Pressure
Temperature Transmitter	1	Mill Inlet Temperature
Temperature Transmitter	1	Bag Filter Outlet Temperature

ANALOG CONTROL SYSTEM DUAL CONTROL DEVICE

Feedwater Control Valve
FD Fan Inlet Vanes
Desuperheater Spray Valve
Signal to "Blower" or Air Compressor Inlet Vanes

NOTE: Flow measurements include flow element and delta p transmitter.

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, air flow and feedwater flow.

The Digital Control System

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

Furnace Draft Controls

The furnace will be a balanced draft unit: the air compressor will be the equivalent of the FD fan; the furnace draft will be controlled by the ID fan. A conceptual schematic is shown as Figure 2-141.

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. The furnace pressure error is used to regulate the ID fan. Air 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 air 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 air 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.

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Figure 2-141 Furnace Draft Control

Steam Temperature Control

The function of the 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 used to control superheater outlet temperature. A cascade control system will be employed utilizing superheater outlet steam temperature and the steam temperature at the desuperheater outlet as shown schematically in Figure 2-142.

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.

Combustion Controls

There will be 2 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.

Six 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 30×10^6 Btu/hr of air atomized Number 2 oil. There will be 6 air atomized ionic flame monitor ignitors and 6 flame scanners.

Thermocouples will be used to monitor refractory temperatures during the warmup. Warmup will include synchronizing the turbine-generator and carrying up to ~ 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 ~ 10% of the air required for complete combustion of the pulverized coal being fired

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Figure 2-142 Steam Temperature Control

in the MHD channel, as the exhaust products of the MHD channel are about 95% stoichiometric and the flue gas exits the boiler at 5% excess air.

Before firing of the MHD channel 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 2-143 shows conceptually how the combustion control system will operate.

Feedwater Controls

The feedwater control system will be a standard 3 element feedwater control system. The feedwater flow is adjusted to maintain drum level at set-point as shown conceptually in the diagram of Figure 2-144.

2.13.2 NO_x Emission Control

2.13.2.1 Introduction

The nitric oxide efflux from the ETF heat recovery steam generator has been calculated under a variety of assumptions. It is found that with suitable adjustment of stoichiometry the NO_x efflux can be kept below the EPA limit. Furthermore, increase of the furnace wall temperature by refractory lining of the boiler tubes reduces the final NO_x level because of increase of the wall heat sink temperature.

We have also found that (1) the NO efflux is practically insensitive to the initial concentration of NO entering the steam generator, (2) the emissivity of the ash particulates from the MHD generator can be neglected in comparison with the gas emissivity, and (3) taking account of the radiation transport in the opaque CO_2 molecular radiation at 5 and 3 μm , which leads to a cold boundary layer at the steam generator wall, leads to a prediction of a 20% larger NO efflux than given by a similar calculation assuming a uniform temperature across the generator.

The estimate of particulate emissivity and comparison with gas emissivities is given in paragraph 2.13.2.2.2. The effect of variation in particle emissivity on NO efflux is given in paragraph 2.13.2.2.3. The dependence on stoichiometry, wall temperature and initial NO concentration is reported in paragraph 2.13.2.4. Paragraph 2.13.2.5 reports on the calculation of the temperature profile across the steam generator because of radiation transport in the opaque spectral regions and the radial dependence of the NO efflux. Section 2.13.2.6 discusses CO-oxidation.

Appendix E discusses the emissivity of particulates.

H3092

Figure 2-143 Combustion Controls

H309I

Figure 2-144 Feedwater Controls

2.13.2.2 Particulate and Gas Emissivities

2.13.2.2.1 Particulate Material Absorption Coefficients

We have reviewed the literature for information pertaining to the radiative properties of the ash particulates (carbon-free) expected from the MHD exhaust. The particulate composition is estimated to be 50% SiO_2 , 25% Al_2O_3 , 6% Fe_2O_3 , 14% CaO , and 5% MgO . From the information summarized below we conclude that the particulate emissivity will be small compared to the gas emissivity and can be neglected. However, by way of contrast we will also consider the case of opaque soot.

The data is presented in a graph of the wavelength dependence of the imaginary part of the index of refraction (n') (Figure 2-145). Also in Figure 2-145 we give lines of constant absorption coefficient (k) where

$$k = \frac{4\pi n'}{\lambda} \quad (2-57)$$

with k in cm^{-1} when λ is given in cm and n' is dimensionless.

Absorption coefficients for typical atmospherical aerosols such as sands and volcanic ash have values in the range 10^3 - 10^4 cm^{-1} (see Figure 2-145).^(48, 49, 50) Unfortunately the data is sparse in the spectral region 1 - 2μ which is most important to us, since this spectral region is where the Planck blackbody at about 2000°K has its maximum. As we show below particulates with material absorption coefficients of this magnitude will add to the radiant cooling in the steam generator and change the NO efflux.

If the MHD generates exhaust gas particulates are transparent like crystal quartz and sapphire, then its emissivity is low and can be neglected. From Plass⁽⁵¹⁾ we have values of the imaginary part of the index of refraction of aluminum oxide and magnesium oxide. These fall at the lower part of Figure 2-145 and in the spectral region 1 - 2μ have $k \lesssim 1 \text{ cm}^{-1}$. Associated studies of radiation from alumina in rocket exhausts support these results.^(52, 53)

We have one comparable example of emissivity of glassy solids from a furnace experiment. Mulcahy⁽⁵⁴⁾ and co-workers quote a total hemispherical emissivity (ϵ_τ) for combustion chamber deposit from p. f. boiler burning Leigh Creek coal (SiO_2 41.1%, Al_2O_3 26%, Fe_2O_3 13.3%, CaO 8.9%) of $\epsilon_\tau = 0.75$ at 1400°K using a fused sample with a thickness of $l \approx 0.3 \text{ cm}$. The absorption coefficient k is related to ϵ_τ by

$$\epsilon_\tau = 1 - e^{-2kl} \quad (2-58)$$

Figure 2-145 Absorption Coefficient and Imaginary Index of Refraction as a Function of Wavelength

Using Eq. (2-58) the corresponding value of the absorption coefficient is $k \approx 2.3 \text{ cm}^{-1}$. The 1400°K blackbody peaks at a wavelength of about $2 \mu\text{m}$. The corresponding imaginary part of the index of refraction is $n' = \lambda k / 4\pi \approx 3.7 \times 10^{-5}$. This is roughly consistent with the results of Plass for the Al_2O_3 and MgO . In any event particulates of this type as we show below are not important in our case. The Mulcay spectral value at $0.9 \mu\text{m}$ is $\epsilon_{0.9} \approx 0.55$ from which $k \approx 1.2 \text{ cm}^{-1}$ and $n' \approx 10^{-5}$. The smaller value at $0.9 \mu\text{m}$ is also consistent with Plass and close to the Plass estimate for magnesium oxide.

2.13.2.2.2 Gas Emissivity

To estimate the gas radiation we scale from the results of Kivel and Hals.⁽⁵²⁾ The dominant radiation sources remain CO_2 , H_2O and CO . The densities are essentially the same for CO_2 and H_2O and less by a factor 2 for CO . As an example, we reduce the distance by a factor 2 from 10 m to 5 m. We further reduce the emissivity by a factor $2/3$ to correspond to a geometry which is more sphere like than cylindrical. Taking account of these factors Figure 2-146 of Reference 51 is transformed to Figure 2-146.

From the lower part of Figure 2-146 we can estimate the radiation integrated over the spectrum to be about $8 \times 10^4 \text{ W/m}^2\text{-steradian}$. Dividing this by the Planck limit at 2000°K of about $3 \times 10^5 \text{ W/m}^2\text{-steradian}$ we estimate the gas emissivity to be $\epsilon_g \approx 0.27$. Since the radiation is primarily from H_2O and CO_2 , this result can be compared with results given by Hottel and Sarofim⁽⁵⁶⁾ in their Figure 6-13. Taking our conditions of $(P_{\text{CO}_2} + P_{\text{H}_2\text{O}}) \times L = 3.5 \text{ ft-atm}$ and a temperature of 3600°R we obtain their result of $\epsilon_g = 0.22$, which is about 20% less than ours. This disagreement is due to differences in approach and is not a fundamental contradiction.

2.13.2.2.3. Combined Emissivity

For comparison we estimate the particle radiation based on the emissivity corresponding to an absorption coefficient $k \approx 4 \times 10^3 \text{ cm}^{-1}$, $n_p = 6 \times 10^3 \text{ particles/cm}^3$, $r_p = 2 \times 10^{-4} \text{ cm}$ particle radius and chamber radius $R = 5 \times 10^2 \text{ cm}$ of $\epsilon \approx 0.42$. In Figure 2-147 we plot the intensity in $\text{W/m}^2\text{-steradian-cm}^{-1}$ as a function of wave number in units of 10^3 cm^{-1} . The smooth solid line is the particle contribution taken as 0.42 times the Planck limit. The sum of particle and gas radiation is found by combining the particle contribution with the gas contribution sketched in the bottom of Figure 2-146. The resultant curve is shown in Figure 2-147. It is limited

Figure 2-146 Molecular Radiators from a 5 m Slab in Comparison with the Planck Blackbody Limit

H2230

Figure 2-147 Spectral Intensity of Combined Particulate and Gas Radiations

by the Planck curve (dashed line). From Figure 2-147 we estimate the total emissivity to be $\epsilon_{Tot} \approx 0.60$. Thus when the absorption coefficient k is $> 4 \times 10^3 \text{ cm}^{-1}$ for the amount of material expected in the steam generator of the MHD/ETF then there will be a large increase in the emissivity and, hence, in the radiant cooling rate. An estimate of emissivity as a function of absorption coefficient is given in Figure 2-148.

2.13.2.2.4 F_E Operator for Engineering Scaling of Particulate Radiation

Bueters⁽⁵⁷⁾ has introduced a factor (F_E) to correct the Hottel and Sarofim gas emissivity (ϵ_g) for particulates and other gas sources to give the correct emissivity (ϵ_{Tot}) for engineering design calculations. His expression is

$$\epsilon_{Tot} = 1 - \frac{1}{F_E} + \frac{\epsilon_g}{F_E} \quad (2-59)$$

F_E is empirically determined. Typical values are $F_E \approx 1.2$ for gas firing and $F_E \approx 1.5$ for oil firing. These values are called out in Figure 2-148. Taking $\epsilon_{Tot} = 0.60$ as determined above and using $\epsilon_g = 0.27$ our value for the gas component, we obtain from Eq. (2-55) $F_E = 1.8$.

2.13.2.3 Kinetics Calculation

We have carried out uniform cooling calculations following Hals and Lewis⁽⁵⁸⁾ using a cylindrical model for the steam generator. The gas compressibility is included to determine the correct time to a given height. The gas emissivity based on Hottel and Sarofim⁽⁵⁶⁾ is taken to be $0.57-0.18T$ where T is the temperature in $10^3 \text{ }^\circ\text{K}$. The flow starts at temperature $2.3 \times 10^3 \text{ }^\circ\text{K}$ and the wall temperature is assumed $1.5 \times 10^3 \text{ }^\circ\text{K}$. The radius is taken as 3.61m and the initial flow speed is 10 m/sec. The wall emissivity is taken as 0.7. The temperature derivative of the enthalpy is given by $0.24 (3.52 - 3.85T + 1.43T^2)$ (cal/gm $^\circ\text{K}$). At the height of 18.9 m (62 ft) the temperature has cooled to 1800°K . The time to reach this height is about 2 sec. The temperature time history is the curve labeled $F_E = 1$ in Figure 2-149.

Uniform cooling calculations have been carried out to show the effect of the increased radiation from soot in furnaces. We use the effective emissivity model of Bueters⁽⁵⁷⁾ with the value $F_E = 1.5$ and 1.2 for soot and as a case without soot we use $F_E = 1$. Temperature profiles for these

Figure 2-148 Dependence of Total Emissivity on Material Absorption Coefficient

Figure 2-149 Uniform Cooling Curves for Several Values of F_E

values of F_E are given in Figure 2-149 as a function of time. The effect of soot is seen in the more rapid cooling rate and the lower final temperature. All curves will eventually approach the here assumed wall temperature of 1500°K . In Figure 2-150 we give the nitric oxide content in ppm as a function of height in meters. Since the nitric oxide concentration exceeds the EPA value of 600 ppm when the value $F_E \approx 1.5$ is used, we conclude that it is important to control the presence of soot which appreciably increased the emissivity.

A table of total emissivities is given below for gas without soot and for increased reduction from soot in the gas with values of $F_E \approx 1.2$ and $F_E \approx 1.5$.

T($^\circ\text{K}$)	ϵ_{Tot}		
	ϵ_g	$F_E = 1.2$	$F_E = 1.5$
2.3	.156	.297	.437
2.1	.192	.327	.461
1.9	.228	.357	.485
1.7	.264	.387	.509
1.5	.30	.417	.533

2.13.2.4 Results for Varied Initial Stoichiometry, NO Content and Furnace Wall Temperature

Nitric oxide composition has been calculated for several values of the stoichiometry, initial content of NO and furnace wall temperature. The temperature history was determined using the uniform cooling model for cylindrical furnace with a radius of 3.61 m. First a wall temperature of 1500°K was assumed. This corresponds to an estimated wall temperature for dirty boiler tubes without refractory lining. Bare boiler tubes would become dirty during normal operation from deposits by fly ash and condensed seed. The dew point for seed (K_2SO_4) is slightly above 1500°K .

Figure 2-150 Nitric Oxide Density as a Function of Furnace Height for Several Values of the Parameter F_E

The flow rate was initially 10 m/s. The initial temperature was taken as 2300°K. Four cases were run with an initial NO content of 2,138 ppm with stoichiometry ranging between .873 and .960. By keeping NO composition a constant fraction of the gas in all examples, we can see the effect of stoichiometry independent of changes in NO initial content. The initial values of all other species are in local equilibrium at 2300°K. The condition thus chosen is typical of the exhaust from MHD furnaces. The results are shown in Figure 2-151 which gives the nitric oxide content as a function of furnace height. A cross correlation graph of the amount of NO at 20 m height in the furnace is given in Figure 2-152. It is seen in Figure 2-152 that the stoichiometry must be less than about 0.94 to achieve a final NO content lower than the EPA limit. From Figure 2-151, we see that above 20 m the NO content does not decrease significantly. Two other runs were made to see the effect of initial NO content. One calculation had a stoichiometry of about 0.9 at an initial NO content of 4×10^3 ppm. The results are plotted in Figure 2-153. The final NO content is insensitive to the initial NO content as can be seen by proximity of the curves at 20 m in Figure 2-153.

The effect of varying the wall temperature between 1500°K and 1800°K was then investigated. The increase of the wall temperature above the dew point for seed (~1525°K) is in practice accomplished by lining of the boiler tubes with refractory material. This reduces heat transfer and gas cooling rate. In this way, condensation of seed is also avoided in the primary radiant furnace.

Figure 2-154 shows uniform gas cooling temperature conditions as a function of time for values of the wall temperature between 1.5 and 1.8 k°K assuming $F_E = 1$. Figure 2-155 shows the calculated NO concentration in ppm for a stoichiometry $\phi = 0.902$. At 20 m furnace height the NO efflux is reduced to its lowest value of 310 ppm at the highest assumed wall temperature of 1800°K. Theoretically, the NO efflux is still decreasing as furnace height increased. Similar results are given in Figure 2-156 for a stoichiometry of $\phi = 0.941$. The result shows that the EPA limit can be achieved with a higher stoichiometry if the wall temperature is higher.

Figure 2-151 Variation of Nitric Oxide Content as a Function of Height for Various Values of the Stoichiometry

Figure 2-152 Concentration of NO as a Function of Stoichiometry at a Height of 20 m in the Steam Generator

Figure 2-153 Concentration of NO as a Function of Height in the Steam Generator for Various Values of the Initial Concentration of NO and Stoichiometry

Figure 2-154 Temperature as a Function of Time for Various Values of the Wall Temperature Assuming the Particulate Emissivity can be Neglected ($F_E = 1$)

Figure 2-155 NO Efflux as a Function of Height in the Steam Generator for Several Values of the Wall Temperature for a Stoichiometry of 0.902

Figure 2-156 NO Efflux as a Function of Height in the Steam Generator for Several Values of the Wall Temperature for a Stoichiometry of 0.941

2.13.2.5 Radiation Diffusion Effect

The radiation transport effect which leads to a radiation boundary layer and more rapid cooling near the wall is treated in this section. The method of Kivel and Hals⁽⁵⁵⁾ is used where the radiation is divided into two groups: a transparent radiation and a diffusing radiation. We first obtain the radial temperature profiles and then do kinetics calculations to get the NO concentration as a function of height in the steam generator at several radial locations. A radial integral is then used to obtain the average NO efflux. The emissivity is chosen to be consistent with the Hottel and Sarofim emissivity developed for uniform cooling calculations.

Radial temperature profiles at several heights are given in Figure 2-157. Also on the righthand ordinate are uniform cooling temperature values.

In the radial furnace calculations we have used an effective emissivity which is close to that used in our 1974 report.⁽⁵²⁾ A slight adjustment has, however, been made to bring the rate of enthalpy flow through the furnace approximately equal for the uniform cooling and the diffusion cases. This has the advantage that we can compare the NO production as treated by the simple uniform cooling model and the more complete diffusion model and have the result interpreted in a way that is insensitive to uncertainties in the gas emissivity. That is, we have chosen the emissivity for the diffusion case to be comparable to that indicated by the Hottel-Sarofim tables and thereby obtaining the average cooling rate in the diffusion case which is almost equal to the cooling rate in the uniform case.

The total enthalpy flux comparison for the uniform cooling and diffusion cooling models is shown in Figure 2-158. The comparison is very good up to about 5 m and then deviates only slightly to a height of 10 m where the difference is only about 1.5%. For stoichiometry 0.9 the first 5 m is the most important where the NO concentration has dropped to about 480 ppm and most of the kinetics is over. The final NO concentration at 20 m is 390 ppm. Even at 20 m the enthalpy difference in the two enthalpy flux calculations is only 6.7%. We conclude that the total enthalpy match is sufficiently close for a reasonable comparison of the

RADIANT FURNACE ($R = 3.6\text{m}$, $\phi = 0.9$, $T_w = 1500^\circ\text{K}$)

Figure 2-157 : Radial Temperature Profiles in the Steam Generator Which Show the Effect of Radiation Transport

Figure 2-158 Enthalpy Flux as a Function of Height in a Steam Generator Using the Uniform Cooling Model and the Radiation Diffusion Model

NO production according to the two models and will serve as a check on the validity of the uniform cooling model for estimating NO efflux from a furnace.

The diffusion cooling calculation has been carried out for a stoichiometry $\phi = 0.9$. The temperature time history at several radial locations was run through the kinetics program to find NO concentrations in the function of height in the furnace. Values of NO as a function of radial position at a height of 20 m is given in Figure 2-159. At the center of the furnace the concentration is about 360 ppm. It is fairly constant in the central region although it falls slightly to a minimum at a radius of about 2.5 m, then rises very rapidly because of the rapid wall cooling due to radiation diffusion. At the wall the concentration is about 850 ppm. Integrating the curve over the area of the furnace we find at 20 m height that the average NO concentration is 460 ppm. This can be compared with the uniform cooling result at 20 m of 390 ppm. Thus the more detailed calculation gives almost 20% more NO efflux and, hence, should be used for definitive work.

2.13.2.6 CO-Oxidation

Complete oxidation of the exhaust gases is accomplished by afterburning in the steam generator. Kinetic calculations were performed to establish a practical lower limit of the afterburner temperature which insures complete oxidation of CO.

Results of calculations with assumed afterburner temperature of 1600 and 1900°F respectively, and 2.5 and 5% excess air are shown in Figures 2-160 and 2-161. Figure 2-162 shows the CO equilibrium temperature as a function of temperature and fuel/air equivalence ratio. Initial CO concentration was assumed to be equilibrium conditions at the respective temperatures for 0.95 air/fuel equivalence ratio. The results indicate that the reaction of CO and O₂ proceeds relatively slowly at 1600°F as shown in Figure 2-160. However, at 1900°F the reaction occurs very rapidly as is shown by Figure 2-161, and equilibrium concentration of CO has essentially been attained in ~0.5 sec. The lower practical limit for afterburner temperature is considered to be around 1900°F.

This is in concord with experimental results reported.

Figure 2-159 Nitric Oxide Content as a Function of Radius in the Steam Generator at a Height of 20 m

Figure 2-160 CO Concentration vs Time

Figure 2-161 CO Concentration vs Time

Figure 2-162 Equilibrium CO Concentration vs Temperature

2.13.3 Stack Gas Cleaning

2.13.3.1 Performance and Tradeoff Analysis

The gas cleanup system is required for efficient recovery of seed and to satisfy emission standards for particulate matter.

A variety of systems (electrostatic precipitators, baghouses, scrubbers...) which are commercially available are believed to meet the ETF design criteria. Quotes were obtained for both an electrostatic precipitator and a baghouse system for the ETF. FOB cost of the baghouse was slightly (3%) greater than the ESP; there were no significant differences in plan area or weight for the 2 systems.

A preliminary selection of an electrostatic precipitator was made based upon consideration of the following factors:

- Economically competitive with other systems
- Compatible with seed regeneration systems
- Widely used in utility power plants
- Facilitates field experimentation
- Relatively low maintenance requirements

2.13.3.2 Electrostatic Precipitator Design

The ESP was designed for 99.26% particulate removal efficiency which is the necessary removal efficiency to meet EPA standards with 90% ash removal in the coal combustor. Reference is made to Section 2.15 regarding seed and ash loading (particulates) in stack gas and required removal efficiencies. The required removal efficiency with 80% ash removal in the combustor and recycling of ash impurities together with recovered seed is calculated to be slightly higher and 99.30%. Therefore, the effect of a slight increase of the precipitator efficiency will be investigated in the remaining design work to provide a certain margin.

The size distribution of particulate matter in the gas stream was assumed to be that shown in Figure 2-163. This figure is based on experimental work with electrostatic precipitation of seed from MHD combustion conducted at AERL.

A preliminary design, prepared by CE Walther, Inc., is presented in Figure 2-164. The dimensions indicated are representative of European-type practice. In addition, the ESP has been sufficiently sectionalized to

Figure 2-163 Log Probability Graph of Particle Size Distribution for ETF

A = 31'-8[±]
 B = 76'-10[±]
 C = 44'-10[±]
 D = 13'-0[±]
 E = 7'-9¹/₄[±]
 F = 32'-8
 G = 32'-8
 H = 4'-4³/₄[±]
 J = 34'-2[±]
 K = 8'-6¹/₄[±]
 L = 29'-8[±]
 M = 19'-0[±]
 N = 15'-4[±]

TWO CHAMBER

MODEL NO. 1 P 2 C 14 D 4 F/ 11 x 35 x 51.2 [4@12.8]

EST. WEIGHT TONS EMPTY / P'RECIP.

Figure 2-164 Precipitator for MHD ETF

permit field experimentation of performance for varying gas and dust conditions.

Design details for this ESP are as follows:

Number of precipitators	1
Number of chambers/precipitator	2
Number of ducts/chamber	14
Duct spacing	11"
Number of fields	4, 12.8' L x 35' H
Total collecting plate area	100,352 ft ²
Total discharge electrode length	58,240 ft
Number of transformer - rectifiers	4 DHW sets at 750 mA each
Total expected power consumption including rappers and I. C. heat	157 kW
Total weight of precipitator and internals	589,000 lbs

Figure 2-165 is an arrangement drawing of the electrostatic precipitator and induced draft fan.

2.13.4 Steam Turbine-Generator

2.13.4.1 Performance and Tradeoff Analysis

A steam turbine-generator (ST-G) will be installed so that ac electric power can be supplied to the local utility grid, converting the energy of the high pressure, high temperature steam from the MHD bottoming plant boiler.

The steam turbine for the electric generator will share the boiler steam supply with the turbine driver for the combustion air compressor. (see Section 2.1.12.5). As a result, the steam turbine will be rated at ~55 MW. For this size machine, standard throttle steam conditions from manufacturers price books are 1250 psig and 950°F. Several U.S. manufacturers indicated that this size machine with these throttle conditions can be considered as an off-the-shelf design.

Throttle steam conditions chosen for the ETF are 1250 psig and 950°F. Although the throttle conditions will not be as high as those expected for a final MHD utility application, the pressure is still considered high pressure by industry and the amount of superheat (375°F) will be comparable to that of a high pressure, 1000°F utility unit. The selection of the 1250 psig/950°F throttle conditions was based on initial comments from two U.S. manufacturers, indicating that this was their standard off-the-shelf design. A third manufacturer indicated he was not presently marketing a unit of this size but would like to receive any further inquiries.

At a latter date one U.S. manufacturer indicated that throttle conditions of 1450 psig/1000°F and 1800 psig/1000°F are not considered as special designs for a 55 MW machine. At that time the design work had proceeded to a point where a change in the throttle conditions could not be incorporated in this document. However, for future reference, an evaluation of the three throttle conditions is discussed in the following paragraphs.

Steam plant efficiency and cost are the major considerations in selecting the throttle conditions. The steam plant efficiency for the three available throttle conditions is shown in Figure 2-166 for a range of turbine back pressures and appropriate turbine efficiencies.

These plant efficiencies are based on the steam plant arrangement used for the ETF. That is, the MHD generator, economizer, burner, diffuser and transition section are in the condensate and feedwater cycles.

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Figure 2-166 Steam Plant Efficiency as a Function of Turbine Back Pressure and Efficiency

The range of turbine efficiencies shown for each throttle condition is based on manufacturers data and also indicates that the basic efficiency of a steam turbine is largely a function of its inlet volume flow. As can be seen, the steam plant efficiency increases from 33.2% to 33.8% to 34% as the throttle conditions change from 1250 psig/950°F to 1450 psig/1000°F to 1800 psig/1000°F, respectively. The total increase in plant costs have also been estimated for the higher throttle pressures and temperatures. It was found that the turbine with throttle conditions of 1450 psig/1000°F will cost 5% less than the turbine with throttle conditions of 1250 psig/950°F. This is due to the fact that both turbines are designed similarly, but that the turbine with throttle conditions of 1450 psig/1000°F would be smaller due to the smaller inlet volume flow and thus less expensive. For the throttle conditions of 1800 psig/1000°F the turbine price increases 12% above the cost of the turbine with throttle conditions of 1250 psig/950°F. This price increase is due to the double shell construction required for turbines with throttle pressures above 1450 psig. Boiler costs increase by 5 and 15% as the throttle conditions go from 1250 psig/950°F to 1450 psig/1000°F and 1800 psig/1000°F, respectively. As a result total steam plant costs increase as the throttle pressure and temperature are raised. Total steam plant cost increases relative to the 1250 psig/950°F throttle conditions are 0.1% and 14% for throttle conditions of 1450 psig/1000°F and 1800 psig/1000°F respectively. The following table summarizes the above discussion;

<u>Throttle Conditions psig/°F</u>	<u>Increase In Steam Plant Efficiency</u>	<u>Increase In Steam Plant Cost</u>
1250/950	base	base
1450/1000	0.6%	0.1%
1800/1000	0.8%	14%

Based on the increase in steam plant efficiency relative to cost increases, the turbine with throttle conditions of 1450 psig/1000°F is recommended to be used for the ETF.

The turbine back pressure chosen is 2.5 in. HgA with a maximum operating back pressure of 5 in. HgA. Back pressures above 5 in. HgA

would require special design and therefore, not be an off-the-shelf item. For further discussion of the choice of design back pressure, see Section 2.13.7, Heat Rejection and Cooling Water Systems.

For the 1250 psig/950°F throttle conditions, used throughout this document, a single uncontrolled extraction point of approximately 190 psig pressure at rated load was selected to provide auxiliary steam for the deaerator, turbine gland sealing, condenser steam-jet air ejectors and for the seed regeneration process. A high pressure extraction was selected at rated load so that adequate steam pressure was available for these services throughout the ST-G load range of 50% and higher. The manufacturers have indicated a preliminary overall efficiency of 83%, thus the expected steam rate will be 7.3 lb/kW-hr.

2.13.4.2 Steam Turbine-Generator and Auxiliaries Description

The steam turbine-generator will be a conventional design machine. The turbine will be rated at ~55 MW and will be a non-reheat, multi-stage, single-flow exhaust, 3600 rpm, condensing unit with 23 in. last stage buckets that exhaust, downward into the condenser. There will be one uncontrolled extraction point at ~190 psia at rated load for the auxiliary steam system.

The steam turbine will drive from the low pressure turbine coupling a 58,000 kVA hydrogen cooled generator with a brushless exciter system.

Steam turbine-generator auxiliaries will include an independent lube oil system with motor driven normal (ac) and emergency (dc) pumps, piping, coolers, and instrumentation and control; a complete steam seal system for turbine glands, emergency steam inlet stop valve, insulation and lagging, directly associated foundations, and electro-hydraulic speed governing system.

2.13.4.3 Steam Turbine-Generator Instrumentation and Controls

The steam turbine-generator will be provided with devices, valves, and control mechanisms to ensure automatic and operator initiated protection of the turbine-generator and its safe operation and monitoring. The devices will include the equipment and their functions that are listed below.

Anti-motoring protection will be through an emergency inlet valve and switches or a pressure switch. This device will initiate the generator main breaker opening in the event of motoring of the generator.

Overspeed protection will be through an overspeed governor with test equipment to test the governor and trip mechanism under full load.

The Emergency Trip System will include manual trip and reset devices and electrically operated 125 Vdc solenoids.

Lube oil and seal oil system protection will have pressure switches to initiate alternate pump or emergency pump start when lube oil pressure falls below predetermined limits.

Lube oil tank heaters will have thermostats to maintain a minimum lube oil tank temperature during periods when the turbine-generator is down.

Turning gear control system will provide turning gear motor power at zero speed to protect the machine shaft from warping. The turning gear starter will be supplied from the Essential 480 V Motor Control Center to provide power during auxiliary electric system outages.

Turbine supervisory instruments will provide speed and camshaft position, eccentricity, vibration, shell and differential expansion, and rotor expansion for input to recorders and computer. Alarm points for all inputs and a turbine trip on excessive vibration will be provided.

Dual element thermocouples, local indicating thermometers and resistance temperature detectors will be provided for indication, alarm, and automatic control as required for all main bearing drains, exhaust hood temperature, thrust bearing drains, oil inlet, outlet of oil coolers, generator cooling mechanism inlets and outlets, and front and back of thrust bearing plate.

Exhaust relief diaphragm and electric low-vacuum trip and alarm contacts will be provided.

Thrust failure trip switches will be provided, one for trip and one for alarm. A thrust wear alarm device will also be provided.

Generator protective, monitoring, and control equipment will include thirteen (13) bushing mounted current transformers with seven on-line terminals, six (6) generator stator resistance temperature detectors, neutral grounding transformer and resistor, potential transformers generation of line-to-line voltage to 120 volt single phase a/c, casing liquid detection, brushless excitation system, cooling medium analysis equipment and purging equipment.

The steam turbine-generator will be furnished with an electro-hydraulic control system. This system will include transducers and receivers for steam pressures, permanent magnet generator, turbine control console, valve position indicators, indicating electric meters for each servo amplifier, four regulated dc power supplies, indicating lights, test devices, alarm contacts, speed indicator, stop valve position control devices and indication, speed indicator, and turbine operating and test panel insert for mounting in the Main Control Room Turbine Panel. A discussion of some of the EHC functions are described in Section 3.0, Instrumentation and Controls.

2.13.5 Air Compressor and Drive

2.13.5.1 Performance and Tradeoff Analysis

An axial flow air compressor will be provided, along with its steam turbine drive and inlet filter and silencer. These pieces of equipment will be located on the operating floor with the turbine generator set. The design conditions for the compressor are 7566.7 lbs per minute at a discharge pressure of 71.2 psia, with atmospheric conditions of 12.2 psia, 80°F, and 50°F wet bulb.

Without intercooling, direct compression could result in a discharge temperature >500°F. Most compressor manufacturers consider 500°F to be the upper limit for discharge temperature in their standard designs. However, one domestic manufacturer, Ingersoll Rand, did offer an axial flow compressor without intercooling that is suitable for the design conditions. The only variation from standard design is that the discharge half of the casing would be made of steel rather than cast iron. Future commercial size plants will use axial flow compressors as the volume flow increases beyond the capacity of centrifugals. Thus, an axial flow compressor was chosen for use in the ETF. The axial compressor will model the performance of commercial size plants, use the heat of compression in the cycle and operate at higher efficiencies than available from centrifugals.

A number of types of compressor drives were considered. The drive(s) that is used will be required to operate the compressor at full load, with or without steam from the bottoming cycle. The compressor requires ~18,270 hp. The available options are electric motor, diesel, gas turbine, steam turbine, or any combination of these options.

Electric motors were eliminated from consideration because of price, difficulty of replacement, and possible problems to the utility grid while starting. Diesels were eliminated from consideration, since their cost, in this size range, is almost twice that of a combustion gas turbine. Operating and capital costs were compared for the remaining options. Based on this comparison, a single steam turbine rated at 1250 psig/950°F was selected to drive the compressor. During startup and the by-pass mode, steam will be supplied by an auxiliary boiler rated at 1250 psig, 900°F and 145,000 lbs per hour. When available steam will be supplied from the bottoming cycle.

2.13.5.2 Air Compressor and Drive Description

An axial flow air compressor sized to provide 7566.7 lbs/min at a discharge pressure of 71.2 psia at 5564 rpm was selected. Figure 2-167 is the compressor performance curve.

Adequate excess capacity will be provided to allow for normal deterioration in performance. The compressor will require 18,270 hp, at rated conditions. It will be a fifteen stage machine with variable stators on the last seven stages. The compressor discharge temperature will be 500°F. This temperature necessitates using steel for the discharge end of the casing, rather than cast iron. A lube oil system to service the compressor and its turbine drive will be included. The air compressor will be a standard design item.

A three stage inlet air filter will consist of an inertial separator, followed by two stages of filter media that will be made of interlaced glass filaments. The inertial separator will have a higher efficiency with larger sized particles (92% on the Arizona Road Dust Coarse and 78% on Arizona Road Dust Fine). Of the air being handled, ~10% will be used as secondary air to carry out the filtered particles. Since this filter will be on the suction side of the compressor, a blower will be required to discharge the secondary air to atmospheric pressure. The second and third stage filters will have efficiencies of ~98%. The pressure drop across the filters will be about two inches of water.

Silencers will be provided between the filters and compressor. They will assure a noise level at the filter inlet of 90 dBA. The silencer

Figure 2-167 Air Compressor Performance Map

pressure drop will be about 1.2 inches of water. The ductwork in the building will be insulated to keep the noise level within acceptable limits.

The steam turbine drive will be rated at 18,270 hp. The turbine will be a multi-stage, condensing machine designed for a back pressure of 2.7 in. HgA. A gland seal system common to the main turbine-generator set (paragraph 2.13.4) will be used. Structurally, the turbine will be designed for 1250 psig and 950°F. The auxiliary boiler will deliver steam to the compressor drive at 1250 psig and 900°F in order to minimize the mismatch in temperature when the waste heat recovery boiler first comes on line at 900°F. However, when the waste heat recovery boiler reaches full load, the compressor turbine drive will see 950°F steam.

The hot air pipe from the compressor to the high temperature air heater will be constructed of carbon steel pipe conforming to ASTM A155 specification. The piping will be insulated to reduce heat loss and expansion joints will be used to absorb thermal expansion.

2.13.5.3 Instrumentation and Controls

The flow rate from the compressor is controlled by varying the speed and stator vane angle. As shown on the compressor performance curve, Figure 2-167, the compressor is operated at 100% speed and a stator vane angle between +10° and -25° for flows down to ~70% of the design flow. For flows <70% of the design flow the stator vane angle remains at the minimum setting, -25°, while the speed is decreased. The compressor cannot be operated in the shaded area of the curve for prolonged periods of time due to unstable flow conditions that occur in the compressor blades. However, the shaded area does not necessarily occur between 50 and 80% speed for all compressors. The machine can be designed so that the shaded area will move somewhat to the left or right depending on the particular process requirements.

The compressor can be brought to full load at whatever rate its driver is capable of accelerating. On startup, the compressor stator vane angle is set at -25° until 100% speed is reached. For further increases in flow, the stator vane angle is increased from -25° to +10° as required.

Protection against operating outside the surge and choke lines must be provided. Operating for extended periods of time below the choke line, has caused blade cracking. A butterfly valve in the discharge line is used to prevent choking. Surge protection is provided by using a blowoff valve. Surge and choke lines are indicated on the compressor performance curve. To control these valves, inlet CFM is monitored by measuring the pressure drop due to the velocity increase at the inlet to the compressor. Compressor discharge pressure is also monitored. The blowoff valve is modulated to maintain a predetermined minimum flow corresponding to each measured compressor discharge pressure. A surge set point line is drawn just below the actual surge line. The choke protection valve is modulated to maintain a predetermined minimum discharge pressure corresponding to each flow. A choke set point line would also be defined on the curve. The performance curve indicates how the compressor operates with the blowoff valve open and closed. Forty percent of design channel flow or 54,000 ICFM is indicated by an "X" on Figure 2-167. The pressure ratio required at this channel flow is 3.2. Since this point is above the surge line, the blowoff valve opens resulting in a compressor volume flow of 70,500 ICFM, still at a pressure ratio of 3.2. This actual compressor operating point is indicated by an "O". The BHP is found by moving vertically down from the mark "O" to the BHP curve. At 40% channel flow the BHP is found to be 6300 hp. At full load or 126,000 ICFM, the required pressure ratio is 5.84. This point is indicated by an "O". Since it is between the surge and choke lines, no blowoff or throttling is required. The required BHP is found by moving vertically down from the full load point, "O", to the BHP Curve. At full load the BHP is found to be 18,270 hp. Input to the compressor control system is the desired weight flow. Actual weight flow is known by measuring inlet, CFM, temperature and pressure.

Various compressor parameters will be monitored. This will provide a continuous check on the compressor operation and the condition of inlet filters. Measured parameters include, inlet and outlet pressure and temperature, inlet air filter pressure drop, shaft speed, rotor vibrations, bearing temperature and lube oil temperature.

The compressor drive turbine will have its own electro-hydraulic governing system and sensing, indicating and recording instrumentation, and control system. Parameters of the steam turbine to be monitored are; steam pressure and temperature, gland steam conditions, bearing oil temperature, shaft vibration, axial shaft movement and items pertaining to the governor control system.

2.13.6 Condensate and Feedwater Systems

2.13.6.1 Performance and Tradeoff Analysis

The arrangement of, and equipment chosen for the condensate and feedwater systems will be consistent with the guidelines of low cost and reliability.

The condensate and feedwater systems will be common to both the bottoming cycle waste heat boiler and the auxiliary boiler for the air compressor drive turbine. This arrangement will eliminate the cost of duplicate systems and provide cooling water to the MHD system components with either boiler in operation. There will be two, half capacity condensate pumps and one boiler feed pump. In the case of a blackout, cooling water to the channel, diffuser and burner will be required. One half the normal condensate flow will be adequate for this purpose. Therefore, to minimize the load on the emergency diesel generator, two half size condensate pumps will be installed. One will run during the blackout condition.

The steam jet air ejector inter- and after-condensers and the MHD generator will be in the condensate system. The condensate temperature is compatible with the electrical insulating material, which has been used successfully, for connecting the generator electrodes to pipes carrying the cooling water supply. A deaerator and polisher will also be used in the condensate cycle. Large and frequent load changes and frequent shutdowns during the ETF test period can result in an excess of oxygen in the feedwater, corrosion products, and carryover from the drum. The deaerator, in conjunction with the deaerating condenser and oxygen scavenging chemicals, will assure low levels of oxygen in the feedwater. A polisher in the condensate cycle will control residual dissolved solids and metals oxides that may otherwise be carried into the boiler and provide cooling water with a low cation conductivity (0-5 mmhos) for the MHD components.

Feedwater to the steam drum will be heated in the economizer, burner, and diffuser so that no further feedwater heating by turbine extraction steam is needed.

2. 13. 6. 2 Condensate and Feedwater Systems Description

The condensate and feedwater arrangements discussed below will be common to the bottoming cycle waste heat boiler and the auxiliary boiler which will provide steam to the air compressor drive and other miscellaneous startup services. The condensate and feedwater systems flow diagram is shown in Figure 2-168.

The condensate pumps will discharge through the steam jet air ejector inter- and after-condensers, condensate polishing unit and MHD generator to the deaerator. Two half capacity condensate pumps rated at 575 gpm at 290 ft total dynamic head (TDH) will be used. They will be of the vertical canned type and be driven by electric motors. The deaerator will be of the direct contact, tray-type deaerating feedwater heater mounted on a horizontal storage tank and will guarantee not more than .005 cc/l of residual oxygen in the feedwater. The storage tank will be sized to provide five minutes of feedwater storage at rated load. It will be fabricated of carbon steel and designed in accordance with the ASME Unfired Pressure Vessel Code for a pressure of 50 psig and full vacuum. Condensate flow will be controlled by the level of condensate in the deaerator storage tank, condensate temperature out of the MHD generator and the minimum flow requirement of the pump. The amount of bypass flow dumped to the condenser will be determined by the larger of two criteria. The first criterion is that the maximum allowable temperature of condensate out of the MHD diffuser not be exceeded. The second criterion is that the minimum flow required by the condensate pumps be maintained.

The boiler feed pump will take suction from the deaerator. Feedwater will be pumped through the waste heat recovery boiler economizer, MHD burner and diffuser and discharge to the steam drum of the waste heat boiler or the auxiliary boiler. The feed pump will be a horizontally split, multistage pump rated at 1230 gpm at 3900 ft thd. It will be driven by an electric motor. Feedwater flow to the boiler will be regulated by a three element feedwater flow control system. Minimum flow through the

Figure 2-168 Condensate and Feedwater Systems Flow Diagrams

pump is assured by the recirculation line to the deaerator. A dump line to the condenser is used to maintain adequate cooling water flow to the burner and diffuser.

A bypass line is also provided around the boiler feed pump. This is used in the case of a blackout. It allows the one condensate pump powered by the emergency diesel generator to provide cooling water to the channel, burner and diffuser.

2. 13. 7 Heat Rejection and Cooling Water Systems

2. 13. 7. 1 Performance and Tradeoff Analysis

A conventional surface condenser will be used in the ETF to condense the exhaust steam from the steam turbine-generator and the steam turbine drive for the air compressor. A counterflow mechanical draft evaporative (wet) cooling tower will be used as the heat sink for the condenser circulating water cycle.

The surface condenser was chosen, in lieu of the air-cooled condenser proposed in the Design Criteria Document, because of the high initial cost of air-cooled condensers. In order to reduce this condenser cost and space requirements, economics dictate that the turbine must operate at higher back pressures, usually at least 8" HgA. Standard steam turbine design for condensing type units limit the maximum back pressure to ~ 5" HgA. Therefore, if an air cooled condenser were selected for the ETF, the steam turbine would be a special design thereby making it more costly and not a desired "off the shelf" selection. It should also be noted that surface condensers are a much more common selection for utility applications in the United States.

The cooling tower was selected as the heat sink since the hypothetical site description does not indicate a nearby river or lake which could be used for once-through cooling. Also, impervious soil assumed for the site makes the construction of an on-site cooling pond unfeasible. The cooling tower will also be the heat sink for various other smaller heat exchangers listed in Subsection 2. 13. 7. 2. All auxiliary equipment will be cooled this way, instead of using well water for some equipment cooling as proposed in the Design Criteria Document.

Since the ETF is primarily an engineering test facility and not a commercial power plant, a kW versus capital cost study for determining the optimum turbine backpressure was not performed. The choice of the turbine back pressure and condenser and cooling tower sizes was based on site conditions and a comparison of initial investment costs. The range of design back pressures considered is from 1.1 to 4.5 in. HgA. The lower limit is set by typical minimum values of cooling tower approach and cooling tower/condenser range, 5 and 10°F, respectively. The upper limit is set by the maximum permissible moisture content of the steam at the turbine exhaust. The site conditions and initial investment costs are discussed in the following paragraph.

The site conditions, given in Table 6-1, are plotted on the wet bulb duration graph in Figure 2-169. The design site conditions are 12.2 psia, 80°F DB and 59°F WB. As the graph shows, the design wet bulb, 59°F, or less occurs 90% of the time. The graph also points out that the wet bulb is significantly lower than 59°F for a great percentage of the year. For instance the wet bulb is < 35°F for 50% of the year. For a particular cooling tower/condenser arrangement, the same type relationship is true, as shown on Figure 2-169. That is for a design back pressure of 3.5 in. HgA, the turbine back pressure can < 2.8 in. HgA 50% of the year. For a design back pressure of 2.5 in. HgA, the turbine back pressure can be < 1.85 in. HgA for 50% of the year. This type of performance and a low plant capacity factor would favor a higher design back pressure and lower initial investment costs.

Initial investment costs were also considered in choosing the turbine back pressure. For a given back pressure the cooling tower/condenser arrangement with the least initial investment was found. The results are shown in Figure 2-170. The brake horsepower of the cooling tower fans and circulating water pumps are also plotted for each back pressure. As can be seen, the initial investment decreases sharply as the back pressure increases from 1 to 2.5 in. HgA. The incremental savings are considerably less as the back pressure increases from 2.5 to 4.5 in. HgA. Brake horsepower and thus operating costs follow the same trend.

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Figure 2-169 Turbine Back Pressure vs Wet Bulb Temperature

Figure 2-170 Cost of Cooling Water System vs Turbine Back Pressure

Based on the above discussion, 2.5 in. HgA, will be used as the design turbine back pressure. The condenser and cooling tower are also sized so that during maximum duty conditions, the turbine back pressure will not exceed 2.8 in. HgA when the wet bulb is 65°F and the dry bulb is 95°F. At design conditions the circulating water inlet temperature to the condenser will be 77°F and the outlet temperature will be 103.6°F. The condenser duty will be 469,563,770 Btu/hr, and the terminal temperature difference is 5.1°F.

The condenser will be located below the steam turbine-generator which exhausts directly into the condenser shell. The air compressor steam turbine drive will exhaust to the condenser through a 78" duct. The condenser will have two water passes and a total surface area of 48,290 sq. ft. There will be 8708 3/4 inch - 19 BWG 90/10 copper nickel tubes. The tube length will be 30 ft, with an 8 ft/sec water velocity in the tubes at the circulating water design flow of 38,000 gpm. The condenser will be of the deaerating type to reduce oxygen in the condensate. Air removal will be by twin two stage steam jet ejectors, with inter- and after-condensers cooled by condensate. Steam at 95 psig will be used as motive power.

The cooling tower will be a four cell mechanical draft counterflow unit. Each cell will be 43 ft by 43 ft with a 100 hp electric motor to drive its fan. At design conditions, the inlet water temperature will be 103.6°F and the outlet temperature 77°F. At an ambient wet bulb temperature of 59°F, the resulting approach is 18°F. With a calculated auxiliary cooling water flow of 3800 gpm, the total water flow to and from the cooling tower will be 41,000 gpm.

In the case of a blackout it will be necessary to provide cooling water to certain critical areas of the plant such as the channel, diffuser, burner, HTAH valves etc. Therefore the condensate, circulating water and cooling water pumps will remain running, with power from the plant emergency diesel generator. To minimize the load on the generators two half size circulating water and cooling water pumps will be installed. One of each will run in the case of a blackout.

The two half size vertical circulating water pumps are rated at 19,000 gpm with a 62 ft TDH and driven by electric motors. The two half size vertical auxiliary cooling water pumps are rated at 1900 gpm with an 87 ft TDH and driven by an electric motor.

During the bypass mode, a large portion of the heat in the exhaust gases will be removed by the bypass duct scrubber system. Heat rejected to the condenser will be from the compressor turbine drive exhaust and channel, diffuser, and burner cooling. Therefore, the cooling tower load will be less during the bypass mode than while operating the bottoming plant.

2. 13. 7. 2 Heat Rejection and Cooling Water Systems Description

The circulating and auxiliary cooling water system is shown in Figure 2-171. The circulating and auxiliary cooling water pumps will be mounted in the cooling tower basin. The circulating water pumps will discharge through rubber expansion joints and motor operated butterfly valves into a 42" diameter steel line, running underground to the condenser. The 42" diameter, steel return line, also underground, will run from the condenser back to the cooling tower. Rubber expansion joints will be provided at the condenser connections. A branch line from the return main, at the cooling tower, will be provided and will run directly to the cooling tower basin, to maintain a minimum circulating water temperature during winter operation. The temperature will be controlled by a temperature control valve that senses the water temperature in the return line. Each of the four cooling tower cells will have a 20" branch, containing a manually operated butterfly valve, from the 42" return main to balance the flows or to isolate a cell if necessary.

The auxiliary cooling water pumps will discharge through rubber expansion joints, check valves, and butterfly valves into a 12" diameter steel line running underground to the turbine building. From the turbine building, branch lines will be routed to the various items of equipment requiring cooling water, including the high temperature air heater subsystem, instrument and service air compressors, lube oil coolers, generator hydrogen coolers, stator cooler, combustor slag quench tank cooling, and other miscellaneous coolers. Also a cooling water line will run to the gasifier

Figure 2-171 Schematic Drawing of Circulating and Cooling Water Systems

subsystem and to the seed regeneration area. The lines from these various coolers will rejoin into a 12" diameter return header which will then connect to the 42" diameter circulating water return header in the turbine building.

Circulating water system blowdown will be via a 4" diameter branch line from the 42" diameter circulating water pump discharge main. The circulating water system blowdown rate will be ~ 216 gpm. Circulating system makeup water will be provided via an 8" diameter line discharging to the cooling tower basin from the clean water holding basin. The circulating water system makeup rate will be approximately 1260 gpm.

2.14 COAL PROCESSING AND HANDLING

2.14.1 Coal Receiving, Storage and Reclaiming

The primary fuel for firing the MHD combustor will be Montana Rosebud sub-bituminous coal and the secondary fuel will be an Eastern bituminous coal, Illinois No. 6. Only the Montana coal will be used as a fuel for the gasification subsystem. The design flow for Montana coal to the combustor will be 71,400 lbs/hr (~ 36 tons/hr) and the design flow for the Montana coal to the gasification subsystem will be 498 tons/day (~ 21 tons/hr). The design flow for Illinois coal to the combustor will be 56,500 lbs/hr (~ 28 tons/hr).

Based on the above coal firing rates and the preliminary test program schedule, see Section 1.5, coal delivery requirements have been established. These delivery requirements assume that the coal will be delivered to the site by rail, not in unit trains, but in 100 ton bottom dump hopper cars. During the plant test period, years one through five, Montana coal will be delivered at a rate of 18 cars per month for the first year, 12 cars per week for years two and three, 26 cars per week for the fourth year and 43 cars per week for the fifth year. For years six through fifteen coal deliveries will be made at a rate of 48 cars per week. This is based on a 50% plant capacity factor. Illinois coal can be delivered to the site during the test period on an as required basis. During the 2000 hr continuous test runs in years two and three, additional coal deliveries will be required at a rate of 40 cars per week.

It was assumed that the distance from the mine to ETF site would not be a constraint in establishing the Montana coal delivery criteria. Rail delivery has been assumed, but as suggested in the Design Criteria Document, truck delivery might be an alternate when the actual site and mine locations have been selected. As assumed in the Design Criteria Document, eastern coal delivery will be by rail only. As shown on the Plot Plan, Figure 4-1, a ladder track is included to facilitate the handling of the coal cars on the site. A receiving hopper and car puller will be provided for coal unloading. A thaw shed will also be provided for handling coal that arrives in a frozen state. The coal receiving hopper will have a storage capacity of 200 tons and will be able to receive and handle precrushed 6" nominal size coal.

From the receiving hopper, coal will be fed through two reciprocating feeders on to an inclined belt conveyor with a telescopic chute and be stacked at the live storage area. The conveyor will be equipped with a belt scale, for continuous weighing and recording of coal quantities delivered to the ETF, and a metal detector. Equipment will also be provided for sampling coal deliveries. Space will be allocated for the live coal storage area that is equal to a maximum delivery of 5000 tons of coal. Based on a maximum angle of repose of 35° and a unit weight of 50 lbs/ft^3 , the live coal storage pile will have a radius of 70 ft and a height of 39 ft. Based on a maximum coal unloading time of four hours, the conveyor from the receiving hopper will be sized for a maximum feed rate of 1250 tons/hr. The maximum conveyor angle is 18° .

From the live coal storage area, the coal will be moved either to the Illinois or Montana coal storage piles by frontloaders, trucks, and/or bulldozers. The Illinois coal storage pile will contain sufficient coal for two 100 hr runs at full load, 5600 tons of coal. The Montana coal storage pile will initially be sized for two 100 hr runs at full load or 11,400 tons of coal; which will be slightly greater than a 30 day storage requirement at a 25% capacity factor. For future operation during years 11 to 15, Montana coal storage will be expanded to 20,805 tons of coal; the equivalent of 30 days of ETF operation at a 50% capacity factor. The Illinois and Montana coal storage piles areas shown on the Plot Plan, Drawing No. Figure 4-1, are based on assumed pile heights of 20 ft, a coal unit weight of 50 lbs/ft^3 , and a maximum angle of repose of 35° .

The coal reclaim layout is shown on Figure 4-1. The coal as received, 6" size, is normally fed to the reclaim conveyor through the reclaim hopper located directly below the live coal storage pile. If this hopper is out of service or if a change of coal is desired, a second reclaim hopper is provided as shown. The coal reclaim conveyor transports the coal to the crusher silo located in the east end of the HTAH building. The coal reclaim system will be sized to transfer and store sufficient coal such that the reclaim operation will be required only during one eight hour shift per day. The reclaim conveyor will have a capacity of 285 tons/hr. The crusher silo will have a storage capacity of 10 hrs of the combustor coal requirement and

15 hrs of the gasifier coal requirement, 660 tons. Figure 4-2 shows the crusher silo and coal transport equipment to the combustor and gasifier. From the crusher silo, coal will be fed by vibrating feeders into the crusher, where it will be crushed to 3/4-inch size. Coal sampling equipment will be provided following the crusher. From the crusher, coal will be fed by bucket elevators and conveyor either to the pulverizer/drier coal silo or to the six storage bins provided with the gasifiers. The pulverizer/drier coal silo will have a 10 hr combustor coal supply, 360 tons. The six gasifier coal storage bins will have a total 5 hr gasifier coal supply, 104 tons.

The various coal storage piles will be managed by bulldozers and frontloaders. Dust removal and suppression equipment will be provided at all handling and transfer points. To aid in dust control, for maintenance and housekeeping, vacuum cleaning equipment will be provided at selected locations.

For Montana coal operation, the coal preparation system is intended to be run on either single or multishift operation as required. Sufficient coal storage is available, though, to run on one eight hour shift per day.

Only Montana coal can be used in the gasifier and either Illinois or Montana coal can be used in the combustor. When the gasifier is used for an Illinois coal test, a cyclic operation of the coal preparation system will be required so as not to mix coal types. The various coal storage silos will include provisions so that they can be emptied during periods of prolonged ETF inoperation. The emptied coal will be returned to the coal storage yard by trucks. The various silos will also have forced ventilation systems, including air cleaning devices for control of dust and methane gas generation. In the coal preparation area, dust removal and suppression equipment and vacuum cleaning equipment will be provided.

The coal reclaiming system will be designed for remote-manual control. Controls will be located in the main control room. Coal conveyors inside the plant will also be controlled and monitored from the main control room.

2.14.2 Coal Drying, Pulverizing and Feeding

2.14.2.1 Performance and Tradeoff Analysis

The coal preparation and handling system of the ETF will be required to process 70,000 lbm/hr of Montana Rosebud coal. The fuel is transported from the raw coal storage bin in a partially crushed state. Following is an analysis of the Montana coal as received:

% by Weight	
C	52.11
H ₂	6.01
S	0.86
N ₂	0.80
O ₂	31.51
Ash	8.71

The coal contains 23% moisture by weight and a higher heating value of 8920 Btu/lbm as received.

The MHD combustor requires coal pulverized such that 70% will pass through a 200 mesh screen. Moisture content will be 5% and the fuel must be fed against a combustor pressure of 6 atm.

Several methods of coal drying were investigated: steam drying, oil drying, and thermal drying. Oil drying was found to be costly, unproven and inconsistent with the goal of reduced oil demand. Steam drying, while used with success in Europe, is a batching process which would be difficult to control and which would require additional pressure vessels in the system.

Thermal drying was selected for the general availability of technology and the specific availability of hot, inert drying gas from the high temperature air heater.

For high pressure injection into the combustor only one proven commercially available system was found; the Petrocarb^R System using a series of lockhoppers to pressurize and feed the pulverized coal. These systems will be explained more completely below.

2.14.2.2 Process Description - Availability of Technology

Thermal drying of coal during pulverization by hot flue gases is a common, accepted, and safe method of reducing coal moisture content. Drying to 10% moisture by weight during milling is often required in coal-fired facilities to aid in the fuel handling process.

The CE Raymond Company, designers of the pulverizing and drying system to be used here, has had extensive experience in coal preparation and has participated in the design and construction of several systems which process high moisture coals to 5% moisture or less.

The drying gas will be obtained from the flue gas stream of the HTAH before it enters the Ljungstrom air heater. The projected constituents will be:

% by Weight	
CO ₂	18.82
SO ₂	0.04
N ₂	71.35
O ₂	1.86
H ₂ O	7.83

and the gas temperature is 700 F.

After the drying process this gas will contain 17% water vapor by weight and will have a relative humidity of 25% at 200 F.

2.14.2.3 Drying, Pulverizing and Feeding Equipment

Crushed coal from the raw storage bin is fed into the CE-supplied bowl mill (#863 RS Bowl Mill w/500 hp-900 rpm motor) by a gravimetric scale feeder (sized by the SE Co.). Flue gas from the HTAH at 700 F is mixed with recycle gas from the coal system baghouse to produce 133,000 lbm/hr gas at 647 F for drying; the gas transports the pulverized coal from the mill to the cyclone filter (CE Raymond #16) where drying is completed to 5% H₂O by weight and the coal and flue gas are separated.

The flue gas is blown into the baghouse (Two Ray-Jet 9 MW-50 dust collectors in parallel) by a manually damped fan (N. Y. B., Series 50, #1500 w/400 hp-1800 rpm motor). The filtered gas, now is 200 F, is vented to the stack except for the 13,300 lb/hr recycled to the bowl mill.

Pulverized coal from the cyclone and fines from the baghouse collection system enter the prepared coal storage bin. Bin capacity has been sized to hold fuel for 2 1/2 hrs of full-load running to provide for temporary mill outages or overload combustor operation. A schematic drawing of coal pulverizer and feed system is shown in Figure 2-172.

The coal is then fed from the storage bin on demand via a bin activator and screw feeder (Vibrascrew, Inc.) to a scalping screen (CE Tyler) for screening of foreign objects greater than 1/4" in size which could jam the Petrocarb system.

The demand coal feeder system works in conjunction with the Petrocarb components as follows.

The upper storage hopper is filled from the coal storage bin by the bin activator, screw feeder and screen system. This hopper (now holding ~20,000 lbm fuel) is then sealed and pressurized to 200 psig with dried flue gas from the HTAH exhaust (see below).

With the pressures of the lockhoppers equalized at 200 psig, the isolating valve between the two is opened and the coal allowed to flow into the primary injector bin under the force of gravity. When the upper bin has been emptied, the isolating valve is closed and the bin depressurized, ready for a new charging.

Coal leaves the lower injection tank under pressure via eight 1-1/2-in. feed pipes. Compressed air is used in the pipes to convey the fuel and inject it into the combustor. The use of the series lockhoppers makes possible an uninterrupted flow of coal under pressure to the combustor. The arrangement of the coal injection system is shown on Figure 2-173.

2.14.2.4 Inert Gas Supply System for Petrocarb

The Petrocarb pressurized injector fuel feed system requires a supply of inert (< 4% O₂ by weight) gas at 200 psig. The supply requirements are 1000 scfm continuously and 3000 scfm intermittently and the gas must be dry enough to avoid any condensation in the Petrocarb System.

The source of this gas is the exhaust from the high temperature air heater system.

This gas, at 250 F from the outlet of the HTAH heat recovery system, is passed through a 2 tray water scrubber (Koch Engineering Company) that cools the gas to 110 F and reduces the moisture content from 7.8% to 6.3%. The cool, saturated gas is then compressed to 200 psig and after-cooled (Ingersoll-Rand Company) to ambient temperature using plant water. Any condensed water is removed in a moisture separator and the gas is ready for use by the system.

Figure 2-173 Schematic Drawing of Coal Injection System

The compressor can be controlled by a simple pressure switch sensing the line pressure to the injector bins. The inert gas flow into the bins will be set by the Petrocarb control system.

2. 14. 2. 5 Steam Tracing

Because of the variable weather conditions at the proposed site, Butte, Montana, steam tracing will be required on all coal bins and transport ducts. This tracing will be sized to prevent freeze up of damp coal under expected winter conditions. Insulation of the ducts and bins will also be used to keep the coal above freezing temperatures.

2. 14. 2. 6 Coal Storage During System Shutdown

During the course of ETF operation it may be necessary to shutdown the CPS with coal still in the storage bins and/or the Petrocarb injectors. It will be necessary in this case to isolate the pulverized coal from the environment to prevent oxidation and self heating. This can be done by filling the bins to reduce the enclosed amount of gas and closing the appropriate isolation valves and airlocks.

Care must be taken to empty the coal feeding ducts and injection lines. These ducts and lines should also be vented to prevent the possibility of a pressure differential across the bin isolation valves. Should such a pressure differential occur, a small valve leak could result in air being drawn across the stored coal, possibly causing the particles to heat and clump together. Thermocouples positioned throughout the storage bins will monitor the temperature of the stored coal and notify the operator if a hazardous situation develops.

2. 14. 2. 7 Instrumentation and Controls

System Instrumentation (see chart) will include temperature and oxygen monitors, flow recorders, load cells and pressure transducers. The bulk of the control system will be used to cycle the Petrocarb injectors, supplying a steady flow of coal to the combustor.

Pressure will be monitored in the Petrocarb injectors, and load cells under the dried coal storage bins and the injectors will keep track of the amount of fuel in each.

Components to be controlled will be the gravimetric scale feeder, setting the flow rate of the coal into the drying system; fan and recycle

dampers, controlling drying gas temperature and flow rate; the bin activator screw feeder, scalping screen and upper isolating valve, the feed system for the Petrocarb storage injector; and the lower isolating valve and inert gas supply system, for pressurizing and transferring the fuel from the storage to the primary injector. Final coal flow rate to the combustor will be controlled by varying the pressure in the primary injector (providing a 3:1 turndown ratio) and/or shutting the valves on 1 or more of the 8 injection lines to the combustor. This will provide a very broad turndown range for the fuel flow.

The coal pulverizing equipment will take coal from the raw coal bunker, pulverize and dry the coal, then deliver the coal to a pulverized coal storage bin.

During startup and operation the pulverized coal will be transported by and stored in an inert atmosphere. Once the high temperature air heater is in operation, flue gas will be used to dry and transport the pulverized coal. Since the high temperature air heater will be started several days before the coal pulverizing equipment, flue gas will be available to purge the coal transport and recycle lines of air. An O_2 analyzer will be used to determine when the lines are sufficiently purged of air to begin pulverizing coal. An inert gas system will be required to maintain an inert atmosphere in the storage bin when the unit is shutdown with pulverized coal remaining in the storage bin.

A source of cool flue gas will be necessary to maintain mill temperature. In lieu of a source of cool flue gas, heat could be removed from the high temperature air heater flue gas to maintain mill temperature.

The Petrocarb fuel storage and handling system will have self contained controls. The storage injector will be supplied with pulverized coal at atmospheric pressure via gravity flow from the pulverized coal storage bin. After transferring the pulverized coal from the storage injector to the primary injector, the primary injector will be isolated and maintained at a pressure up to 100 psi > 90 psig of the MHD combustor.

Controls List

Equipment to be Controlled

Controller

Cyclone Air Lock

Pulverizer Control

Coal Feeder

Prepared Coal Level

Bin Activator

Screw Feeder

Scalping Screen

Petrocarb

Injector Pressure Valves

Petrocarb

Inert Gas Compressor

Self controlled by demand pressure.

Damper

Drying gas flow and temperatures.

Injector Valves

Petrocarb

2. 15 SEED RECOVERY AND MANAGEMENT

Efficient seed recovery is necessary for economical commercial operation. Seed recovery is also combined with effective removal of sulfur from the MHD combustion gases. This is feasible because of the known high chemical affinity of potassium seed to sulfur in the gas. The chemistry of seed and ash in MHD combustion gases has been investigated by several investigators in the MHD field. These investigations have revealed that the amount of seed which can be dissolved in ash is a strong function of temperature and that it depends upon seed and ash chemistry including kinetics and the ash composition.

The higher volatility of seed compared to the mineral matter in coal ash is utilized in the recovery of seed.

A major fraction of the coal ash (90% max) is assumed removed in the MHD combustion process. Furthermore, as described in Section 2.7 of the MHD coal combustor design, seed is added to the high temperature MHD combustion gases produced in the combustor in such a way so as to avoid seed loss with molten ash removed from the coal combustor. The boiler design has also been developed with careful consideration for attaining efficient recovery of seed. Slag is removed from the primary radiant furnace at the highest MHD exhaust gas temperature in order to minimize the amount of seed dissolved and lost in the molten slag removed from this furnace. The gas exit temperature from this primary furnace (2900°F) is well above the dew point of seed in the gas (2250°F), and the furnace wall boiler tubes are refractory lined. Thus, condensation of seed will not occur in the gas in the primary boiler furnace. Furthermore, the boiler design incorporates a secondary furnace where the gas is cooled down to a temperature (1900°F) sufficient for condensation and solidification of potassium sulfate. Part of the condensed seed with some additional fly-ash is recovered from this secondary furnace and also from the subsequent part of the boiler including its economizer. The remaining portion of the condensed seed in the gas is removed in electrostatic precipitators at stack gas temperatures of 275°F together with a smaller fraction of fly-ash in the gas.

A certain amount of seed recovered is processed for removal of sulfur. This permits utilization of seed recovery for removal of sulfur from the gas for air pollution control. The particular aspect of processing of recovered seed is described in Section 2.16.2. The processing seed is recycled together with the remaining portion of the seed recovered.

Preliminary seed and ash mass balances applicable to Montana sub-bituminous coal are shown in Table 2-57 and Table 2-58. The data listed pertain to an ash removal of 80% and 90% from the coal combustor respectively. This covers the range of ash removal assumed in the coal combustor design with 90% as the maximum ash removal design goal. The data listed in Table 2-50 is based on the assumption that no ash impurities are contained in the seed recycled. This necessitates removal of ash impurities from all of the seed recovered by, for instance, aqueous extraction of seed from ash and subsequent seed precipitation by crystallization and/or water removal by evaporation. The data listed in Table 2-57 considers recycling of the recovered seed with all of the ash impurities collected, together with the recovered seed, except for a very small amount of ash which is considered removed in the seed regeneration process (modified formate process).

The calculated loss of potassium seed in liquid slag removed from the primary radiant boiler furnace is based upon 12% K_2O dissolved in this slag. This is in line with the values of seed absorption in slag shown in Figure 1-174 which is reproduced from ERDA's report, "Baseline Power Plant Overall Plant Design Description" performed on ERDA Contract E(49-18)-2228 and -2243. The curve is indicated to be an equilibrium curve. 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 support this. In any event, even the calculated seed losses with slag based on mentioned equilibrium conditions are relatively small and acceptable. They range from 0.5% to 2.2% depending upon the amount of ash removed in the MHD burner and whether or not a smaller amount of ash is recycled with the seed.

TABLE 2-57

SEED AND ASH MASS BALANCE FOR ETF POWER SYSTEM

Basis: Recycling of recovered seed without ash impurities.

Raw coal feed rate to MHD burner	71,400 pph		
Ash contained in MHD burner coal feed	6,210 pph (8.7%)		
Seed feed rate (as K_2SO_4)	11,500 pph (1.0%)		
MHD Coal Combustor Ash Removal	%	80	90
Total amount of ash to bottoming plant	pph	1242	621
Slag removed in primary boiler furnace (40%)	pph	510	255
Seed loss in slag from primary boiler furnace (maximum):*			
as K_2O	pph	64	32
converted to K_2SO_4	pph	120	60
as per cent of total	%	1.0	0.5
Seed and ash removed in balance of boiler:			
Seed as K_2SO_4 (30%)	pph	3450	3450
Ash (30%)	pph	220	110
Seed and ash in gas to ESP:			
Seed as K_2SO_4	pph	7930	7990
Ash	pph	512	256
Particulates in stack gas with 99.26% ESP eff:			
	pph	62.5	61.0
as lbs/MBtu coal input to MHD combustor		0.100	0.097
Seed loss in stack gas with 99.26% ESP eff:			
as K_2SO_4	pph	59	59
as per cent of total	%	0.5	0.5

* Based on 12% K_2O in slag.

TABLE 2-58

SEED AND ASH MASS BALANCE FOR ETF POWER SYSTEM

Basis: Recycling of recovered seed with ash impurities.

Raw coal feed rate to MHD burner	71,400 pph		
Ash contained in MHD burner coal feed	6,210 pph (8.7%)		
Seed feed rate (as K_2SO_4)	11,500 pph (1.0%)		
MHD Coal Combustor Ash Removal	%	80	90
Raw ash carry over from combustor	pph	1242	621
Additional ash recycled with seed	pph	1528	764
Total amount of ash to bottoming plant		<u>2770</u>	<u>1385</u>
Slag removed in primary boiler furnace (40%)	pph	1120	560
Ash removed in seed processing	pph	122	61
Seed loss in slag from primary furnace (maximum):*			
as K_2O	pph	140	70
converted to K_2SO_4	pph	260	130
as per cent of total	%	2.2	1.1
Seed and ash removed in balance of boiler:			
Seed as K_2SO_4 (30%)	pph	3450	3450
Ash (30%)	pph	500	250
Seed and ash in gas to ESP:			
Seed as K_2SO_4	pph	7790	7920
Ash	pph	1150	575
Particulates in stack gas with 99.30% ESP eff:			
	pph	62.6	59.5
as lbs/MBtu coal input to MHD combustor		0.100	0.095
Seed loss in stack gas with 99.30% ESP eff:			
as K_2SO_4	pph	55	55
as per cent of total %		0.5	0.5

* Based on 12% K_2O in slag.

Figure 2-174 Seed Absorption by Slag with Temperature

The required collection efficiency of the electrostatic precipitator to meet EPA standards of 0.1 lb particulate/MBtu fuel input range from 99.24% to 99.30% for the conditions listed. This is referred to the thermal input with coal to the MHD burner only. The loss of seed with stack gas with a precipitator efficiency of 99.26% (99.30%) is 0.5%, which is small and acceptable.

In the case of removal of all ash impurities from the seed recovered before seed recycling a certain amount of seed may be lost with this ash. Data for an exact evaluation of this is presently lacking, but this is in any event not considered to be significant. The small amount of potassium contained in the raw coal ash feed has been ignored in these preliminary seed calculations.

Recycling of seed together with ash impurities is preferred and this will be investigated further in the remaining work.

2.16 SEED PROCESSING AND HANDLING

2.16.1 Seed Regeneration - Performance and Tradeoff Analysis

In the conceptual design of the ETF, potassium salts are injected continuously into the combustor so as to provide a 1% K concentration in the channel based on the plant design mass flow. As required by the design criteria, a portion of these potassium salts are in a form capable of removing enough sulfur from the combustion gas by chemical combination to meet the current EPA SO_2 emission limit of $1.2 \text{ lb}/10^6 \text{ Btu}$ input.

Provisions have been made to recover from the bottoming plant for reuse at least 95% of the seed injected into the combustor and to regenerate enough sulfur-free potassium salt for recycle to satisfy the sulfur removal criteria. Provisions have also been made to receive, store and transfer to the MHD system the quantities of potassium salts required for test operations. Table 2-59 shows the quantitative basis for the regeneration process.

It was assumed that the species recovered from the combustion gas will be K_2SO_4 , a portion of which must be converted to a sulfur-free potassium salt. However, if under the reducing conditions projected for operation of the MHD combustor, all or part of the sulfur-free potassium salt injected combines to form K_2S , then the regeneration of seed may be simplified. If the kinetics are favorable, K_2S can simply be converted to K_2CO_3 by reaction with H_2O and CO_2 (flue gas). Presently, however, lack of thermodynamic and kinetics data precludes reliable projections of the proportions of different species (K_2S or K_2SO_4) formed. Therefore, for the tradeoff analysis and for the Seed Regeneration Process conceptual design presented in earlier reports on this contract, 100% K_2SO_4 formation, the more conservative case, was assumed.

Four chemical concepts for regenerating sulfur-free potassium salt from recovered seed were studied. Three were identified in the Design Criteria Document previously submitted; the fourth emerged from exploration of other possibilities:

1. PERC (Pittsburgh Energy Research Center) Process
2. Hydrated Lime (Causticizing) Process
3. Formate Process
4. Carbon Reduction Process

TABLE 2-59

SULFUR CONTENTS AND SEED REGENERATION REQUIREMENTS

BASIS: Per 100 lbs of Coal as Fed

	Montana Coal (dried to 5% H ₂ O)		Illinois Coal (dried to 2% H ₂ O)	
	<u>lb</u>	<u>lb mole</u>	<u>lb</u>	<u>lb mole</u>
Sulfur Content	1.04	0.0324	3.55	0.1107
EPA SO ₂ Emissions Limits	1.32	0.0206	1.45	0.0227
Potassium Requirements For Seeding:				
K	9.0	0.230	9.6	0.248
K ₂ SO ₄	20.1	0.115	21.6	0.124
Requirements to Meet EPA SO ₂ Emissions Limits:				
K ₂ SO ₄				
Reprocessing	2.06	0.0118	15.3	0.088

Descriptions and detailed technical tradeoff analyses of these four process options were previously reported (Avco Everett Research Laboratory, Inc., Contract No. EF-77-C-01-2614, Engineering Test Facility-Conceptual Design, Volume II, pp. 467-515). For the sake of completeness, this material is also included in this report as Appendix F.

Although the Formate Process is subject to the resolution of certain process uncertainties, it is presently preferred over all other options examined. It appears to be the most technically and economically practical process and it is environmentally compatible for application to the MHD ETF program. It is thermodynamically attractive and was successfully practiced on an industrial scale in Germany during the 1930's to manufacturer K_2CO_3 . The formate process can be applied to the MHD seed regeneration program with a minimum of further development using currently available industrial equipment.

(It should also be noted that a potassium formate flue gas scrubbing and regeneration process has been explored during recent years in the United States.)⁽⁵⁹⁾

A detailed description of the Formate Seed Regeneration Process was presented in Section 2.16.2 of the aforementioned report. The basic chemical reaction for the process is:

A water solution of K_2SO_4 is reacted with $Ca(OH)_2$ and CO at 500 psia and 380°F to form KCOOH, a very soluble sulfur-free potassium salt and $CaSO_4 \cdot 2H_2O$ or gypsum. The latter is filtered out and disposed of as solid waste; water is evaporated from the filtrate to produce dry KCOOH for recycle.

It is recognized that the formate process produces $CaSO_4$ as a solid waste disposal product, and that the PERC process and carbon reduction process have the potential of yielding elemental sulfur as the final waste product. However, both of these two waste products were considered equally acceptable in the ETF conceptual design analysis, whereas technical uncertainties and risks were minimized.

The Carbon Reduction Process is considered as a potential candidate for future phases of the ETF design. However, not enough is known about its application to potassium salt reduction (vs sodium salt reduction as practiced in the pulp and paper industry) to be able to recommend it at this time as a practical ETF option. A more detailed analysis of the Carbon Reduction Process on a pilot plant scale has been recommended to establish its overall merit more conclusively.

2.16.2 Seed Regeneration - Process Design Description

The quantitative basis for the reference system design of the seed regeneration facility is shown in Tables 2-59 and 2-60. The latter was computed from the ETF plant size design parameters selected for the overall study - i. e., a mass flow rate of 7.2 kg/s for Montana coal dried to 5% moisture content and a potassium seed injection requirement of 1.2 kg/s computed as K_2CO_3 .

The proposed Formate Process is analyzed theoretically in Section 2.16.1 of the Conceptual Design Report previously cited. The reference system design of the seed regeneration facility for the selected ETF plant size was developed only for Montana coal. However, mass balance and heat balance data is presented for the Illinois coal case. Because of its higher sulfur content, design for Illinois coal would require a seed regeneration plant about seven times as large. Assuming a regeneration plant sized for Montana coal is built, test operations of the MHD system using Illinois coal feed must be limited to physical constraints of processing and storing enough regenerated seed to meet this 7-fold requirement. As a practical matter the number of hours of continuous test operation on Illinois coal will have to be somewhat limited.

The Formate Process involves five primary engineering sequences:

1. Gasification to produce carbon monoxide (CO);
2. Dissolving of recovered seed (K_2SO_4) and slurring of lime ($Ca(OH)_2$);
3. Reaction of CO, K_2SO_4 and $Ca(OH)_2$ to produce soluble potassium formate (KCOOH) and insoluble calcium sulfate ($CaSO_4$);
4. Filtration of $CaSO_4$;
5. Evaporation of water from KCOOH.

TABLE 2-60
SULFUR CONTENTS AND SEED REGENERATION REQUIREMENTS
BASIS: ETF Plant Size

	Montana Coal (dried to 5% H ₂ O) <u>57,143 lb/hr (as fed)</u>		Illinois Coal (dried to 2% H ₂ O) <u>51,919 lb/hr (as fed)</u>	
	<u>lb/hr</u>	<u>lb mole/hr</u>	<u>lb/hr</u>	<u>lb mole/hr</u>
Sulfur Content	594	18.5	1,843	57.5
EPA SO ₂ Emissions Limits	754	11.8	753	11.8
Potassium Requirements for Seeding:				
K	5,143	131.5	5,036	128.8
K ₂ SO ₄	11,486	65.9	11,214	64.4
Requirements to Meet EPA SO ₂ Emissions Limits:				
K ₂ SO ₄				
Reprocessing	1,175	6.7	7,944	45.6

Supplementary operations required include compressing and scrubbing the gasifier output to remove carbon dioxide (CO_2); heat exchange, and conveying and storing the gases, liquids, and solids involved in the regeneration system.

A reference system flow diagram and material balances for both Montana and Illinois coal feeds to the MHD combustor are presented in Figures 2-175 and 2-176. An integrated reference system instrumentation and control design for the seed regeneration facility is shown in Figure 2-178. Figure 2-177 presents theoretical heat balances for both Montana and Illinois coal feeds at the ETF plant size chosen for the overall study. An instrument list is presented in Table 2-61. A tabulation of the cost of major equipment appears in Table 2-67 at the end of this section. Preliminary equipment arrangement plan and elevation schemes for the proposed Seed Regeneration Plant appear in Figures 2-179 and 2-180. From these it is apparent that a 6000 sq ft building will be required.

Gasification

The source of the CO for the ETF will be a coke gasifier as shown in Figures 2-175 through 2-180. Since Montana or Illinois coal feeds will create gas purification problems for the CO feed to the reactor, coke is the preferred gasifier feed. The cost of the amount of coke required will be small compared to the alternative of separating oils, tars and volatiles from the CO stream. The theoretical CO requirements for the seed regeneration facility indicate a feed of only 235 lb/hr of coke (10% ash) or about 2.82 tons per day.

A 60" diameter Wellman-Galusha, refractory lined coke gasifier manufactured by the McDowell-Wellman Company of Cleveland, Ohio is proposed. This model unit is presently in operation gasifying calcined petroleum coke. The % by volume expected gas composition burning petroleum coke blown with air and steam is:

CO	29.0%
H ₂	10.0%
CH ₄	0.7%
N ₂	56.8%
CO ₂	3.5%

MASS FLOW (lb/hr)
PLANT SIZE BASIS: MONTANA COAL - 57,143 lb/hr AS FED

INPUT 1 atm.						OUTPUT 1 atm.			
	lb/hr	Temp. (°F)		lb/hr	Temp. (°F)	lb/hr	Temp. (°F)		
Dissolver: K_2SO_4	1401	70	Gasifier: Coke (10% ash)	235	70	$CaSO_4 \cdot 2H_2O$	1152	70	
$Ca(OH)_2$	496	70	Air	1105	70	K_2SO_4	232	150	
H_2O	7010	40	H_2O	141	40	KCO_2H	1126	150	

STREAM:	A, A ¹ , A ²	B	C	D	E	F	G	H	R, R ¹ , R ²	U, U ¹	V	W, W ¹	Y	Z
LIQUID-SOLID														
K_2SO_4	1424	256	256	240	240	232	8	232	-	16	-	-	16	.24
$Ca(OH)_2$	496	-	-	-	-	-	-	-	-	-	-	-	-	-
KCO_2H	113	1240	1240	1162	1162	1126	36	1126	-	77	-	-	77	1.18
$CaSO_4 \cdot 2H_2O$	-	1152	1152	-	-	-	-	-	-	-	-	-	-	1152
H_2O	4696	3997	3967	3967	3384	3278	106	-	4000	3684	906	4030	4590	346

STREAM:	L, L ¹ , L ²	M, M ¹	N	O	P	S	T
GAS							
CO	431	431	56	-	-	-	-
CO ₂	82	-	-	16,666	16,666	-	-
N ₂	845	845	845	62,697	62,697	-	-
H ₂	11	11	11	-	-	-	-
H ₂ O	-	-	460	-	3278	30	583
CH ₄	6	6	6	-	-	-	-

STREAM:	A	A ¹	A ² , B, M ¹ , N	C, D, S	E, F, G, T, U ¹	H, P	R, V	R ¹	R ²	W	W ¹	U	Y	Z, L ¹	L	L ² , M	O
Temp. (°F)	230	230	390	381	212	150	40	148	148	156	323	373	305	70	1200	293	300
Press (atm)	1	35	35	14.3	1	1	1	1	13.6	13.6	13.6	13.6	1	1	1	35	1

Figure 2-175 Formate Process, Reference System Design Flow Diagram and Materials - Montana Coal

MASS FLOW (lb/hr)
PLANT SIZE BASIS: ILLINOIS COAL - 51,919 lb/hr AS FED

INPUT 1 atm.						OUTPUT 1 atm.					
	lb/hr	Temp. (°F)		lb/hr	Temp. (°F)		lb/hr	Temp. (°F)		lb/hr	Temp. (°F)
Dissolver: K_2SO_4	9549	70	Gasifier: Coke (10% ash)	1604	70	$CaSO_4 \cdot 2H_2O$	7860	70			
$Ca(OH)_2$	3386	70	Air	7535	70	K_2SO_4	1584	150			
H_2O	48302	40	H_2O	843	40	KCO_2H	7879	150			

STREAM:	A, A ¹ , A ²	B	C	D	E	F	G	H	R, R ¹ , R ²	U, U ¹	V	W, W ¹	Y	Z
LIQUID-SOLID														
K_2SO_4	9708	1745	1745	1634	1634	1584	50	1584	-	109	-	-	109	1.7
$Ca(OH)_2$	3386	-	-	-	-	-	-	-	-	-	-	-	-	-
KCO_2H	769	8456	8456	7918	7918	7879	239	7879	-	530	-	-	530	8
$CaSO_4 \cdot 2H_2O$	-	7860	7860	-	-	-	-	-	-	-	-	-	-	7860
H_2O	31,836	27,065	26,856	26,856	22,780	22,087	697	-	27,510	25,361	5784	27,719	31,139	2358

STREAM:	L, L ¹ , L ²	M, M ¹	N	O	P	S	T
GAS							
CO	2943	2943	384	-	-	-	-
CO ₂	558	-	-	126,530	126,530	-	-
N ₂	5764	5764	5764	411,897	411,897	-	-
H ₂	73	73	73	-	-	-	-
H ₂ O	-	-	3126	-	22,087	209	4081
CH ₄	41	41	41	-	-	-	-

STREAM:	A	A ¹	A ² , B, M ¹ , N	C, S, D	E, F, G, T, U ¹	H, P	R, V	R ¹	R ²	W	W ¹	U	Y	L ¹ , Z	L	L ² , M	O
Temp. (°F)	230	230	390	381	212	150	40	148	148	156	327	377	306	70	1200	293	300
Press (atm)	1	35	35	14.3	1	1	1	1	13.6	13.6	13.6	13.6	1	1	1	35	1

Figure 2-176 Formate Process, Reference System Design Flow Diagram and Materials - Illinois Coal

ENTHALPY (10 ⁶ Btu/hr)*					
STREAM	MONTANA COAL	ILLINOIS COAL	STREAM	MONTANA COAL	ILLINOIS COAL
1. A	.822	5.575	17. O	4.539	30.793
2. A ¹	.822	5.575	18. P	5.021	34.051
3. A ²	1.644	11.150	19. R	-.120	-.825
4. B	1.481	10.040	20. R ¹	.314	2.137
5. C	1.430	9.692	21. R ²	.314	2.137
6. D	1.326	8.984	22. S	.036	.244
7. E	.523	3.523	23. T	.670	4.540
8. F	.506	3.416	24. U	1.124	7.827
9. G	.016	.108	25. U ¹	1.043	7.089
10. H	.023	.158	26. V	-.027	-.173
11. L	.434	2.962	27. W	.350	2.381
12. L ¹	0.000	0.000	28. W ¹	1.020	7.121
13. L ²	.085	.584	29. Y	1.016	6.916
14. M	.083	.555	30. Ash @ 1200°F	.041	.279
15. M ¹	.117	.796	31. K ₂ SO ₄ leaving MHD System	.153	1.040
16. N	.689	4.686			

HEATS OF REACTION					
Reactions	ΔH (kcal/qmol)		10 ⁶ Btu/hr		
I K ₂ SO ₄ + Ca(OH) ₂ + 2CO = CaSO ₄ + 2KCO ₂ H	- 27.1		MONTANA COAL	ILLINOIS COAL	
II C + CO ₂ = 2CO	38.62		-.327	-2.229	
III H ₂ O + CO = CO ₂ + H ₂	- 9.838		.3764	2.467	
IV C + 2H ₂ = CH ₄	- 20.5		-.0131	-.086	
V C + H ₂ O = CO + H ₂	28.78		-.0136	-.089	
VI C + O ₂ = CO ₂	- 96.65		.275	1.801	
VII 2KCO ₂ H + O ₂ = K ₂ CO ₃ + H ₂ O + CO ₂	-109.9		-1.1369	-7.444	
VIII K ₂ CO ₃ + SO ₂ = K ₂ SO ₄ + CO	- 23.17		-1.3254	-9.03	
IX CO + 1/2 O ₂ = CO ₂	- 67.636		-.2794	-1.904	
X CO + 1/2 O ₂ = CO ₂	- 67.636		-.8157	-5.557	
XI CH ₄ + 2O ₂ = CO ₂ + 2H ₂ O	-191.759		-.245	-1.67	
XII H ₂ + 1/2 O ₂ = H ₂ O	- 57.7979		-1.42	-.86	
XIII CaO + H ₂ O = Ca(OH) ₂	- 16.6		-.660	-3.76	
			-.200	-1.365	

* NOTE: Enthalpy of streams relative to 70°F.

Figure 2-177 Formate Process, Reference System Design Flow Diagram and Heat Balances - Montana and Illinois Coal

Figure 2-178 Formate Process, Reference System Design Flow Diagram - Instrumentation

TABLE 2-61
PRELIMINARY INSTRUMENT LIST
SEED REGENERATION PLANT

<u>Item</u>	<u>Application</u>
T ₁	Temperature control of reactor slurry feed
T ₂	Temperature control of reactor
T ₃	Temperature control of gasifier
T ₄	Temperature control of gas cooler output gas
T ₅	Temperature control of reactor gas feed
T ₆	Temperature control of flue gas input to spray drier
T ₇	Temperature control of dissolving tank
T ₈	Temperature control of CO ₂ scrubber-regenerator system
L ₁	Solids level control of recovered seed feeder
L ₂	Solids level control of lime feeder
L ₃	Solids level control of coke feeder
L ₄	Liquid level control of reactor
F ₁	Flow control of reactor slurry feed and recycle
F ₂	Flow control of dissolver water feed
F ₃	Flow control of coke feed to gasifier
F ₄	Flow control of lime feed to dissolver
P ₁	Pressure control of reactor
C ₁	CO analyzer and flow control of gas feed to reactor

TABLE 2-61

PRELIMINARY INSTRUMENT LIST
SEED REGENERATION PLANT (Continuous)

<u>Item</u>	<u>Application</u>
PRV-1	Pressure control of reactor off gas to bottoming plant or flare
PRV-2	Pressure control of filter slurry feed
PRV-3	Pressure control of filter washwater feed to dissolver
PRV-4	Pressure control of spray drier feed and dissolver recycle feed
<u>1</u>	Lime feeder test point
<u>2</u>	Recovered seed feeder test point
<u>3</u>	Reactor slurry feed test point
<u>4</u>	Compressor output gas test point
<u>5</u>	Reactor gas feed test point
<u>6</u>	Reactor gas output test point
<u>7</u>	Reactor slurry output test point
<u>8</u>	Spray drier slurry feed test point
<u>9</u>	Spray drier output test point

Figure 2-180 Seed Regeneration Plant, Equipment Arrangement

The space allocation shown in Figures 2-179 and 2-180 is based on this equipment. The coke feed system proposed includes a Model 203B-105Z gravimetric feeder manufactured by Acrison, Inc. of Carlstadt, N. J., with auxiliary hopper and bucket elevator as shown in Figures 2-175, 2-179 and 2-180. Coke is supplied to the feeder from the coke silo (capacity 50,000 lb or 200 hr operation at full load) by pneumatic conveyor. Comparable feeders with similar capabilities are manufactured by Vibrascrew, Inc. of Totawa, N. J., BIF Division of General Signal Corporation, Providence, R. I., and other companies.

In order to supply to the reactor the volume of CO at 500 psia required by the process, a gas compressor preceded by a gas cooler must be used. An Ingersoll-Rand Type ESH, three stage reciprocating compressor with intercooling and pressure storage tank is proposed. The separately driven first stage (booster), which has a 13" diameter cylinder and a 5" stroke, will raise CO pressure to 58 psia. The tandemly driven second and third stages, which will have 7" strokes and 6" diameter and 4" diameter cylinders respectively, will raise CO pressure from 58 psia to 505 psia. The space allocation shown in Figures 2-179 and 2-180 is based on these units.

As standby for the gasifier-compressor system, a supply of commercially purchased CO is proposed. The tankage can be either a vendor owned 110,000 cubic ft capacity 2000 psi tube-tank trailer or a permanent tank storage system into which the tube-tank deliveries can be transferred. The space allocation shown in Figures 2-179 and 2-180 is based on tube-tank trailer requirements.

An ethanolamine CO_2 scrubber is incorporated in the gasification sequence to preclude the possibility of undesirable side reactions occurring in the reactor. However, omission of the scrubber system step may merely add a small quantity of CaCO_3 precipitate to the CaSO_4 solids formed in the reactor. Because there may be a small amount of Ca^{++} in the reacting solution, presence of CO_2 in the entering gas may actually facilitate its removal by CaCO_3 precipitation.

As indicated by Heat Exchanger X-2 in Figure 2-177, CO reheat will be required to satisfy thermal requirements of the reactor.

Dissolving

In this sequence a water solution of recovered seed and slurry of lime are prepared for feeding to the reactor. A 1000 gallon, mixer-equipped dissolving tank is proposed to accept recovered seed, lime wash water from the filter containing recovered potassium salts and recycled process solution. Rates of feed of lime and recovered seed are controlled by instrumented gravimetric feeders. A residence time of one hour is provided. Heat and water requirements are satisfied by the combination of the recycle stream, wash water from the CaSO_4 filter and makeup process water. Pressure and temperature of the recycle stream are reduced to 1 atm and 212°F by a pressure reducing valve (PRV-4) and flash tank in the filter discharge line.

Lime and recovered seed are conveyed to the feeders pneumatically from the lime and recovered seed silos. The former has a capacity of 50 tons (200 hr operation); the latter has a capacity of 15 tons (20 hr operation). Provisions have been made for a recovered seed silo in the bottoming plant with a capacity of 50 tons. The gravimetric feeders proposed are Model 203B-105Z manufactured by Acrison, Inc. Comparable units are available from other manufacturers including Vibrascrew, Inc. and BIF Division of General Signal Corporation.

Although not specifically indicated in the flow diagram, quicklime is proposed as the source of CaO to minimize raw material cost, reduce material handling problems and to take advantage of energy recovery from the substantial heat of hydration. Quicklime can be hydrated either during dispersion in the dissolver or in a preceding slaker.

Reaction

In this sequence CO , $\text{Ca}(\text{OH})_2$ and K_2SO_4 are reacted to form KCOOH and byproduct $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (gypsum). A single, multiple section reactor with a residence time of 1 hr is proposed. (The German industrial approach used multiple reactors.) Other design options include a bubble cap tower or a sieve tray tower. More precise information will have to be obtained either from pilot studies or past German industrial practice or both, before a sufficiently reliable reactor design can be proposed.

A 42" i. d. x 26' long jacketed, multisection continuous reactor (known as "Ergulator") having a working volume of 170 cubic ft manufactured by the

Bethlehem Corporation, Easton, Pa. is a technical possibility. This unit can be designed for either concurrent or countercurrent flow, sectional gas injection and has multiple turbine mixers, one in each section, to facilitate good contact between reacting components. The space allocation shown in Figures 2-179 and 2-180 is based on this equipment.

A Moyno Model 9P6 Type SSQ, 316 stainless steel, positive pressure slurry pump with a capacity of 15 gpm at 500 psi discharge pressure is proposed both for the reactor feed and for the filter feed pumps. This equipment is manufactured by Moyno Pump Division of Robbins and Meyers Company of Springfield, Ohio.

Filtration

The choice of filter equipment to be used for the ETF will have to be based on the physical character of the precipitate. CaSO_4 solids may form as the dihydrate (gypsum) or mixtures of compounds at various levels of hydration. Small amounts of unreacted lime and CaCO_3 may be present.

On the basis of information currently available, a Bird-Young 2' diameter x 3' face pressurized rotary drum filter is proposed. Experimental tests will have to be performed before this type of solids separation equipment can be specified with assurance. A pressurized filter is preferred to insure the filterability of the CaSO_4 formed in the reactor. Alternatives may include an unpressurized rotary drum filter, a horizontal filter, or a two-stage continuous centrifuge (one for solids separation, one for cake washing). Manufacturers of equipment to fit these alternatives include Dorr-Oliver Company of Stamford, Conn. and Eimco Division of Envirotech, Inc., Salt Lake City, Utah. The proposed unit is manufactured by the Bird Machine Company of South Walpole, Mass. If an unpressurized filter can be used, a simplified piping and wash water recovery system will be possible (Figure 2-181).

Drying

A spray drier is proposed to evaporate water from the KCOOH product solution discharged by the filter in order to exploit what otherwise would be low grade waste heat in the off gas from the bottoming plant (or the auxiliary boiler when the former is not operating). About 150,000 cfm of flue gas at 275°F , will be discharged from the electrostatic precipitators

Figure 2-181 Formate Process, Unpressurized Filter Washwater and Heat Recovery Flow Diagram

of the ETF. A portion of the heat can be recovered in the spray drying step although supplementary flue gas reheat may also have to be employed (Figures 2-175, 2-178, 2-179 and 2-180). If for any reason flue gas is not available, then preheated air will have to be used as the drying medium. Provisions will have to be made for supplying the thermal energy required for that eventuality either by recovering heat from the off gas or the gasifier and by utilizing steam produced by the auxiliary boiler or by the bottoming plant itself.

A Swenson, stainless steel, three component (drier, cyclone and dust collector) spray drier manufactured by the Whiting Corporation, Harvey, Illinois, is proposed for this application. Other manufacturers offer similar units. Space allocation shown in Figures 2-179 and 2-180 is based on requirements for Swenson equipment selected for an inlet drybulb temperature of 300°F and an outlet dry bulb temperature of 150°F. Since there will be only a small quantity of SO₂ in the flue gas used, gas exit conditions below the dew point of SO₂ are not expected to cause serious corrosion problems.

Silo Storage and Solids Conveying

As indicated by Figure 2-175, 2-179 and 2-180, silo storage and associated pneumatic conveying systems are provided for recovered seed, lime, coke, virgin K₂SO₄ and KCOOH product. The sizes chosen are as follows:

		<u>Capacity</u>		
		<u>cu ft</u>	<u>ton</u>	<u>(full load) hours operation</u>
K ₂ SO ₄	recovered seed ballast	300	15	20
CaO	lime	1500	50	200
C	coke	1000	25	200
K ₂ SO ₄	virgin potassium sulfate	1500	50	---
KCOOH	potassium formate ballast	300	10	18
KCOOH	potassium formate storage	1500	50	90

Space allocation in Figures 2-179 and 2-180 are for the above sizes. Equipment can be purchased from a number of manufacturers. Cost estimates are based on information supplied by H. P. Fuller Division of GATX Company, Catasauqua, Pa.

Instrumentation

The control instruments proposed are listed in Table 2-62 and shown functionally in Figure 2-178. All but one are standard solids or liquid level controls, temperature, pressure or flow controls. Discharge control from the feeders is integral with those units. A cascade control system is proposed in which feed rates of coke to the gasifier and lime and water to the dissolver are proportioned exactly to the preset flow of recovered seed. The latter is the key setting since it establishes the operational load of the Seed Regeneration Plant as a whole. One instrument deserves special note: a CO analyzer manufactured by the Environmental Data Corporation, Monrovia, California is proposed. It applies infrared spectroscopic detection devices to measure CO and CO₂ (and ultraviolet spectroscopic detection devices to measure SO₂ and NO if required). For this application a measurement of differential CO concentration between the gas feed and off gas is suggested as a way of controlling CO input to the reactor and measuring the extent of reaction.

Heat Balance

Theoretical heat balances at the chosen ETF plant size for both Montana coal and Illinois coal feeds are shown in Figure 2-177. The values were determined by making heat balance computations around each of the major pieces of equipment: dissolver, gasifier, compressor, reactors, heat exchangers, filter and spray drier. The energy requirements for the seed regeneration system as a whole are summarized in Table 2-62. The subtotal requirements of 6.2×10^6 Btu/hr and 40.1×10^6 Btu/hr for Montana and Illinois coal, respectively, can be theoretically reduced by the aggregate "heat recovery" values of the flue gas enthalpy consumed (considered "free" because it is otherwise lost to the atmosphere) and combustion of CO, CH₄ and H₂ in the off gas from the reactor system. The net totals of 1.8×10^6 and 10.8×10^6 Btu/hr, respectively, for Montana and Illinois coal are equivalent to net energy charges to the ETF facility of about 0.5 and 3.3 MW, respectively. These estimates do not include projections of heat losses or the practical limits of heat transfer in equipment shown.

TABLE 2-62

ENERGY REQUIREMENTS
SEED REGENERATION PLANT

		10^6 Btu/hr *	
<u>Item</u>		<u>Montana Coal</u>	<u>Illinois Coal</u>
1.	Dissolver	- 0.210	- 1.45
2.	Lime Slaking	- 0.200	- 1.36
3.	Heat Exchanger x-1	0.822	5.57
4.	Heat Exchanger x-2	0.035	0.24
5.	Reactor System	0.083	0.55
6.	Spray Drier	3.452	23.42
7.	MHD Channel (seed feed system)	- 2.245	- 15.29
8.	Gasifier	3.067** (235 lb Coke 10% Ash)	20.93** (1604 lb Coke 10% Ash)
9.	Auxiliary Power	1.005	4.58
Subtotal		5.81	37.19
10.	Less Flue Gas Heat	2.959	20.08
11.	CO Combustion	- 0.245	- 0.86
12.	H ₂ Combustion	- 0.660	- 3.76
13.	CH ₄ Combustion	- 0.142	- 1.67
Net Total		1.80	10.82
		(0.541 MW)	(3.25 MW)

* Heat demand on the system

- Heat evolved from the system

** Basis: 14,500 Btu/lb Carbon

Preliminary Equipment Arrangement

The preliminary arrangement of major process equipment shown in Figures 2-179 and 2-180 were developed to allocate space for the Seed Regeneration Plant. An enclosed structure about 100' x 60' will be adequate, assuming that the large storage silos are located outdoors. The seed regeneration area was positioned with respect to the rest of the ETF MHD plant to facilitate receipt of recovered seed from the bottoming plant and transportation of regenerated seed to the combustor.

Solids Receiving and Storage

The coke and lime silos are sized for a 200 hr reserve and located adjacent to the rail siding to facilitate pneumatic unloading. The KCOOH storage and ballast silos together will hold 108 hrs reserve. Quantities beyond that which may be required for normal ETF operation, e. g., startup or runs with Illinois coal feed, will either have to be received and unloaded at more frequent intervals or held in hopper cars as temporary storage.

Plant Operation - General

The seed regeneration plant can be operated together with or as an independent component of the ETF system using either virgin K_2SO_4 as feed or seed recovered from earlier ETF plant operation and stored for later processing. For MHD component testing in the bypass mode of operation, K_2SO_4 seed can be fed to the combustor from the virgin K_2SO_4 silo storage system, and sulfur-free seed required to combine with SO_2 can be fed either as virgin potassium carbonate (K_2CO_3) or as potassium formate (KCOOH) regenerated from earlier seed regeneration plant operation and stored for later processing. Provisions for storing large quantities of K_2CO_3 have not been made. It is assumed that K_2CO_3 inventoried in 100 lb bags or that the KCOOH storage silo can be used. For larger quantities, temporary storage capabilities in hopper cars or additional storage silos will have to be provided.

In the event of an MHD plant malfunction, the capacity of the recovered seed storage silo located in the bottoming plant will permit the seed regeneration plant to continue to operate for 72 hrs. Similarly, in the event of a seed regeneration plant malfunction, the KCOOH storage silo will permit injection of regenerated sulfur-free seed into the combustor to continue for

80 hrs. The Seed Regeneration Plant will satisfy normal operating program requirements for the case of Montana coal feed.

For the case of Illinois coal feed, the operating procedures for the Seed Regenerating Plant are uncertain because its capacity would have to be 7 times greater to match regeneration requirements. One option is to start up the MHD combustion system with Illinois coal feed using virgin K_2CO_3 as the sulfur scavenging seed feed in order to inventory enough recovered K_2SO_4 for reprocessing. Then the seed regeneration plant could be operated separately for 7 times the expected Illinois coal test period in order to inventory enough regenerated KCOOH. Alternatively, enough KCOOH could be manufactured in the seed regeneration plant using virgin K_2SO_4 as raw material. In any event, the seed plant operating time on Illinois coal will have to be determined in advance. For all practical purposes, it will have to be somewhat limited. A 2000 hr test of the MHD plant for the Illinois coal feed case would require about 14,000 hrs of operation of the Seed Regeneration Plant (1.6 years, 24 hr/day, 7 days/week), which is not considered to be practical.

On the startup with Montana coal feed, it is proposed to inject virgin K_2SO_4 and virgin K_2CO_3 into the combustor for a length of time sufficient to produce enough acceptable recovered seed starting material for the Seed Regeneration Plant. A 40-hr startup interval without relying on seed recovery or seed regeneration has been assumed - i.e., inventory requirements of about 220 tons of K_2SO_4 and 25 tons of K_2CO_3 . Rail car storage for this purpose is assumed. Makeup for the expected 5% losses of potassium sulfate in the MHD system plus the < 5% expected losses in the seed regeneration plant will be supplied from the 200 hr capacity, virgin K_2SO_4 storage silo. Makeup of sulfur-free seed required by malfunction or low yields in the seed regeneration plant will be supplied from an inventory of K_2CO_3 in 100 lb bags.

When the bottoming plant is not operating in its entirety together with the topping plant, the seed regeneration facility will not be operated as a continuous component of the ETF system. The seed regeneration plant is conceptually designed to operate continuously as a part of the overall MHD system during Montana coal feed but, except for starting material requirements, it is independent process wise.

Integral Process Control

A proposed instrumentation system for controlling the continuous operation of the Seed Regeneration Plant as a whole is shown in Figure 2-178. Raw material feeds (coke, lime, water) to the plant are controlled by a cascade system which proportions flows as required by the process to the preset feed rate of recovered seed. Thus the entire Seed Regeneration Plant can be operated systematically at full load or part load by initially establishing the K_2SO_4 (recovered seed or virgin) feed rate.

Heat requirements are supplied by 180 psig steam from the bottoming plant or the auxiliary boiler, and by the flue gas received from the bottoming plant. Makeup and cooling water are supplied either by the ETF circulating water system or from a service water system (not identified). Discharges from the Seed Regeneration Plant include reactor off gas (to flare or to bottoming plant for energy recovery), heat-stripped flue gas from the spray drier to the stack, cooling water to the plant sewer, $CaSO_4 \cdot 2H_2O$ (gypsum) and coke ash to solid waste disposal, a small quantity of wet steam carrying CO_2 to external vent from the scrubber system regenerator and a small quantity of steam from the gasifier, and pneumatic conveyor air exhaust to the atmosphere. The dissolver instrumentation includes level and temperature control (cooling is required). Reactor instrumentation includes level, temperature, pressure and gas feed controls. The pressure filter instrumentation includes a system for depressurizing the feed from the reactor and the wash water recycle to the dissolver.

The spray drier instrumentation includes control for depressurizing the feed from the pressure filter and temperature control of the inlet drying gas.

Nine test points are included at appropriate places in the proposed control scheme in order to be able to sample flows manually or automatically for quantitative physical and chemical analysis.

Although not shown in Figure 2-178, steam and watt meters will be included in the plant to measure external heat and power inputs. Raw material consumption (both rate and integrated) will be recorded by feeder instrumentation.

Operating Procedures

Details of proposed initial, normal and emergency operating procedures appear in the following tables:

Table 2-63 Component Testing Program

Table 2-64 Normal Startup Procedure

Table 2-65 Normal Shutdown Procedure

Table 2-66 Emergency Shutdown Procedure

Because the Seed Regeneration Plant is operated essentially independently of the rest of the ETF, a discussion of full load and part load operation is not pertinent. Ample silo storage systems are provided both for recovered seed coming from the bottoming plant and for KCOOH product. Thus, the MHD topping and bottoming plants can operate for extended periods entirely independently of the Seed Regeneration Plant and vice versa. In special situations (bypass mode testing, startup, KCOOH or recovered seed shortages) virgin K_2SO_4 and K_2CO_3 in proper proportion can be fed to the combustor by the Petrocarb seed feed system, and seed collected from the bottoming plant can be collected in the latter's storage silo. Similarly, the Seed Regeneration Plant can be fed either with virgin K_2SO_4 or with recovered seed from their respective storage silos, and KCOOH product can be transferred to the KCOOH storage silo. It should be noted that when the ETF is being operated in bypass mode, process steam and flue gas must be supplied by the auxiliary boiler. In the case of flue gas shortages or supply malfunction, preheated air can be alternatively used as the drying medium for the spray drier. This will require an additional supply of 4427 lb/hr of 180 psig super-heated steam (50% of the capacity of the auxiliary boiler).

System Test Plan

Once the Seed Regeneration Plant has been constructed and all components have been tested for mechanical function, a system test program can begin. Initially, virgin K_2SO_4 will be fed as raw material and the KCOOH product will be stored for later use as feed for the MHD combustor. It is expected that a 30-day test of continuous, 24-hr/day operation will be sufficient to establish all process control values. An additional 10-11 months of continuous operation at least 40 hr/week will be required to evaluate process effectiveness. This will include evaluations of product yields and losses, raw material conversion rates, energy consumption operating costs, and equipment durability.

COMPONENT TESTING PROGRAM SEED REGENERATION PLANT

Components	Operator Actions	Engineering Observations
1. Recovered Seed Feeder	Energize Virgin K_2SO_4 Silo Airveyor. Fill feeder hopper. Set feeder rate. Energize feeder.	Check flow rate at test point Δ . Vendor checkout.
2. Lime Feeder	Set lime feeder rate via cascade control link to recovered seed feeder. Energize lime silo airveyor. Fill feeder hopper. Energize feeder.	Check flow rate at test point Δ . Vendor checkout.
3. Coke Feeder	Set coke feeder rate via cascade control link to recovered seed feeder. Energize lime silo airveyor. Fill feeder hopper. Energize feeder.	Check flow rate at feeder discharge port. Vendor checkout.
4. Dissolver, Reactor Feed Pump, Heat Exchanger x-1	Fill dissolver with hot water. Energize mixer motor. Energize temperature controller. Energize Virgin K_2SO_4 airveyor, lime airveyor, seed feeder, lime feeder. Operate for 1 hour. Energize reactor feed pump, heat exchanger x-1 and pump out dissolver into reactor. Open reactor drain line to sewer.	Check dissolving and dispersing action overtime at at test point Δ . Checkout T_1 operation.
5. Filter, Filter Feed Pump and Filter Auxiliaries	Disperse $CaSO_4 \cdot 2H_2O$ in hot water in dissolver. Use proportion of plant size mass flow. Pump into reactor. Energize filter feed pump, filter and filter auxiliaries. Close line to spray drier. Pump mixture from reactor through filter and filtrate and wash-water back to dissolver. Repeat, pressurizing reactor to 500 psia with tanked N_2 or air.	Check unpressurized operation of filter and auxiliaries. Check pressurized operation of filter and auxiliaries. Vendor checkout.

TABLE 2-63

COMPONENT TESTING PROGRAM
SEED REGENERATION PLANT (Continued)

Components	Operator Actions	Engineering Observations
6. Spray Drier and Auxiliaries Formate Ballast Silo	Prepare solution of $K_2SO_4/KCOOH$ in water at plant design concentrations in dissolver or auxiliary tank. Set up temporary piping connections and test pump to feed from dissolver to spray drier. Energize air heater (flue gas reheater), spray drier, exhaust fan and spray drier auxiliaries. Pump test solution through spray drier. Feed product to formate ballast silo.	Check dried product, airveyor operation, temperature control system, operation of drier and auxiliaries. Vendor checkout.
7. Compressor, CO Pressure Tank, CO Reserve System	Set up for test operation on air feed. Operate and feed to CO pressure tank. Bleed pressure tank. Leak test, all components. Energize building CO detection system (not shown). Repeat test feeding depressurized CO from CO reserve tank.	Check compressor operation, cooling water feed, CO reserve tank system, CO pressure tank and reactor as pressure vessel. Vendor checkout.
8. CO_2 Removal System, Heat Exchanger X-2, Reactor Pressure Vessel	Fill regenerator with water. Energize scrubber pump, heat exchanger X-2 and set PRV-1 on reactor. Close reactor feed and discharge lines. Using compressor on air feed, bleed air from CO pressure tank through scrubber system into reactor. Allow CO pressure in reactor to increase to 500 psia max. Repeat using amine scrubbing solution in regenerator. Leak test all components. Energize building CO detection system. Repeat using CO from CO reserve system.	Check operation of scrubber system, heat exchanger X-2 and reactor pressurizing. Vendor checkout.

TABLE 2-63

COMPONENT TESTING PROGRAM
SEED REGENERATION PLANT (Continued)

Components	Operator Actions	Engineering Observations
9. Reactor	Preheat reactor via steam jacket to 390°F. Energize turbine mixers. Prepare operating reactor feed mixture in dissolver as in (4). Set up CO feed from CO reserve system and CO pressure tank. Close reactor drain lines. Pressurize reactor to 500 psia. Pump dissolver contents into reactor. Maintain 500 psia CO pressure. After 1 hour drain reactor to temporary external tank. Flush reactor.	Check all systems and analyze composition of reactor discharge. Vendor checkout.
10. Gasifier and Auxiliaries	Energize coke feeder and all gasifier auxiliaries. Light off and test operate per vendor's instructions and under vendor supervision. Energize gas cooler, compressor and CO pressure tank systems. Feed gasifier output to pressure tank.	Vendor checkout. Analyze gas composition at test point $\triangle$

TABLE 2-64

NORMAL STARTUP PROCEDURE
SEED REGENERATION PLANT

Pre-Startup Conditions

1. 180 psig steam line energized & all branch steam supply lines operational
2. Water line energized & all branch water supply lines operational
3. Condensate return line operational
4. Instrument air supply energized
5. Coke, lime, virgin K_2SO_4 and/or recovered seed silos filled
6. Formate ballast silo empty
7. Instrument control set points positioned at operating values & all instruments operational
8. Pressure reducing valves set at operating conditions
9. Coke, lime & K_2SO_4 (virgin or recovered seed) feeder hoppers filled
10. Flue gas or air supply to spray drier operational
11. Scrubber system regenerator filled with diethanolamine solution
12. Gypsum sludge disposal vehicle in place
13. Recovered seed feeder discharge control set at desired mass flow rate
14. Gasifier coke supply hopper filled

TABLE 2-64

NORMAL STARTUP PROCEDURE
SEED REGENERATION PLANT (Continued)

Startup Sequence

1. Light off gasifier & begin bleeding off gas through gas cooler to compressor. Energize coke feeder (cascade controlled by recovered seed feeder), energize gas cooler washwater pump and discharge to sewer.
2. Energize compressor & build up pressure in CO pressure tank after bleeding air to outside atmosphere or stack.
3. Energize scrubber system pump and allow CO to bleed through heat exchanger x-2 into reactor. Purge reactor and flare off gas.
4. Fill dissolver with hot water & energize mixer.
5. Energize lime and recovered seed feeders.
6. After 1 hour (ballast time in dissolver) energize reactor turbine mixers and reactor feed pump. Allow reaction mixture to pass through heat exchanger x-1 to fill reactor. Continue raw material feeds to dissolver.
7. After 1 hour more (ballast time in reactor) energize filter & auxiliaries. Energize filter feed pump.
8. Energize spray drier exhaust fan & auxiliaries. Energize spray drier airveyor to deliver product to formate ballast silo.
9. Energize formate ballast silo airveyor for transporting product to formate storage petrocarb seed feed system.
10. Switch reactor off gas flow from flare to bottoming plant if latter is operational.

TABLE 2-65

NORMAL SHUTDOWN PROCEDURES
SEED REGENERATION PLANT

1. Shut off recovered seed feeder. (Coke feeder and lime feeder will stop by instrument control). De-energize coke feeder and lime feeder.
2. Allow gasifier to burn down and then turn off gasifier air supply fan.
3. Direct all filtrate flow from filter to spray drier (i. e., block recycle flow to dissolver) and divert filter washwater flow to sewer. Shut off process water feed to dissolver.
4. Empty dissolver via normal operation of reactor feed pump and shut off reactor feed pump. Deactivate dissolver and reactor feed temperature controls. Turn off dissolver mixer.
5. Drain reactor via normal operation of filter feed pump. Turn off filter feed pump. Turn off reactor mixer. Deactivate reactor temperature control.
6. Drain filter via normal operation of spray drier feed pump. Turn off filter and auxiliaries and spray drier feed pump.
7. Turn off spray drier exhaust fan and auxiliaries. Deactivate spray drier temperature control.
8. Turn off CO₂ scrubber pump and deactivate scrubber system temperature control.
9. When gasifier fuel is no longer burning, shut down gas compressor. Close line from CO pressure tank and depressurize reactor gas feed lines and reactor by venting reactor to bottoming plant or flare.
10. De-energize all airveyors and all instruments.
11. Water flush dissolver, reactor, filter, spray drier and all liquid pipelines.
12. Deactivate 180 psig steam, water and condensate return lines and valve off flue gas supply line from bottoming plant or auxiliary boiler.

TABLE 2-66

EMERGENCY SHUTDOWN PROCEDURE
SEED REGENERATION PLANT

A. Power Failure to all Systems (blackout)

1. Fail-safe valves operate to:
 - (1) Close 180 psig steam supply
 - (2) Release CO from gasifier to external stack vent
 - (3) Depressurize reactor and line from CO pressure tank to external stack vent
 - (4) Close CO pressure tank feed to process
 - (5) Divert flue gas from bottoming plant to stack
 - (6) Bleed compressor to external stack vent
 - (7) Depressurize filter and auxiliaries to sewer and stack vent.
Manual valves operated as back for (1) - (7) above.
2. Drain to Sewer:
 - (1) Reactor and line from dissolver
 - (2) Filter and line from reactor
 - (3) Dissolver and lines from filter
 - (4) Line from filter to spray drier
3. Nothing must remain operating during blackout.

B. Power Remains

1. Divert CO from gasifier to stack vent and shut down gasifier air supply fan
2. Shut down compressor
3. Shut down recovered seed, lime, and coke feeders
4. Close line from CO pressure tank to reactor
5. Depressurize reactor and line from CO pressure tank to stack vent
6. Shut down reactor feed pump
7. Shut down filter, filter feed pump, filter washwater pump and spray drier feed pump
8. Shut down gas cooler water pump (filter washwater feed)

TABLE 2-66

EMERGENCY SHUTDOWN PROCEDURE
SEED REGENERATION PLANT (Continued)

9. Shut down spray drier exhaust fan and cyclone airveyor
10. Shut down airveyor at formate ballast silo
11. Close 180 psig steam supply
12. Drain to sewer: dissolver, reactor, filter and related liquid handling pipelines
13. Shut down reactor mixer

TABLE 2-67

MAJOR EQUIPMENT COST ESTIMATE
SEED REGENERATION PLANT

<u>Item</u>	<u>Materials</u>	<u>Installation</u>	<u>Total</u>
	(\$)	(\$)	(\$)
1. Gasifier	130, 000	35, 000	165, 000
2. CO Compressor	65, 000	18, 000	83, 000
3. Reactor	150, 000	40, 000	190, 000
4. Filter	300, 000	81, 000	381, 000
5. Spray Drier	120, 000	32, 000	152, 000
6. Silos (6)	70, 000	19, 000	89, 000
7. Airveyors (7)	74, 000	20, 000	94, 000
8. Feeders (3)	25, 000	7, 000	32, 000
9. Heat Exchangers (5)	13, 000	4, 000	17, 000
10. Scrubber System	8, 000	2, 000	10, 000
11. Dissolver	10, 000	3, 000	13, 000
12. Pumps (5)	40, 000	11, 000	51, 000
13. Misc. Tanks	7, 000	2, 000	9, 000
14. Instruments	<u>100, 000</u>	<u>36, 000</u>	<u>136, 000</u>
Subtotal	\$1, 112, 000	\$310, 000	\$1, 422, 000
15. Misc. Piping & Electrical	<u>89, 000</u>	<u>100, 000</u>	<u>189, 000</u>
TOTAL	\$1, 201, 000	\$410, 000	\$1, 611, 000

For this program it will be desirable as early as practical to feed seed recovered from the bottoming plant in order to execute the system test program under the most realistic conditions. The effect of contaminants and other characteristics of the recovered seed on regeneration operations is a vital consideration. Similarly, it will be desirable to recycle as early as practical, product KCOOH to the MHD combustor. Barring unforeseen difficulties or requirements for major plant modifications, it is expected that the Seed Regeneration Plant can, after this one-year test program, be operated routinely as a part of the overall MHD power plant.

2.16.3 Seed Feeding

Seed will be fed to the combustor using a Petrocarb or other similar pressurized feeding system. A schematic of the seed feed system is shown in Figure 2-182.

The system consists of a storage injector tank and a pressurized primary injector tank with multiple feed lines to the combustor. The storage injector tank will alternately be depressurized while being filled and pressurized to discharge its seed contents to the primary injector tank. A supply of dry air is required for pressurizing the tanks and transporting the seed. The continuous demand for transport air will be 207 scfm. The intermittent demand for pressurization of the storage injector will be 415 scfm for 3 min, every 20 min. Air will be supplied by the same booster compressor used for the coal feed system. The storage injector tank is fed by two bins. One bin will hold an eight hour supply of potassium formate (KCO_2H) or potassium carbonate (K_2CO_3) in the case that seed is not being regenerated. This bin will be filled pneumatically with KCO_2H from the seed regeneration plant or with purchased K_2CO_3 . The second bin will hold an eight hour supply of K_2SO_4 . This bin will be filled pneumatically with K_2SO_4 which has been recovered from the steam generator and precipitator.

Volumetric feeders will meter K_2SO_4 and KCO_2H (or K_2CO_3) at the desired rate to a mixing screw conveyor. The mixing screw conveyor will provide a homogeneous mixture of seed to the storage injector tank. Seed feed rate will be monitored in the main control room. The Petrocarb system has a turndown ratio of 4 to 1. Flow from the Petrocarb System is monitored by weighing the primary injector tank.

Figure 2-182 Schematic Drawing of Seed Feed System

2.17 INVERTER AND ELECTRICAL EQUIPMENT

2.17.1 Inverter System

This section describes the fundamentals of a conceptual design for the conversion of dc power from the ideal Faraday and diagonal types of MHD channels of the Engineering Test Facility.

The conversion system chosen will be a line commutated static type inverter, using the ac voltage and frequency as the source for the conducting periods of its thyristors, and will be regulated by feedback controls to initiate the conducting periods to match the voltage current characteristics of the MHD outputs. The system will be modularized in such a way that all the possible modes of channel loading may be accommodated by changing connections on the dc side only.

A discussion of the rationale for this choice as against, for example, forced commutated inversion systems, is given after the design description, when the complexity of the dc to ac interfacing problems may be better appreciated.

At this point however, it is pertinent to note a guiding philosophy which has in a pragmatic way, forced the choice of conversion system, first of all, to static types over possible electro-mechanical systems (e. g., dc motor ac generator sets); and then favored the more conventional proven state-of-the-art line commutated inversion system. This philosophy is that the ETF shall be principally a pilot scale demonstration facility involving the demonstrating of MHD power in an ac system, rather than a test and development facility. Further, to the extent that development is involved, this should focus on the MHD related components.

The conversion system then, should not be such that it might require extensive technical and/or commercial development to be available to the ETF; nor become a possible major area of ongoing test or development, interfering with the ETF demonstration function.

One final introductory note: the main utility need is not for a stand-alone MHD power supply, i. e. ; to feed a load without connection to an ac system of other synchronous sources. Therefore, lack of this capability does not become a disadvantage for the line commutated system, or conversely, existence of this capability is not an advantage for a forced

commutated one. In point of fact, this capability is not entirely inherent in the forced systems - it has to be designed into them. And for that matter, by special means, the same capability can be given to a naturally (line) commutated inverter.

2.17.1.1 Inverter Requirements from the MHD Side

The total power handling capacity and operating range is summarized in the following Table 2-68.

TABLE 2-68
INVERTER SYSTEM CAPACITY AND OPERATING RANGE

$\dot{m}/\dot{m}_{des}$ ($\dot{m}_{des} = 65 \text{ Kg/sec}$)	MHD Elec. Output, MW	
	2500°F Preheat	3000°F
Min - (0.4)	11 (0.31)	14.1 (0.31)
Baseload - 65 (1.0 pu)	35.5 (1.0 pu)	45.6 (1.0 pu)
Max - (1.25)	44.7 (1.26)	57 (1.25)

Variations as a function of other MHD parameters, e.g., Mach number, result in power outputs within the above range so that these may be used for sizing the inverters and establishing their control boundaries.

The minimum levels above are not understood to be normal or long duration types of part load condition, since the MHD efficiency would be relatively poor. Therefore, while the inverter system can include these within its range - indeed it must phase down to zero load - it need not do so with its best efficiency either. As discussed in Section 2.3.3 MHD efficiency will remain almost constant down to about 70% load, and the inversion system should aim for correspondingly good performance to the same level.

Also, different channels are planned for the two preheat temperatures so that the inverter system does not have to conform to both conditions simultaneously, although it is desirable that change of inverter configurations should be small.

2.17.1.2 Inverter System Design

The inverter system must be adaptable for connection to the two basic types of MHD channels, the segmented Faraday and the diagonal channel. The

segmented Faraday has 900 electrodes. The two diagonal channels are planned for three-terminal and five-terminal connections (three and five load circuits).

Consolidation schemes for the Faraday channels are described in Section 2.6. These are desirable not only to reduce the number of individual load circuits by "collecting" the current from groups of electrodes, but also provide a necessary preconditioning of the power prior to the bulk inversion to ac by exercising some precontrol over the steady-state fluctuations of MHD voltage and current.

The number of load circuits to be inverted is thus very materially reduced to 40 consolidated outputs at 2500°F and to 44 at 3000°F. Nevertheless, these are still large numbers from the standpoint of inverter configuration simplicity -- because each consolidation terminal pair differs from its adjacent pair by the potential gradient of the Hall voltage developed axially along the channel, this voltage being furthermore variable as a function of load. Thus, it is not possible to configure inverter bridges (arrays of thyristor valves connecting the dc to 3-phase ac) either in series or in parallel on the MHD side. They must be kept isolated on the dc side from each other and paralleled on the ac side via separate windings of the converter transformers.

Furthermore, the output voltage, current and power, for a steady state operating condition of the channel, are not the same for each of the consolidated outputs. These differ according to their relative position along the channel, and the differences (especially in the voltage and current which are the important parameters for inverter control) are appreciable.

The values at baseload are listed in Table 2-69 for the 3000°F pre-heat case, and Table 2-70 for 2500°F. The consolidated outputs are grouped when the currents in each lie within about 5% of each other. Also shown are the apparent load resistances.

Beginning with the channel entrance (upstream), the relation between voltage and current is in general that the voltages increase as the currents decrease, as reflected in the Tables. Obviously this kind of variation is not conducive to the most efficient sizing of components in a power conditioning device. In this circumstance a reasonable approach has been followed, which is to make each consolidated group of electrodes deliver the same power.

TABLE 2-69
SEGMENTED FARADAY - 3000°F PREHEAT BASELOAD

<u>No. of Consolidations</u>	<u>Range per Consolidation</u>		
	<u>Volts</u>	<u>Amps</u>	<u>R = V/I Ohms</u>
1	970	1070	0.91
1	1070	970	1.10
1	1160	895	1.30
1	1240	840	1.48
2	1310-1380	795-755	1.65-1.83
2	1430-1480	725-700	1.97-2.11
4	1520-1630	685-640	2.22-2.54
4	1660-1750	625-595	2.66-2.94
4	1780-1860	585-560	3.04-3.32
4	1890-1980	550-525	3.44-3.77
4	2010-2110	515-490	3.90-4.31
4	2140-2250	485-460	4.41-4.90
4	2290-2410	455-430	5.03-5.60
4	2450-2550	425-405	5.77-6.29
2	2550-2500	405-415	6.29-6.02
<u>2</u> 44	2420-2320	430-450	5.63-5.15

1.04 MW per consolidation = 45.6 MW Total

TABLE 2-70
SEGMENTED FARADAY - 2500°F PREHEAT BASELOAD

<u>No. of Consolidations</u>	<u>Volts</u>	Range per Consolidation	
		<u>Amps</u>	<u>R = V/I Ohms</u>
1	1200	740	1.62
1	1340	660	2.03
1	1470	605	2.42
1	1600	555	2.88
2	1660-1720	535-515	3.10-3.34
2	1770-1810	500-490	3.54-3.69
4	1860-1970	475-450	3.92-4.37
4	2000-2080	445-425	4.49-4.89
4	2100-2180	420-405	5.00-5.38
4	2200-2290	405-385	5.43-5.95
4	2320-2430	380-365	6.10-6.65
4	2460-2550	360-350	6.83-7.29
4	2590-2660	340-335	7.62-7.93
<u>4</u> 40	2665-2450	335-360	7.95-6.80

0.89 MW per consolidation = 35.5 MW Total

In the course of the inverter design it has been sometimes necessary to take into account the voltage and current values at power levels other than baseload. This is done using a normalized curve of per unit volts and amperes as a function of per unit mass flow, which with an accuracy sufficient for the purpose allows the relationship that both voltage and current vary as the square root of the ratio of the electrical powers.

The electrical output quantities for the diagonal channels are tabulated, as given, in Table 2-71 for the three-terminal connection and in Table 2-72 for the five-terminal, both for 3000°F preheat. For each of these connections there are two possible arrangements of the loading terminals, designated as the independent connection and parallel connection. The schematic figures in Table 2-71 illustrate the meaning of these terms.

The power in Tables 2-71 and 2-72 are close to the maximum load for 2500°F preheat (See Table 2-68). Therefore, the 2500°F diagonal channels need not be considered in detail for sizing the inverters.

From Tables 2-69 and 2-70, it is clear that at least 44 independent thyristor bridges are needed to satisfy the Faraday channels; and it appears that a savings in ratings may be made by specifying the larger number for say 500A and the remainder at about 1250 A. However, when these basic modules are arranged to satisfy all four diagonal channel configurations as well, it turns out that a significantly larger number of the total must be placed in parallel to meet the current requirements than if the bridges are standardized at a higher rating for all. For example, using dual bridge ratings the 3-terminal independent connection diagonal requires 5, 3, and 2 bridge strings in parallel and a total of 40 bridges, against 3, 2 and 1 in parallel for a total of 24 using single 1250 A bridges.

The cost of the thyristors with their immediate ancillaries is only a small part (about 13%) of the total cost of the inversion system so that the tradeoff is not considered worth the added complexity of controlling more bridges in parallel than necessary.

Taking into account the requirements for bridges in parallel in the diagonal circuits at maximum load, we can choose thyristors of 450 A average (1350 A bridge) current, with a 10% overload capability, and a non-repetitive (surge) on-state withstand of about 12 kA peak, this based on a line-to-line short circuit on the thyristor side of the connecting system transformers.

TABLE 2-71

3-TERMINAL DIAGONAL - 3000°F PREHEAT BASELOAD

<u>Volts</u>	<u>Amps</u>	<u>MW</u>	<u>R = V/I Ohms</u>
<u>Independent Connection</u>			
7000	2950	20.6	2.37
8200	2140	17.5	3.83
<u>5800</u>	<u>1290</u>	<u>7.5</u>	<u>4.50</u>
21000		45.6

Parallel Connection

7000	810	5.7	8.64
15200	850	12.9	17.90
21000	1290	27.0	16.30

TABLE 2-72

5-TERMINAL DIAGONAL 3000°F PREHEAT BASELOAD

<u>Volts</u>	<u>Amps</u>	<u>MW</u>	<u>R = V/I Ohms</u>
<u>Independent Connection</u>			
3400	3740	12.7	0.91
4500	2650	12.0	1.70
4500	2020	9.1	2.22
3500	1490	5.2	2.35
<u>5100</u>	1280	<u>6.6</u>	3.98
21000		45.6	
<u>Parallel Connection</u>			
3400	1090	3.7	3.12
7900	630	5.0	12.55
12400	530	6.6	23.40
15900	210	3.4	75.70
21000	<u>1280</u>	<u>26.9</u>	16.40
	3740	45.6	

With regard to the voltage rating of the bridges, the technical disadvantage of attempting to specify two levels is actually a risk, compared again to a slight incremental cost gain. The important characteristic is the peak inverse voltage (not the working dc voltage).

In the absence of information about the surge and dynamic overvoltages of the connecting ac system, a tentative PIV (peak inverse voltage) may be arrived at as follows:

(a) Largest rated load dc bridge voltage in any configuration	2600 V
Multiplier for largest maximum load dc voltage	1.15
Corresponding no-load (ideal) dc voltage, depending on
converter transformer reactance and firing angle,
approximately	1.16
Corresponding 1-1 crest ac voltage = $\sqrt{2} (\pi/3 \sqrt{2}) =$	1.047
System steady state ac voltage deviation	1.05
System dynamic overvoltage, due to ac grid disturbance
or dc load rejection	1.2
Maximum repetitive blocking voltage = $(1.15 \times 1.16 \times$
$1.047 \times 1.05 \times 1.2) 2600 = 1.76 (2600) = 4570$ V crest	
This also determines the reseal voltage of arresters.	
(b) For the transient non-repetitive blocking voltage produced
from the dc side, we may have, again beginning with the
largest rated dc voltage	
Multiplier for largest maximum load dc voltage	1.15
Corresponding no-load dc voltage	1.16
Peak transient dc overvoltage, due to fault on dc side,
commutation overshoot or open circuit, approximately	2.0
Minimum arrester sparkover level = $1.15 \times 1.16 \times$
$2.0 = 2.66$ pu	
(c) For the transient non-repetitive blocking voltage due to
surges from the ac side, again beginning with the
largest rated dc voltage	2600 V
Assume maximum ac surge will not occur when dc
voltage is max	
Multiplier for corresponding no-load dc voltage	1.16
Corresponding 1-1 crest ac voltage	1.047

Transient ac overvoltage	2.2
Minimum arrester sparkover level = $1.16 \times 1.047 \times$	
2.2 = 2.67, which is the same as in (b)	
Surge protective level, with arrester sparkover spread	1.15
Margin of thyristor withstand above protective level	1.15
Surge PIV = $(2.67 \times 1.15 \times 1.15) 2600 = 3.52 (2600) =$	
9150 V crest	

In some respects this may be a little conservative, since it does not take into account the buffering action of the main inverter transformer which interposes between the inverter primary ac bus and the ac grid (see Figure 2-183). The precise PIV assignment is not critical to the conceptual design - it can only be determined when the actual installation is engineered, by which time continuing progress in thyristor specification ratings will allow a more realistic insulation coordination for the entire system, using best available arresters and including possibly special surge protection across the bridges to guard against anomalous surges resulting from MHD channel dynamic behavior.

Tentatively we may choose thyristors with a PIV of about 3000 V (compatible with the 450 A average current rating) and use three in series in each leg of the bridge.

Similarly the question of the required redundancy against individual thyristor failure cannot be precisely investigated here. However, with a PIV of about 3000 V, the failure of one thyristor or the bypassing of a bridge in series with other bridges in a diagonal load circuit, leaves ample margin over the maximum repetitive blocking voltage of 4570 V crest in (a) above.

It is not necessary to belabor the obvious choice for the bridge type being the conventional 3-phase, 6-pulse Graetz bridge from high power HVDC usage. Apart from allowing the use of conventional transformer winding arrangements compared to those of other possible bridges, its advantage for MHD application lies in that it gives the least repetitive blocking voltage for the same ac line voltage, a value equal to 1.047 times the no-load dc voltage.

The basic 6-pulse inverter module is then as shown in Figure 2-184, where each of the six legs consists of a valve group of three thyristors in series. The other two elements (smoothing reactor and bypass switch) in the module are treated later.

H5322

Figure 2-183 Inversion System Arrangement

Figure 2-184 Basic Six Pulse Inverter Module

Each module is insulated for the full axial Hall voltage of the channel to ground, which is in the order of 20 kV dc.

Figures 2-185, 2-186, 2-187 and 2-188 show the arrangement for each of the diagonal loading connections. Each box represents the module of Figure 2-184 with its own permanent connections to the transformer secondary winding. The only reconnections necessary are the dc leads at top and bottom of each bridge.

2.17.1.3 Note on Scale Up

Before proceeding with the conceptual design, it is in order to note that in some respects involving only sizing and arrangement, the inversion system for the ETF cannot be directly scaled on a unit basis to a future commercial plant. This is not important because the larger plant will inherently favor a reduction in complexity and better utilization of larger unit components without significantly altering the principles of application.

For the ETF the sizing and arrangements of components of the inverter must satisfy different MHD channels and loading circuits with different voltage, current, and power characteristics. For a commercial plant, presumably one will be dealing with a single type of channel and a single configuration of loading outputs. For example, in the case of a multi-circuit diagonal, the number of individual thyristors required to withstand the voltage of a load terminal pair would be in series inside of just two 6-pulse bridges (themselves in series) -- and not spread out among 4 or 8 or 10 bridges in series. The two bridges would be connected, one to a wye transformer, the other to a delta forming a 12-pulse group and just the two transformers would handle the power of the channel loading output circuit. With high power thyristors now available with mean on-state current ratings of about 1000 A the series strings inside the two 6-pulse bridges could be paralleled for increase current capacity -- rather than paralleling bridges as in the ETF.

In other words, if one has to match one channel only, realistic state-of-the-art component optimizing can be done and total inverter power (and MVA) can be matched more exactly to machine capacity.

It may incidentally be noted that obviously an MHD channel of the diagonal type is preferred from the standpoint of simple inverter design, but even with a segmented Faraday machine as the only type, one could do a better matching job than is possible in the ETF.

H5312

Figure 2-185 Connection Diagram, 3-Terminal Diagonal, 3-Independent Outputs

H5313

Figure 2-186 Connection Diagram, 3-Terminal Diagonal, 3-Parallel Outputs

H5310

Figure 2-187 Connection Diagram, 5-Terminal Diagonal Channel, 5-Independent Outputs

H5311

Figure 2-188 Connection Diagram, 5-Terminal Diagonal Channel, 5-Parallel Outputs

Also before proceeding, it should be remarked that from time to time the absence of knowledge about the ac system is noted in what follows. This is necessary to bring out the considerations involved in inverter design. However, the absence of these system characteristics does not change the conceptual design, and can be taken into account when the ETF location is known.

2.17.1.4 Converter Transformers

Since the ac connections to the bridges are permanent, the bridge and transformer are in effect one integral unit.

In order to obtain 12-pulse operation from the 6-pulse bridges, two bridges carrying equal current are connected one to a wye secondary winding, the other to a delta connected winding obtaining the necessary 30° shift. It appears from the standpoint of fabrication and also of optimizing leakage reactances between windings, that a four-winding secondary is a reasonable limit. Two adjacent windings form a delta, ungrounded wye pair; the next two form the other pair. The primary could be delta or wye, grounded or not depending on ac system preference. (See Figure 2-185.)

With a total of 44 bridges at the ETF, eleven converter transformers are needed.

The advantage of 12-pulse operation lies of course in eliminating the injection of 5th and 7th harmonic currents into the ac system. Theoretically the lowest harmonic will then be the 11th, followed by the 13th, then the 23rd and 25th, etc. The higher the harmonic, the lower its magnitude and the easier to eliminate by suitable ac filters.

However, while the bulk of the low order harmonics ought to be eliminated by this arrangement, a certain residue may appear as abnormal harmonics. The multiplicity of bridge arrangements and their large number makes it almost inevitable that such a residue result from unequal current divisions, small deviations in firing angles and other disymmetries inherent in a large number of independently controlled bridges.

In the diagonal channel circuits, 12-pulse operation is assured by putting sufficient bridges in series such that the total is an integral multiple of two. This is indicated in Figures 2-185 through 2-188. In the Faraday configurations, the bridges do not form matched load current pairs. Additionally, in the Faraday case, there may be variations due to channel dynamics. The inverter controls will tend to "force" the same current, but cannot be expected to do so perfectly at every instant.

One has also to consider that even a small magnitude of these abnormal harmonics may produce resonance amplification depending on the impedance vs frequency characteristics of the ac system (which is unknown at this time). It is recommended that space be allowed for future addition of a low order harmonic filter which may be finalized during the actual on-site engineering.

2.17.1.4.1 Rating of the Converter Transformers

What is required is the MVA ratings. However, since this will turn out to be in the same proportion to the MW's for any channel and loading circuit, we can work with the powers to arrive at a reasonable sizing of power per bridge, and a reasonable minimum of total transformer capacity -- realizing in advance that some fairly considerable excess capacity will be required. Considering to begin with the two Faraday channels only, all transformer windings would simply be rated for the larger unit power at baseload:

11 transformers x 4 secondary windings/transformer

$$\times 1.1 \text{ MW} = 11 \times 4.4 = 48.4 \text{ MW}$$

or a little in excess of baseload power at 3000°F preheat of 45.6 MW (Table 2-68).

But this is far from the need. In the four sets of loading configurations for the two diagonal machines (Tables 2-69, 2-70, 2-71 and 2-72) it is important for good inverter performance that the voltages be evenly divided between the bridges in series and that the currents be evenly divided between bridges in parallel -- at least to the extent automatically produced by the uniformity of the thyristors, and their ancillary circuitry. The power will then be evenly divided among the bridges in the same loading circuit.

From the tables, the power per bridge at baseload and 3000°F preheat is tabulated here merely for easy reference.

3-terminal independent	12 bridges at 1.7 MW
	8 bridges at 2.2 MW
	4 bridges at 1.9 MW
3-terminal parallel	4 bridges at 1.4 MW
	6 bridges at 2.15 MW
	12 bridges at 2.25 MW

5-terminal independent	6 bridges at 2.1 MW
	8 bridges at 1.5 MW
	4 bridges at 2.3 MW
	4 bridges at 1.3 MW
	4 bridges at 1.65 MW
5-terminal parallel	2 bridges at 1.85 MW
	4 bridges at 1.25 MW
	6 bridges at 1.1 MW
	8 bridges at 0.45 MW
	12 bridges at 2.25 MW

The number of bridges in series in diagonal loadings has in a few cases been increased from what the voltage would allow in order to avoid large unit powers which would tend to further increase the total transformer capacity. For example, in the 5-terminal independent connection one of the two 4500 V circuits has double the number of bridges to reduce the power per bridge from 3 to 1.5 MW. Similarly in both parallel connections, the largest string of 12 reduces the unit power for a large number of transformer windings.

By choosing the minimum number of the highest rated windings required by any one loading configuration, and then assigning these first to match remaining bridges in all configurations in the order of descending power per bridge, one arrives at the following ratings for the eleven transformers of four secondary windings each.

$$\begin{array}{rcl}
 6 \times 4 \times 2.1 \text{ MW} & = & 6 \times 8.4 = 50.4 \text{ MW} \\
 5 \times 4 \times 1.2 \text{ MW} & = & 5 \times 4.8 = 24.0 \\
 \hline
 11 & & 74.4 \text{ MW}
 \end{array}$$

which are 60% in excess of baseload of MHD plant.

For transformers of this size a forced air (FA) rating equal to 1.25 of self-cooled rating is standard, which then satisfies the maximum plant load of 57 MW (1.25×45.6).

These will match all the channels, the Faraday included. Note that an integral number of transformers (primary windings) is always used in any string of bridges in diagonal loading. This is indicated in Figure 2-187.

Spare secondary windings are not connected to bridges of a parallel string. This serves to isolate the consequences of a fault in one transformer; and also simplifies the physical layout of connections since each group of four bridges remains permanently connected to the same transformer.

It may be asked whether a smaller excess capacity would result had the thyristor bridges been divided into two ratings, instead of one. The answer is yes - to the extent of at most a few MW. But, granted that these transformers account for about 40% of the inversion system cost, the minor reduction of capacity would result in loss of operational simplicity: it would not be possible to keep permanent connections from all bridges to the same converter transformers.

As a minor point perhaps, the result in those cases where oversized transformers are coupled to a bridge is not all "bad". It does mean that losses are a little less, and that voltage regulation of the bridge is a little better as the effect of the transformer leakage reactance on the dc side is a little less.

Before translating the above MW capacities into MVA ratings, it is best to treat the question of matching the ac secondary voltage of the transformers to the dc voltage of the bridge.

2.17.1.4.2 Converter Transformer Voltages

Dividing the output voltages (at rated load) of the diagonal channel circuits (both preheat temperatures) by the number of bridges in series across each, and combining these with the output voltages of the two Faraday channels, gives more than 30 working dc voltages. Since any bridge may find itself facing all or nearly all of these depending on its position in the ten different loading configurations, there appears to be no alternative to providing taps on the windings of the associated transformers.

These are not to be confused with on-load tap changing, whose function is to compensate for deviations in the ac system voltage and to assist the inverter controls during off-baseload operation. This is treated later.

We do not need as many taps as there are nominal working voltages. However, the tapping intervals should be chosen to satisfy the following criteria:

1. To keep the inverter operating in its "natural" constant voltage mode (constant extinction angle control), large compensation of voltage should not be allowed by automatic variation of the firing angle.
2. A fine tuning of the inverter voltage is desirable after the transformer tap is set, to allow selection of the most stable point of operation on the voltage-current characteristic of the MHD output. This is done by allowing a manually adjustable change of the set extinction angle from its normal value.
3. After a valve (thyristor) has fired, there is, of course, no possibility for the automatic controls to compensate for a sudden reduction of the steady-state ac supply voltage, or a sudden increase in the MHD dc current. The commutation time (angle) will then increase, cutting into the margin between set extinction angle and the absolute deionization angle required by the valve. The remaining margin should still be enough to allow for further reduction of the ac system voltage as the result of faults, etc.

The deionization angle for high power thyristors should not be taken as less than 4 to 6°.

It is calculated that to meet the above conditions, a manual variation of no more than ± 3 to 4° should be allowed around a normal setting of 20°, i.e., a normal margin over the deionization angle of 16 to 14°. This means a corresponding compensation of about 3% of the dc working voltage, which in turn means a tapping interval of 6%.

On this basis the taps, expressed in dc volts, are (neglecting voltage drop in the cables between MHD channel output and inverter bridge which can be allowed for later without changing the relative numbers):

$$1850 + 7 \times 5.95\%, - 6 \times 5.95\%$$

If the taps are put on the secondary windings, the dc voltages above are translated into ac using the following relations from the inverter equations.

$$\frac{V_d}{V_o} = \cos \delta - \frac{dV}{V_o} \quad (2-60)$$

$$\frac{dV}{V_o}, \text{ the per unit voltage drop} = \frac{X_t^{\text{pu}}}{2} \frac{I_d}{I_d - \text{full load}} \quad (2-61)$$

$$V_o = \frac{3\sqrt{2}}{\pi} E_{1-1} = 1.35 E_{1-1} \quad (2-62)$$

where

V_d = terminal voltage of the inverter (the "counter - voltage")

V_o = internal ideal no-load voltage

δ = set extinction margin angle, taken as 20°

I_d = direct current

X_t is the transformer leakage reactance on the transformer base. It appears on the dc side as a resistance (commutating resistance) but introduces no power loss -- only a voltage drop. Its value should be high enough to produce a well defined slope to the inverter voltage characteristic; yet not so high as to result in too large firing angles, and so too large reactive power production by the inverter. We have taken 15% for the present purposes.

Solving for E_{1-1} the required ac voltage taps would be:

$$1585 + 7 \times 5.95\%, - 6 \times 5.95\% V_{1-1} \text{ rms}$$

It is however simply too cumbersome - and too expensive - to have twelve taps of any kind on each of 44 secondary windings. We shall make them common taps placed on the primary of each of the 11 converter transformers; even as we recognize that in the Faraday channels there are a few single consolidated outputs whose voltages are too far apart to be served by one change of the turns ratio. We shall not fuss with this problem now; the numbers and arrangements of the consolidated outputs may change during the final engineering, or if not, a few special taps may then be calculated for a few secondary windings.

Because of the turns ratio, taps on the high side (13.8 kV primary) cannot be uniformly 6% corresponding to 6% increments around a middle secondary voltage. An unusual but workable set of taps is as follows:

$$13.8 \text{ kV} - 2 \times 5.5\%, - 4 \times 5.0\%, + 2 \times 6.5\%, + 5 \times 8.5\% \text{ } 1-1 \text{ rms}$$

These taps may be manually switchable at no load.

2.17.1.4.3 MVA Ratings of the Converter Transformers

These are now assigned to the MW capacities of Section 2.17.1.4.1 above, by calculating the reactive requirement of the inverters.

Equation (2-60) of the previous section also gives (to a very close approximation) the power factor:

$$\frac{V_d}{V_o} = \cos \phi = \text{pf} \quad (2-63)$$

and further

$$\cos \phi = \frac{\cos \beta + \cos}{2}, \quad (2-64)$$

where β is the firing angle and is equal to $\gamma + \delta$ where γ is the angle required for the commutation, the commutating or overlap angle.

Using the calculations for the previous section, $\cos \phi = 0.866$ so that $\sin \phi = 0.50$ and $\tan \phi = 0.577$. Thus the active power delivered is 0.866 of the MVA; the reactive power is 0.50 of the MVA; and the ratio of reactive to active power is 0.577.

Hence the MVA rating corresponding to the MW rating of Section 2.17.1.4.1 is:

$$\frac{\text{MW}}{0.866} = 1.155 \text{ MW}$$

or $1.155 \times 74.4 \text{ MW} = 86 \text{ MVA}$, $\text{MVAR} = 43$.

(We can also calculate a corresponding firing angle of 38° , and a commutation angle of $38 - 20 = 18^\circ$, which turn out to be quite close to those in high power HVDC transmissions at rated load.)

These MVAR demands satisfy the inverter when it operates on its "constant voltage" (constant extinction angle) characteristic. Some additional MVAR should be allowed for operation when the inverter is controlling the current (constant current characteristic). This is estimated as an additional 10% of reactive, i. e., 47.3 MVAR total which means 88 MVA, or a factor of $1.188 \times \text{MW}$.

(If the ac amperes corresponding to the dc current are more correctly considered to include the harmonics generated by the 6-pulse bridge rather than the rms value of the fundamental component only, the ac power capability

of the transformers is really 1.047 times the dc power. This would further increase the MVA rating. However, some of the harmonics are cancelled in the primary windings; and the MW rating was already a little generous. This additional small increase is neglected for both MW and MVA rating purposes).

This total MVA rating is distributed according to the MW ratings assigned in Section 2.17.1.4.1:

$$\begin{array}{rcl} 6 \times 10.0 & = & 60 \text{ MVA} \\ 5 \times 5.6 & = & 28 \\ \hline & & 88 \text{ MVA} \end{array}$$

Thus the eleven converter transformers (3-phase units) will be:

$$\begin{array}{l} 6 @ 10/12.5 \text{ MVA OA/FA} \\ 5 @ 5.6/7 \end{array}$$

As for the MW ratings, if the ETF plant power were based on one channel and one loading configuration as is possible in a future commercial plant, the MVA would be only $1.188 \times 45.6 \text{ MW} = 54.1$ self-cooled, and 67.5 MVA forced air cooled.

2.17.1.4.4 Primary Voltage of the Converter Transformers and Other Considerations

Referring to Figure 2-183, it is proposed to step up the secondary winding voltage of 1.60 kV to an intermediate level, i.e., the eleven transformers to be paralleled at 13.8 kV (but not connected to the bottom plant generator 13.8 kV leads). This has the following advantages.

1. The turns ratio for stepping up directly to the assumed ac system 115 kV level would be too high for such small transformers to make for an efficient design. In particular it makes it difficult to obtain equal leakage reactance between the primary and each of the four secondary windings -- which is important for inverter performance.
2. The high voltage insulation (BIL) for 115 kV would otherwise be required on eleven transformers instead of one, making for a more costly net installation along with larger space requirement in the yard.

3. The intermediate bus provides an ideal location for the harmonic filters and any static capacitors for additional compensation of the inverter MVAR.
4. The interposition of a main inverter transformer between the primaries of the converter transformers and the system high voltage connection makes for a buffer against surges on the ac system, including a somewhat reduced range for some faults which lead to commutation failures of the inverters.
5. For faults in the individual inverters requiring tripping of the ac source, only the involved converter transformer needs to be tripped. If the MHD machine can continue to operate, the plant output need not be lost entirely.

Individual tripping devices can be relatively inexpensive low voltage circuit switchers or breakers.

The main inverter transformer need not have the combined MVA rating of the converter transformers since reactive compensation and harmonic filtering take place at the intermediate bus.

An on-load tap changer, with standard taps, is needed on the main inverter transformer to take care of the steady-state voltage regulation of the ac system; and to assist the voltage control of the MHD output by the inverter. Since this control, unlike the fixed taps which were for individual load voltage matching, should influence simultaneously the inverters of all load circuits, a single automatic tap changer on the main transformer avoids the complexity of synchronizing eleven different time delay mechanisms.

Figure 2-183 is a simplified one-line diagram of the major components of the inversion system, including ratings.

It may be noted in passing that at an earlier stage the thought was entertained of paralleling the 13.8 kV converter transformer bus with the generator bus, via a bus tie breaker which could be operated normally closed or open. The general idea was to gain experience for the MHD-inverter interface for conditions more representative of a strong ac voltage (good commutating voltage source and high short circuit ratio with respect to inverted power), as well as conditions more representative of a weaker ac system of relatively poorer voltage and var support.

The implied premise was that the actual site chosen and the interconnection point into the grid might indeed prove less representative than would be the case for a large commercial plant. Since this is not necessarily the case; and since successful MHD-inverter control development with a weaker system can only be improved when facing a stronger one, this has been abandoned. Also, it would have entailed a larger short circuit duty on all breakers on the 13.8 kV bus - not prohibitive but still a disadvantage; and more attention would have to be given to harmonic penetration in the design of the ac alternator.

This last consideration may be an important, although soluble problem, for large MHD topping plants.

2.17.1.5 Harmonic Filters and Reactive Compensation

The design of filters really requires a knowledge of the harmonic impedance characteristics of the ac system because they should be designed on the basis of reducing the harmonic currents to an acceptable level, rather than the harmonic voltages. Acceptable level is defined in terms of communication interference, and the avoidance of possible resonance at points in the network remote from the interconnection to the MHD plant. It also includes the smallest possible injection of harmonic currents into the rotating machines at or near the plant.

Theoretically the magnitude and frequency of harmonics already existing from other sources on the ac system should also be known since the filters will act as "sinks" for these in addition to those produced by the inverters. System frequency deviation (steady-state) is another parameter affecting the tuning of the filters.

In the absence of knowledge of these ac system characteristics, the designer can do little more than to work on the basis of reducing the harmonic voltages to some reasonable level and make judgements about the other factors. If the capacity of the inverter plant is small relative to the system, then this may be sufficient. That the ETF is small in this sense, is assumed until its actual location is known.

Since the filter capacitors also supply a portion of the total vars required for inverter operation, it is necessary first to have some idea of the total vars required at different power levels, and of how these should be subdivided to allow switching on or off in blocks to give reasonably unit power factor.

From the previous work, the power factor with allowance for current control mode by the inverter, comes out to be 0.843; so that $\cos \phi = 0.843$, $\sin \phi = 0.537$ and $\tan \phi = 0.635$. That is, the active power is 0.843 of the MVA, the reactive 0.537 of the MVA, and the ratio of reactive to active power is 0.635. (These values do not remain strictly constant at all power levels but the assumption is adequate for present purpose.) This ratio is now applied to the true plant power (not the inflated transformer ratings) giving columns (1) and (2) in the Table below:

<u>3000°F Preheat</u>	MW (1)	MVAR			
		Req'd. (2)	Filter + Switched		Excess
125% Load	57	36.2	13.9	3 x 7	- 1.3
Baseload	45.6	29	13.9	2 x 7	- 1.1
75% Load	34.2	21.7	13.9	1 x 7	- 0.8
50% Load	22.3	14.5	13.9	0	- 0.6
31% Load	14.2	9.0	13.9	0	+ 4.9
<u>2500°F Preheat</u>					
125% Load	44.4	28.2	13.9	2 x 7	- 0.3
Baseload	35.5	22.5	13.9	1 x 7	- 1.6
75% Load	26.6	16.9	13.9	0	- 3.0
50% Load	17.8	11.3	13.9	0	- 2.6
31% Load	11	7.0	13.9	0	+ 6.9

Short of complete optimization which is unwarranted for this conceptual phase, it appears that 21 MVAR switchable in three blocs of 7 MVAR, combined with 13.9 MVAR in filtered provide good coverage as indicated by the last three columns in the Table above. The excess at very low partial loads is not unduly large and besides may be compensated locally by the bottom plant ac generator.

2.17.1.5.1 AC Filters

The filters which should always be in service, provide about 50% of the total requirement at full load (3000°F Preheat) - a typical percentage in power HVDC stations. The hi-pass filter usually incorporates more capacitance than the 11th and 13th, and so a tentative assignment is made:

11th Harmonic Filter	1.3 MVAR/phase	3.9 MVAR/3-phase
13th	1.3	3.9
Hi-Pass	<u>2.0</u>	<u>6.0</u>
	4.6	13.8

Next, filter design is attempted on the basis of producing the "minimum cost" tuned filter, i. e., that combination of capacitance and inductance resulting in least cost. Based on maximum MHD plant power of 57 MW, the 11th harmonic is calculated to be about 135 A (with commutation period included in the firing angle); the 13th about 110 A; and the 23rd about 25 A. The fundamental current for this load is 2830 A at 13.8 kV.

As expected, the resulting filter sizes (the capacitor MVAR at fundamental frequency) turn out to be only about half the assigned values. The cost versus filter size rises rather slowly above the minimum cost, and the total cost of ac filters is estimated as only 2.6% of the total inversion cost. With little penalty the sizes are increased. The filter components (exclusive of the small resistors) are given below, all on a per-phase basis:

Tuned For	Capacitors			Inductors	
	Microfds	Size at 60 Hz	Rating, Incl. Harm Current	Millihenry	Rating, Incl. Harm Current
11th harm	54	1.3 MVAR	1.38 MVAR	1.07	0.09 MVAR
13th harm	54	1.3	1.38	0.77	0.08
Hi-Pass*	83	2.0	2.0	0.211	0.035

*Second order type, tuned for 20th harmonic and above.

The filter capacitors are standard but high quality paper impregnated, liquid insulant filled, having a low temperature coefficient to minimize detuning by change of capacitance with ambient temperature or self-heating. The inductors are made with non-magnetic cores. Assuming no significant system steady-state frequency deviations, the ac filters should suppress the characteristic harmonics from 12-pulse inversion to less than one percent of fundamental voltage, that is less than 80 V line-to-ground rms.

2.17.1.5.2 Reactive Compensation

From the previous section, 21 MVAR of capacitive compensation is required in addition to the filter provision at 57 MW, and 14 MVAR at 45.6 MW baseload.

The ac generator of the bottoming plant will have at least this much reactive capability and so it may be felt that additional compensation in the form of static capacitors is not needed. Indeed some HVDC installations connected with generation or large synchronous condensers at the immediate ac bus, do

not so provide. But the question is not so simple, and again one returns to the characteristics of the ac system as seen from the point of interconnection. We are concerned with the "stiffness" of the system in steady-state conditions and the short circuit power during disturbances, especially faults.

When the ac voltage falls in either case, the reactive power from the inverter momentarily increases, i.e., the power factor becomes more leading. At the same time, the voltage drop means that the reactive power of the static capacitors is reduced. Therefore, the system must be capable of increasing its reactive output to an extent at least equal to the sum of the decrease in reactive output from the capacitors plus the increase required by the inverter.

The proportion of vars (in excess of filter vars) to be supplied by capacitors, by local rotating machinery, and by the system is therefore not so easily determined. For the ETF in particular, there is also the consideration of MHD operation at appreciable load factor when the local generator is out of service.

In favor of static capacitors is that the reduction of their var support with voltage drops takes place with a time constant relatively long compared to the response time of inverter controls. Immediately after a sudden load or fault disturbance, they can sustain the voltage and give the inverter a better chance to rapidly adjust firing angle thereby reducing the incidence of commutation failures. This appears to be an important consideration for the ETF.

Therefore, as a matter of judgement, three banks of 7 MVAR each of capacitors will be connected to the intermediate 13.8 kV bus, each via automatically controlled circuit switchers with fast shunt trip devices. Automatic tripping will be needed in the event of load rejection; and may be needed in some conditions of dynamic over-voltage depending on the ac system behavior.

The bottom ac generator is then left as reserve, assisting the ac system to absorb or supply transient imbalance reactive power.

2.17.1.6 Principles of Control

2.17.1.6.1 General

In the process of converting the MHD dc power into ac, the inverter system performs two broad functions: it "follows" the electrical outputs of the machine, and at the same time it assists to control the stability of these outputs at any given operating level.

The inverter exercises some control over the MHD generator channel specifically by impressing across the terminals that dc voltage which corresponds to the desired or most efficient operating point for the power demand.

For any set of operating conditions involving mass flow rate and heat input, there is an optimum power output which corresponds to the optimum plant efficiency. This optimum power is for each load condition reached by one combination of terminal dc voltage and current. If the channel operating voltages and currents deviate from these optimum values, the plant efficiency and electrical power output will be less.

The MHD machine, unlike a conventional generator, cannot influence its internal generated emf by change of field excitation. But if its terminal voltage, i.e., the voltage presented by its apparent load, is made equal to the optimum efficiency voltage then the internal electrical parameters should adjust to the required condition.

The inverter is the apparent load seen by the machine; and the inverter can produce within reasonably wide limits any desired dc voltage from the ac voltage on its "output" side. From this point of view it is useful to consider the inverter as a device which transforms an ac voltage on its load side into dc voltage on its input side, and conversely transforms dc input current into ac load current.

Thus, the inverter can control or assist in the control of the machine in the sense described. Because the inverter is a passive device it must be given the information as to what is the optimum operating dc voltage. There appear to be two general ways for achieving this.

The first involves an on-line computation of the desired voltage as reference input to the inverter control. The actual voltage is measured and compared to this reference input voltage employing feedback control.

The computation of an optimum reference voltage assumes that a mathematical "model" for the MHD generator has been developed and exists.

A second way would be to use a special control scheme incorporating measurements and control of certain channel operating parameters for self optimization of the channel operation. In theory this might be accomplished by always seeking to adjust the channel loading parameter for optimum power output.

Much further work is required to develop the optimum inverter control scheme for the MHD channel. However, the capability seems to be there to be implemented. The lack of actual operating experience with inversion of MHD power is noted.

The rest of this section reviews the two broad functions of inverter control stated in the first paragraph.

2.17.1.6.2 MHD Characteristics

Figure 2-189 shows the inverter control characteristics imposed graphically on to the MHD channel electrical characteristics to allow a visual interpretation of the system behavior. A control block diagram is included with the drawings in this Report.

Figure 2-189 plots first the "ideal" voltage vs current (V-I) characteristics of the MHD outputs on a normalized basis. The 1 pu operating point represents the baseload values seen by any one of the individual dc bridge-converter transformer modules working in any assigned position in any of the six loading configurations previously discussed. An arc of the 1 pu constant power circle is sketched through this point.

The MHD output is in fact restricted to a small range around the operating point, which is here considered to be the point of maximum efficiency. It is well known that an active dc device delivers maximum power when the load resistance equals its internal resistance. The V-I characteristic has a slope equal to this resistance, and the load line is perpendicular to the V-I curve at the operating point.

It will also be true that as the device delivers more or less power, the terminal voltage and current both change as the square root of the change in power. For illustration, part load and maximum power of 0.68 and 1.28 per unit respectively, are used. Below about 70% load, absolute efficiency tends to be relatively poorer. The corresponding operating points are then plotted at 0.82 and 1.13 pu volts and amps and the power loci are sketched in.

This relation between change in power and corresponding change in voltage and current is known to be at least approximately true for the real MHD machine; so that the idealized representation is not too bad, particularly within the range of interest (taken generously at $\pm 10\%$ around the operating

Figure 2-189 Inverter and MHD Characteristics

point). Beyond this range, the actual characteristic curves do in general change slope although they are still essentially linear over fairly large segments.

A change in slope can also take place within the operating range -- for example a decrease in conductivity makes for a slightly steeper slope corresponding to a higher internal resistance. Or, during a change in power level, the slope of the new V-I line may differ. But it is seen that these variations do not alter the control application. It is also noted that moderate departures from the operating point (maximum efficiency) do not result in large reductions from the locus of maximum power, as indicated in Figure 2-189.

2.17.1.6.3 Inverter Characteristic - Natural Voltage

Turning to the inverter, the quasi-horizontal line "A" is the natural voltage characteristic of the inverter according to Eq. (2-60) (Section 2.17.1.4.2) with the voltage regulation corresponding to a 15% converter transformer reactance, and the no-load internal voltage equal to $V_o \cos \delta$ which from Eq. (2-62) is also equal to $1.35 E_{1-1} \cos \delta$, where δ has been taken typically as 20° . As can be inferred from Eq. (2-63) and (2-64) along this line the firing angle β increases (advances) from left to right, and decreases (retards) from right to left.

Along this natural voltage line, the inverter controls function in the constant extinction angle (CEA) mode, the circuitry for which is well established. Its inputs are the line-to-line ac voltage taken from the ac bus (the intermediate but with the harmonic filters); the dc current from a dc current transducer; the set value of the extinction margin angle δ ; and the known value of the transformer reactance seen as a resistance on the dc side. The output is the calculated value of the smallest firing angle β which will allow commutation to be completed by the time the angle reaches δ ; this already having a set margin over the true deionization time of the thyristor valves. This deionization angle (4 to 6°) must not be encroached upon if commutation is to be successful.

There is also a di/dt sensor which detects any transient rise of the dc current and rapidly advances the firing angle beyond the CEA computed value in an effort to prevent a possible commutation failure.

The firing angle can be calculated separately for each of the six thyristor arms of the bridge and their gates triggered at the best times for each; or, it is calculated every one-half or one cycle interval of the power frequency and the same firing signal given to all in appropriate sequence and spacing (equidistant firing control). This last appears best for the MHD case.

The CEA control as described is an open-loop control. It could be closed-loop feedback where the actual extinction angle at end of commutation is compared to the set angle and additional correction made to the firing angle. This, as well as the variants of firing control in the previous paragraph, are just two examples of the kind of optimization or "development" which has to wait for actual experience from a realistic MHD-to-ac system marriage. But they are either already available and tried in other applications, or can be developed from a sound state-of-the-art control technique base for line commutated current inverters.

On the graphical representation, if the MHD dynamics try to move downward on the V-I curve, the inverter counter-voltage of the CEA line becomes larger than the machine voltage and tends to force the current back to the initial operating intersection point of the two lines. If the dynamics move upward on the V-I line, the counter-voltage is momentarily less than machine voltage, but this does not mean a "run-away" condition. The firing angle may retard a little in response to the reduced current, but the very difference in voltage reverses the current decrease. Again there is a tendency to return to the operating intersection.

The dc smoothing reactor (choke) which is treated later in connection with protection aspects, also assists to smooth out these excursions.

If the ac voltage falls or rises (normal fluctuations, not severe disturbances), it is as if the inverter presents a smaller or larger resistance load to the machine, i. e. ; the load line rotates clockwise or counterclockwise respectively. The MHD power reduces slightly and the bottoming plant generator output tends to increase. This could be corrected by ordering a proportional increase to the combustor input in response to the voltage change with some penalty in efficiency; or when the voltage change is large enough and persists, the main transformer load tap changer (LTC) operates to return the voltage to near its previous level.

If in response to the generation demand signal a change, such as an increase in power output is called for, the MHD characteristic shifts to the right and the new intersection with the inverter line represents a less efficient operating condition. But again compensation is available by tap changer operation, initiated by the dc voltage change and/or the change of firing angle. The inverter CEA line moves from A to A' or higher as required.

It should be noted, however, that forcing the operating point by tap changing of the ac voltage alone will not generally be a very smooth control and subject to some oscillation if the voltage change is made in steps which are too large.

The degree of stability and the damping of oscillations around an operating point cannot depend on the inverter alone. The MHD characteristic can be considered roughly as replacing the rectifier in an HVDC transmission or in a back-to-back rectifier-inverter frequency changer -- with the important difference that the rectifier is equipped with a sensitive feedback current regulator whereas the MHD machine regulates power by virtue of its combustor input and with time lags of one to two orders of magnitude larger than those of the inverter.

Therefore with constant extinction angle control as the only mode there would be inherent current variations resulting from fluctuations of the MHD voltage and the ac system voltage.

2.17.1.6.4 Inverter Current Control

A current regulator can be added to the inverter to improve both the degree and stability of control. This characteristic is shown on Figure 2-189 by the quasivertical lines with a small positive slope determined by the electrical constants of the system and the gain given to the current regulator amplifier. Along such a line the firing angle β increases (advances) from top to bottom to lower the counter-voltage, and decreases (retards) from bottom to top increase the voltage.

For example, normal base power (1 pu) would be achieved by raising the natural voltage line to A' using predetermined connection to the converter transformer taps, the main transformer LTC, and as necessary by fine tuning with the extinction margin angle setting up to a limit of $\pm 3-4^\circ$. With the current reference setting of the regulator corresponding to 1 pu, an error signal between this desired current and the measured actual current adjusts the firing angle to the proper value on the vertical line B'.

The current setting can be ordered as a current level or as a power level. If it is ordered as a power level and since the measurement of power is generally not sensitive or accurate enough for feedback purposes, this order could be divided by the available dc voltage to produce a current reference (on a continuous basis but using dc voltage averaged over sufficiently long periods free of transient dynamics). A current reference so derived obviously may not correspond to the maximum MHD efficiency for that power.

If the reference setting is ordered as a current level, this assumes that the current (or voltage) corresponding to the Maximum efficiency is known or can be calculated on-line. It is at this point that the possibility for the inverter control of the machine emerges as raised in the discussion earlier. A combined voltage and current feedback could be devised and such combined loops have in fact been investigated with simulations for HVDC transmission systems, albeit not implemented in real life.

However, assuming a form of current regulator, and without detailing the sequences, it can be seen that if the channel dynamics create a temporary increase in current, the error signal to the current regulator retards the firing angle, raising the inverter voltage and forcing the current back. An opposing action takes place if the dc current falls. In both cases, the net response should be smoother than with CEA control alone.

Of course, CEA control always overrides to maintain a safe commutation margin angle. If the ac voltage falls sufficiently, there is now a smooth transition of the working point upward and then on to the A' line which has dropped to say A or even A'''. The current reference position does not change, but the firing signal is now determined by the CEA control. Again tap changer operation can be used to raise the CEA line back up above the MHD characteristic, which restores the current control.

The current regulator is especially useful during power changes. In the coordinated mode of power control for the combined plant, the generation demand signal is applied to both the combustor system and the turbine valves. The current reference can be automatically geared to the combustor controls to increase or lower its setting, thereby both following the MHD output and buffering it to the new level.

Of course, the amount of current following depends on the position of the natural voltage line of the inverter with respect to the V-I MHD characteristic for the new power level. If for example, the change is from baseload (1 pu) to maximum 1.28 pu power and the inverter characteristic is A' B', the current reference (power divided by voltage) moves to the right and the operating point moves into the CEA mode. When the extinction angle limit is reached the tap changer increases the ac voltage to effect a rise of the natural voltage line of the inverter to A'', whereupon the current regulator can resume control along the characteristic A'' B''.

On the other hand, if the current reference is not changed, as the V-I line moves to the right for increasing power, the current regulator seeks to prevent a current increase and retards the firing angle until the CEA assumes control. Again when the extinction angle limit is reached the tap changer operates. The new operating point will be along a new natural voltage line between A' and A'' and in general may not correspond to maximum efficiency; but it may be improved by an appropriate increase of the current setting.

The A''' B''' characteristic illustrates a reduction of power. It may be noted that such combined inverter control also makes possible the response of the MHD machine to improve ac system stability, at least within the limits of its own time constants. The current reference can be changed in accordance with a frequency deviation signal from the ac bus. Such a technique is already used by HVDC transmissions.

It appears then, that combined CEA and current control of the inverter has a large degree of flexibility and of options. It can be automatic, or under operator control, or eventually under programmed control where a "model" of the MHD machine calculates the best sequence for the inverter to arrive at the V-I operating point calculated by the model for a new power level.

2.17.1.6.5 Buck-Boost Inverters

It has been suggested that a way to obtain a good match with the source dc voltage is to split the inverter and associated transformer winding into two, in series. The larger inverter always operates at the most favorable firing angle (CEA control), while the smaller device inverts or rectifies. By this means, the pf is improved over the range from maximum to minimum load.

This would be true if the inverter counter-voltage had to be fixed permanently to the highest MHD voltage and all of the reduction down to minimum power taken up by advancing the firing angle. Such operation would indeed be extravagant of reactive power.

But this assumes no control over the inverter ac voltage by LTC, which is an easier way to accomplish the same end, without the additional thyristors and special control.

The buck-boost split inverter would have a great deal more merit if it could prevent commutation failure. But since the buck-boost part is just as prone to these as the companion inverter, it cannot boost the voltage to compensate for the reduction in ac voltage which is the chief cause of commutation failures.

2.17.1.7 Principles of Protection

2.17.1.7.1 General

The consideration which proves determining is that the channel is more vulnerable to damage from high voltage than it is from a short circuit at its terminals. An open circuit should not be allowed for longer than a few cycles; while a short circuit can probably be sustained for the order of a second.

Therefore, to protect the channel against open circuit or complete load rejection, the simplest and most effective technique is to deliberately short its terminals, followed perhaps by a reduction of combustor input.

A short circuit of the channel output, i. e., a bypass of the inverter on the dc side, is also appropriate as protection to the inverter and its ac connection under some operating conditions.

The approximate levels of open circuit voltage and short circuit current appear to be two times the terminal load voltage and current, with some variation depending on particular type of channel. It is interesting to note that if one assumes the "ideal" V-I characteristics of Figure 2-189, it follows that the internal emf which is the open circuit voltage would be twice the operating voltage and the short circuit also twice the operating current.

The time lag for a rapid reduction of combustor input firing may be relatively long, about 50 msec for the channel lengths of the ETF. But this time is short compared to the length of time the short circuit could be sustained.

Also, it is about the same time normally required to clear faults on the ac system, 3 to 5 cycles. (In the event of a breaker failure contingency backup tripping is achievable in 12 to 15 cycles.) Therefore if a fault on the ac side leads to a momentary dc short circuit, it seems entirely possible for the MHD channel to continue to operate perhaps even without a temporary cutback of its firing. When the ac disturbance is cleared the inverter will recover.

An open circuit anywhere between the channel electrodes and inverter can be detected by the complete collapse of dc current. A load rejection may be detected by loss of ac current from the inverter.

Consideration must be given to the position of the shorting (bypass) device. This involves the probable mode of failure of the channel electrode consolidation circuitry, and whether the protection of this circuitry results in an open circuit of the output leads, as with fusing protection. From the point of view of the channel, a shorting device should be as close as possible to the electrodes; but with practical physical constraints there will always be some unprotected exposure so that in the last analysis the machine has to protect itself against open circuit which may ultimately be a matter of electrode insulation design plus some quick response element in the mass flow quantities.

From the point of view of the inverter a shorting device should be close to the thyristor bridge(s), since malfunctions may develop when the inverter is energized from the ac side only (e. g., start-up, testing, to take one bridge of a series connection out of service, etc.) which require the service of a bypass.

Another consideration arises with regard to the speed of operation required of a shorting device. Again, the MHD channel would appear to be more demanding than the inverter. For the inverter, the more probable malfunctions can be handled by a very rapid bypass around the bridge (or the temporarily faulted elements therein) followed by a rapid removal of the bypass. A bypass thyristor string was considered. These would be of special rating and special gating techniques, which could carry the full load and transient dc current for a short time, but not long enough for the possible durations of machine level short circuit current. On the other hand, there are less likely but more severe bridge faults where a heavy duty bypass device is needed but its operating speed is not too important.

2.17.1.7.2 Bypass Switch and DC Smoothing Reactor

On balance we choose for this conceptual design a fast bypass switch as in Figure 2-190. It is placed on the input side of the reactor so that the reactor does not need long-time overload capability. The switch is a vacuum interrupter type with a high speed operating mechanism to close into the short circuit in approximately two cycles. It opens in three cycles, during which time aided by the inverter momentarily firing as a rectifier, the arcing current is commutated out of the switch and into the dc bridge.

For those bridge faults where more rapid bypass and un-bypass action is advantageous, this is possible with some control complexity following the practice of HVDC transmissions. By selecting and firing together at the proper instant a pair of valves (thyristor strings) opposite each other in the bridge, the other faulty elements are shorted. This action (internal or "electronic" bypass) replaces an external bypass valve as was used with mercury arc converters. Of course, if the internal bypass fails, the bypass switch closes immediately.

The dc reactor (choke) is a vital element of the system. In steady state operation it serves to reduce dc harmonics (no other dc filtering is planned subject to experience with the ripple content of the MHD output); and it smooths the dc ripple to prevent the current from becoming discontinuous at very light loads.

In abnormal states it serves to limit the rate of rise of dc current, in this way decreasing the incidence of consequent commutation failure in the same bridge or in other bridges in series; and similarly to decrease the incidence of failure during ac voltage dips. In these functions it works in cooperation with the momentary firing angle advance ordered by the di/dt sensor of the CEA control.

In an HVDC transmission this current limiting function of the reactor is also greatly assisted by the current regulator at the rectifier which phases the "source" voltage down. This of course is missing in the MHD application; but since the short circuit steady state current is approximately only twice load prefault current, there is an inherent current limiting effect.

A preliminary value of 4 mH has been calculated for the dc reactor of each bridge, based on the criteria of preventing consequent commutation failure. The result is to limit the dc peak to twice rated current or less for the order of

one to 1.5 msec ($21-32^\circ$) of commutation time. This is coincidentally again approximately the machine short circuit current. It may be noted also that a "time constant" effect may be introduced by the internal resistance of the MHD channel. Since this is of the order of 1 to 6 Ω (in the "ideal" case equal to the apparent load resistance, see for example Tables 2-69 and 2-70), the time constant L/r with the 4 mH inductance is of the order of 0.25 to 1.5 msec which is also appreciable in terms of firing time to allow successful commutation.

Where bridges are connected in series for diagonal channels, the total inductance will in general be unnecessarily large - and the resistance losses will increase. Provision could be made to bypass the reactors in some of the bridge modules.

2.17.1.7.3 Protective Operations

Within the general considerations of the first section, and using the reactors, bypass switch and internal bypass feature, protection sequences may be outlined. These are shown schematically and tabulated in the figure, "Simplified Block Control and DC Protection Diagram" of this Report.

All inverter faults result in a short circuit of the dc terminals at some stage. Commutation failures are characterized by a dc short lasting for about 135° in one cycle, or in more than one cycle if they are recurring. Very rarely a double commutation failure is possible in one cycle. They are detectable in about 1 msec.

In some HVDC installations the quality of thyristors and controls is such that no protective measures are needed even for a three phase fault at the converter ac terminals. However for the MHD application, it seems prudent to initially aim for somewhat less excellence in this respect considering that MHD channel stresses are involved and not just inverter stresses. Therefore protective action is made contingent on the voltage severity of the ac disturbance.

If a commutation failure occurs only once (the dc reactor and rapid firing advance successfully preventing consequent failures), no protective action is taken.

If all phase voltages at the inverter during the ac fault remain above say 65% and commutation failures recur more than once for a time a little

longer than normal ac fault clearing, then the bridge is blocked (removal of all firing pulses) and the internal bypass is activated. When the ac fault is cleared, the bridge is deblocked and resumes operation. Note that if the fault clearing time is normal on the ac side, i.e., not involving breaker failure, then no blocking would take place. If the disturbance lasts for a longer time, or the commutation failures may be due to control malfunctions, then blocking is followed by closing of the bypass switch. Again inverter operation is resumed when the disturbance is cleared.

If the ac voltage falls to a lower level, e.g., between 50% and 20%, a similar action may be employed with a time delay coordinated with the ac system fault clearing times. Only when the fault voltage falls to say $< 20\%$, a block and bypass switch closing needs to be used with a short time delay to ascertain that more than one commutation failure has occurred. With this low ac voltage which is also the reference commutating voltage, synchronizing of the firing pulses may be lost. On voltage recovery, deblocking and opening of the bypass switch allow resumption of inverter operation.

As indicated in the Block Diagram, only very unlikely faults such as a thyristor arc-through would require tripping of the ac breakers and shutdown of the machine.

Even in the case of load rejection (except by open circuit fault in the dc leads) shutdown may not be necessary if the MHD channel can sustain a short circuit through the bypass switch and the combustor input or power reduced in some relatively quick way. That is, if loss of load was in consequence of fault clearing by ac breakers and if these high-speed reclose successfully, the load can be picked up by deblocking the inverter, etc. - similar to a start-up operation.

2.17.1.7.4 Start-Up and Shutdown

The inverter transformers are energized from the ac side and with the bypass switches closed. When the MHD current through the switches is sufficiently above discontinuous conduction for the inverter (about 10% load depending on ripple magnitude), the inverter is started as a rectifier. As the bypass switch opens, the arc drop together with the forward drop in the thyristors and the momentarily negative voltage of the inverter creates a small load. Current commutates out of the switch and into the bridge. The inverter

current regulator follows the rising current retarding the firing angle into inversion and increasing the counter-voltage to match the MHD generator voltage.

The operation can be made automatic with a start control unit or under manual supervision.

A normal shutdown is essentially the reverse with the bypass switch closing when the current and voltage reach very low levels.

An emergency shutdown amounts to load rejection. The inverters are blocked, bypass switches closed and the ac breaker(s) tripped. Depending on the ac system reaction, the shunt capacitors may also be tripped to prevent dynamic overvoltage. Cooling air to the bridges should continue to be available for an estimated 15 min from the standby house power.

Since startup without connection to the ac system is not required, the inverter does not need the bottom ac generator. However it may be noted that in the event of islanding the system, the MHD plant could serve the load if the ac generator is also available to provide the commutating voltage.

2.17.1.7.5 Additional Control Aspects

The multiple power outputs inherent with the Faraday channels presents some problems regarding the number of controllers needed to implement the operation and protection systems.

From the MHD regulation and optimization point of view it appears that each of the separate bridges should have its own controllers with constant extinction angle, current control, and as developed voltage feedback control.

However, and as part of the learning experience, it may be sufficient or possibly desirable to control groups of bridges whose nominal consolidated currents and voltages are within 5% of each other with a common regulator, especially as the consolidations have been arranged to each deliver the same power. This reduces the number of regulators and feedback loops substantially. For each such group, the dc currents could be continuously averaged and the result serve as a single feedback to the group CEA controller and current regulator to generate the same error signal and same firing signal to all bridges of that group.

For the diagonal channel configurations there should be no special problem in voltage sharing by bridges in series since each is fixed by its own ac voltage.

Where strings of series bridges are in parallel they may not share the load equally, unless the circuit conditions are such that each would be on its current part of the characteristic (Figure 2-189). In this case the feedback is provided by the total dc current of the load circuit and scaled equally to each string of bridges -- obviously all bridges in one string must receive the same firing order from a common mode regulator.

But when the conditions are such that each parallel string could be on its natural voltage (constant extinction angle) characteristic, the joint operation can be unstable. One string tends to operate on its voltage line while the other shifts to a current mode and equal current sharing does not take place. It appears necessary to provide some kind of current balancing control; and this will have to be addressed in final engineering design if at that time parallel strings are still necessary.

This kind of problem does not arise when thyristor strings are paralleled inside a bridge since in that case current sharing is designed with the ancillary circuits.

2.17.1.8 Physical Aspects and Testing

While most of the bridge components are "off-the-shelf" items, it is also true that the configurations discussed are not to be found as "packaged products." Thus the application at this point in time is unique, although the same components and control principles have been extensively used in HVDC transmission.

Inverter physical sizing and arrangement are shown in Figure 2-191 and 2-192. These drawings together with the Inversion System equipment list and general specifications elsewhere in this report are self explanatory. The latter also gives the requirements of auxiliary power supply for the inverter system.

Three points are made here:

1. The division of the total MHD power generated leads more to industrial type of inverter packaging than to high voltage, high power assemblies.
2. This being so, some advantage is taken to eliminate radio interference type of noise (a by-product of thyristor switching) by enclosing the bridges in metal clad cubicles. In contrast the entire valve hall of HVDC stations is built as a Faraday cage screen.

Figure 2-191 Inverter Room

Figure 2-192 Inverter System Plan

3. Similarly the cooling is simplified by separate metal clad cubicles. Simple open-ended forced air seems sufficient, but air-to-air or air-to-water heat exchangers could be added without much trouble. In the open type of converter construction for HVDC, the entire valve hall is partially pressurized and an air plenum provided below the building.

As for testing the inverters prior to connection to the MHD source, there are standard on-delivery and on-installation tests that are in common use. In progressive phases each bridge module can be operated individually as a rectifier into the resistive load, and then pairs of bridges can be tested back-to-back as rectifier-inverter, with no net power except losses, taken from the ac auxiliary supply. Commutation failures and other malfunctions can be simulated.

2.17.2 Transmission Plant and System Tie

The substation and transmission facilities associated with the Engineering Test Facility (ETF) will include:

1. Construction power during the construction phase of the ETF;
2. Station service to the ETF auxiliaries independent of ETF operating mode;
3. A means of transferring the output of the MHD inverter and/or the turbine generator to the local utility system.

The operating level for the substation and associated transmission facilities will be 115 kV nominal.

Commercial power will be taken from the Montana Power Company at a nominal 115 kV. Supply power for the construction phase and to supply the ETF auxiliaries when neither the MHD inverter or the turbine generator are operating will be provided by a 115 kV/4.16 kV transformer rated 12/16/20 MVA.

The task of designing the substation and transmission facilities is preliminary in nature, since the site of the ETF is not firm and accordingly the actual voltage of the tie to the Montana Power Company has not been definitely selected. However, five general areas for the site have been investigated. Since the MHD must operate in an integrated system, the areas were evaluated in part for their capability to provide reasonably good facilities for testing the integration of the combined MHD-Steam Generating Plant into a utility system.

Four of the five areas, including the area around Butte, do appear to offer these facilities. The area near the Glasgow Air Force Base in the Northeast corner of Montana, is by far the weakest connection from a transmission standpoint.

Since these various areas do differ in the amount of generation, impedances, and other system characteristics, Transient Network Analyzer (TNA) Studies cannot be performed to determine the exact equipment characteristics and grounding requirements until the site is selected.

The predominant voltage in each of the five areas is 100 kV. While this voltage is not an industry standard, it is sufficiently close to and below 115 kV, which is an industry preferred standard. All equipment for the substation and the line will be designed using the 115 kV level but with recognition that the normal level will be closer to 100 kV.

2.17.2.1 Substation

The bus configuration for the ETF substation will be a ring bus. Several other schemes were investigated, among them radial feed, breaker-and-a-half, and double breaker. The ring bus was selected on the basis of economy, reliability, and yet allow one circuit breaker at a time to be out for maintenance. The cost of the ring bus is among the lowest of all the schemes considered. Although the scheme does not allow for maintaining service on all components in the event of a second breaker operation, sufficient reliability for a test facility is expected. The one line for the station is shown on Figure 2-193.

Since the location of the ETF is not firm, nothing is known regarding the availability of commercial power sources of sufficient voltage and KVA capacity for construction power. To this end, the layout of the substation is such that it can be constructed in two phases: first, installation of a single circuit breaker and the construction power/station service transformer to provide for construction power; and, second, installation of three circuit breakers and the step-up transformers for both the MHD inverter and the turbine generator.

The layout of the switchyard is based on the use of ground supported equipment. This will allow for ease of operation and ease of maintenance while maintaining the flexibility required of a test facility. While this type of layout does require a larger land area than others, its low level and flexibility will more than compensate for the additional land area. All structures within the

substation will be lattice type steel. This includes transmission line terminal structures, strain structures within the substation, disconnect switch supports, bus supports and equipment supports. These structures will be designed to withstand a 100 mph wind and will be deflection limited so that equipment operation (i. e., opening or closing disconnect switches) is possible. In addition, the structures will be designed to take the full short circuit possible within the substation. All design will be in accordance with AISC Code. Layout of the station is shown on Figure 2-194.

Lattice steel was selected on the basis of low first cost, ease of erection, minimum maintenance and reasonable esthetic appeal.

Foundations for the structural steel will be reinforced concrete. All foundation design will be based on seismic loading data for the particular substation location. All designs will be based upon information developed by subsurface soils investigation and will incorporate criteria of ACI as a minimum.

The substation site will be a well drained site. If possible the site will be graded so that precipitation run-off will not affect the electrical conduit system. Should this prove impossible at the selected site, then a system of drains must be designed to accomplish the same effect.

Grounding the substation will be by copper or copper-clad steel cables. The choice between the two will be largely decided by the corrosion study conducted at the site. Should this study indicate significant corrosion activity, then the copper system will be used, with a suitable cathodic protection system. Since no ground fault currents are available because of the absence of TNA studies, no substation ground system has been designed. However, the design will be in accordance with IEEE 80, the recognized Industry standard and will be done so that voltage use will be within accepted "touch and step" potentials.

The transformers will all be triple-rated, either OA-FA-FOA (self-cooled-forced air cooled-forced oil to air cooled) or OA-FA-FA (self-cooled-forced air cooled-additional forced air cooled). The triple rated design was selected in part on the basis of costs and the expected number of hours of ETF operation. The losses of these triple-rated units at a specific load, above the self-cooled rating of the triple rated unit, are larger than the equivalent two rated unit, as are the power requirements of the fans and pumps. However, due to the low load factor of the ETF, significant savings will result through the use of the triple-rated units.

Figure 2-194 Switchyard, Equipment Plan & Elevation

The sizing of the transformers will be as follows:

Construction power and unit auxiliary	12/16/20 MVA
MHD inverter step-up	40/53/66 MVA
Turbine generator step-up	40/53/66 MVA

The circuit breakers to be used at the ETF will be 115 kV oil circuit breakers, frame mounted. The current rating will be 1200 amps with an associated interrupting capability of 5000 MVA. This size will be verified by the TNA Study when the actual site is chosen. In the unlikely event that the interrupting capability of 5000 MVA be exceeded, then the circuit breakers will be rated 1600 amps, 10,000 MVA interrupting.

The control and metering relaying philosophy of the incoming commercial feeder will be determined to a large degree on the existing systems now being used by the Montana Power Company. Again, the lack of a definite location for the ETF makes the design of this part of the relay system of the electrical substation impossible because of the lack of data on the neighboring utility system. Relaying for the equipment within the substation will include differential, overcurrent, sudden gas pressure and breaker failure. Distance relaying will be utilized to back-up the Montana relaying. The transmission relays (impedance, carrier, etc.) will depend on the specific application of the Montana Power Company's relay scheme.

The bare cable that is to be used on the ETF will be 795 kcmil, aluminum conductor steel reinforced (ACSR). This size will handle the output of the step-up transformers for both the MHD inverter and the turbine generator. The stranding of this wire is 26 aluminum strands over a 7 strand steel core. Accessories for this size and stranding of cable will be readily available.

The bare tubular bus that is to be used will be 2 in. schedule 40 IPS aluminum. Fittings and connectors for the tubular bus will be of the bolted type. Expansion connectors will be used on all tubing runs so as to minimize mechanical loading on the equipment bushings. This tubing will coordinate with the 795 kcmil ACSR cable design described above.

All disconnect switches to be used in the ETF substation will be manually operated, three pole, single throw, gang operated, 115 kV and 1200 amps. These switches will be mounted on post type insulators.

All insulation, including suspension type ball and socket for overhead strain bus, station post insulators for bus supports, bushings for circuit breakers and transformers, etc., will be of wet process porcelain conforming to ANSI standards. All suspension type ball and socket insulators will be manufactured in accordance with ANSI Class 52-3.

All station post insulators will be in standard strength units and manufactured in accordance with ANSI-Technical Reference No. 286. Bushings for circuit breakers and transformers have not been finalized, due to lack of specific design information from TNA Studies.

2.17.2.2 Transmission

The voltage level for the transmission facilities for the ETF has been selected as 115 kV.

The transmission line will be designed in accordance with the National Electric Safety Code, Heavy Loading District as a minimum. Meteorological conditions will also be investigated and further information on extreme ice and extreme wind and a combination of both will form additional design constraints.

The type of structure that will be used will be a wood pole H-Frame with suitable X-Braces between poles and V-Braces supporting the cross-arms. This type structure is common to the Western sections of the U.S., offers one of the lowest cost types of construction and yet is reliable for ETF operation. The poles, assuming a normal topography, will average 65 to 70 ft in height. The poles would be either Douglas Fir or Western Red Cedar, Class 1 or 2. All wood structural material (cross braces, V-braces) will be Douglas Fir. All wood products will be full length treated with pentachlorophenol for decay prevention. The poles of each structure will be spaced some 12 to 14 ft on center with a 12 to 14 ft phase spacing. The structures will be spaced an average of 750 ft apart along a 125 ft cleared right-of-way.

The conductor will be a 795 kcmil aluminum conductor steel reinforced (ACSR), the same wire as that used in the substation. This wire has an ultimate tensile strength of 31,500 psi and will be installed according to vibration criteria. The criteria indicates that at 60°F, the sag and tension for an average span will be 15 ft of sag at a tension of 5,000 lbs. The data indicates a clearance from phase conductor ground, at low point of sag, in excess of 30 ft.

This clearance is well above the NESC limit.

The shield wire for lightning protection will be a 7 #8 Alumoweld. The 60°F sag for this wire will be some 10 ft and the corresponding tension will be 1,800 lbs.

The insulation will be either 7 or 8 ball and socket insulator units, ANSI Class 52-3. The number of insulators will be dependent on the results of the TNA Study.

The grounding of the structures will be accomplished by driven rods at each pole location. The upper limit of ground resistance or tower footing resistance will be determined by the insulation and TNA Study. Should additional grounding be required, counterpoise will be installed to meet the maximum ground resistance for good lightning performance.

2.17.3 DC Resistive Load

A dc resistive load is proposed during initial plant operation to dissipate the generated MHD power prior to connection to the inverters and the power grid.

The primary function of the load bank installation is to provide a discretely variable choice of voltage and current selections that cover a reasonable range of power dissipating capabilities. Flexibility for simulating various load lines of the MHD generator throughout its operating range is obtained by various series-parallel connections of the resistor elements. Such an arrangement also permits bringing the generator up to full power gradually in a predetermined step-wise fashion during the initial checkout and shakedown period. Finally, a variable load bank system allows the study of the MHD generator over a range of off-design conditions resulting in detailed performance maps.

Load banks for MHD generators typically consist of an array of water-cooled stainless steel tubes. Given the predicted generator V-I characteristics, power output, and available cooling water pressure and flow, selection of the optimum tube configuration is primarily a trial and error process. A good selection for the ETF generator load bank turned out to be 1/2" O.D. x .01" wall x 18 ft long stainless steel tubes. With a total water pressure drop of 100 psi available, ~ 85 psi is used across the tube, the remainder being accounted for in the manifold, fittings, and connector hose losses. The base

pressure in the closed loop cooling water system is maintained at 50 psig with a resultant saturation temperature of $\sim 300^{\circ}\text{F}$. The water bulk temperature rise across the tube has been chosen as 150°F (from 100°F inlet to 250°F outlet). Given these conditions the operating characteristics of a single tube were calculated and the results summarized in Table 2-73.

A single load bank is composed of 10 of the above resistor tubes manifolded to be hydraulically in parallel and electrically in series. The electrical rating of the load bank thus becomes:

Resistance	4.42 Ω
Max Dissipation	4 MW
Max Current	950 amps
Voltage Drop	4200 V

Twelve load banks are required for the ETF generator to give 48 MW dissipation capability and the flexibility for sufficient series-parallel combinations to cover a wide range of operating conditions.

The physical arrangement of the load bank consists of 120 tubes which are hydraulically in parallel and electrically isolated from the cooling water headers by a length of insulating hose. Deionized water is used in the closed-circuit cooling system to minimize conductivity and the possibility of short-circuiting the bank to ground. The resistance tubes are electrically arranged in series connected banks of ten. Twelve such banks are mounted vertically and electrically isolated from each other. Since each bank has an equivalent resistance of 4.42 Ω , various series-parallel combinations of load resistance can be made in 4.42 Ω , increments, by arranging the patch bar connections accordingly. These bars are for the purpose of connecting the resistance elements of the load bank to the generator bus.

TABLE 2-73

PERFORMANCE CHARACTERISTICS OF A SINGLE RESISTOR TUBE
1/2" O.D. x .01" Wall x 18' Long

Water Flow	18.4 gpm
Water Velocity	32.6 fps
Reynolds No.	300,000
Film Coefficient	7500 Btu/hr--ft ² --°F
Tube Temperature	330°F max.
Heat Flux	590,000 Btu/hr/ft ²
Burnout Flux	3 x 10 ⁶ Btu/hr/ft ²
Safety Margin	5
Dissipation Capacity	400 kW
Resistance	.442 ohms
Maximum Current	950 amps
Voltage Drop	420 volts

2.18 MHD ALTERNATE EXHAUST GAS BYPASS

The alternate exhaust bypass system provides a means for routing the MHD generator exhaust gases directly to the stack. This enables initial and separate testing and operation of the MHD topping cycle components independent of the bottoming steam generator plant, and thus provides for progressive testing of the ETF with increasing degree of operational complexity.

In addition to initial separate testing of MHD components, different channels and burners may also later be tested separately before integrated operation of these with the complete power system.

The operational flexibility provided by the exhaust bypass system is considered an advantage for the ETF and is preferred. The exhaust bypass system can also provide for possible testing and operation of MHD components before construction of the entire ETF is completed.

2.18.1 Performance and Tradeoff Analysis

The alternate exhaust by-pass proposed for the ETF is a compromise between emission control and minimum cost. MHD components tests using the alternate exhaust bypass are considered to be of relatively short duration. Thus in order to save costs, variances from gas emission standards will be requested. This pertains to NO_x emission, CO emission and plume opacity.

2.18.1.1 Requirements

The alternate exhaust will satisfy the following requirements:

- Reduce the exhaust gas temperature to a level compatible with conventional discharge of the effluent gas and removal of particulate matter (seed and fly-ash).
- Cost effectiveness.

The removal of seed is considered combined with sulfur removal from the gas by the use of K_2CO_3 as initial seed material. The removal of particulate matter and sulfur (SO_x) is considered to comply with emission standards for these pollutants. Figure 4-163 shows the estimated size distribution of the particulates in the effluent gas. In order to use conventional scrubbing equipment for removal of particulates from the gas and to keep ducting to the scrubber and exhaust stack simple, the hot MHD generator ($2300\text{--}2400^\circ\text{K}$) exhaust gas is cooled by water quenching.

NO_x control by two-stage combustion with controlled cooling of the exhaust gas at higher temperatures (>1900°K) and after burning would involve additional complexity and costs. In order to avoid this, variance from NO_x emission standards is proposed.

The exhaust gas bypass introduced the problem of deflecting a hot gas stream (2300-2400°K) containing ash impurities. The simplest solution considered was to water quench the gas as it leaves the MHD diffuser. This protects the deflector, and cools the gas to a temperature compatible with conventional ductwork.

A wet scrubber was chosen for particulate removal. It effectively reduces the gas to an adiabatic saturation temperature compatible with conventional wet scrubber materials. Wet scrubber technology is well established, and effectively removes the particulates.

A further advantage of the wet scrubber is that (if the quench and scrub water is available at less than the adiabatic saturation temperature) the water introduced by the scrubber reduces the evaporation loss of the quencher. This is shown by Figure 2-195. A water to gas mass flow ratio of 1.28 produces an adiabatic saturation temperature of 193°F at reference MHD exhaust conditions. The intersection of the total water and lower vapor curves shows conditions for which 100% of the quench water would be evaporated, assuming 80°F water inlet temperature. The excess water required for scrubbing raises the water/gas ratio to nearly 10:1, and reduces the temperature to 170°F. Both horizontal and vertical scrubbers were investigated. A horizontal venturi can be aligned with a relatively simple 45° gas deflector/quencher. However, according to several scrubber manufacturers contacted, vertical orientation of venturis is standard practice. A vertical venturi was selected which requires a 90° vertical deflector, plus two more 90° elbows to redirect the gas to the venturi. Pressure drop was reduced by co-flow water injection, and enlargement of the ducts to venturi inlet diameter. Figure 2-196 shows that for a fixed quench water flow rate, the I. D. fan and water pumping power is minimized when water is sprayed into the quencher at 75 ft/sec in the same direction as the gas flow.

Figure 2-195 Alternate Exhaust Quench for ETF

Figure 2-196 ID Fan and Water Pump Power Tradeoff for ETF Alternate Exhaust

2. 18. 2 Gas Quenching and Scrubbing Equipment Design

Figure 2 -197 shows a schematic elevation of the MHD diffuser, alternate exhaust quencher, scrubber, and demister. When the MHD train discharges through the alternate exhaust bypass the transition section between the diffuser and boiler is removed. A 90° cooled elbow is attached to the diffuser. Gas flows vertically upward from the elbow (which is also the injection zone for 70% of the quench water). A second 90° elbow approximately 30 ft above the MHD centerline turns the gas horizontally. The remaining 30% of the quench water is introduced at this elbow. A straight duct runs to a point directly over the scrubber venturi. A third 90° elbow directs the quenched gases downward to the scrubber venturi which terminates in a flooded elbow discharging horizontally into the demister.

The Chemico scrubber shown features a variable area venturi to maintain scrubbing efficiency at different gas flow rates. Spray headers provide for periodic washing of the mist eliminators in the separator.

The scrubbed wet gases move horizontally from the top of the mist eliminator through a 12 ft diameter duct to a 90° elbow. The elbow directs the flow downward to a plenum joining the induced draft fan. The I. D. fan discharges to the main stack.

2. 18. 2. 1 Description of Quencher

Figure 2-198 shows the elbow which turns the gas 90° to the vertical direction after it leaves the MHD diffuser. Seven water cooled turning vanes deflect the gas.

The reason for providing the turning vanes are as follows:

- The vanes reduce the pressure drop of the 90° turn from 8.5 "H₂O (90° mitre) to 0.7 "H₂O. 8.5 "H₂O is 43% of the overall pressure drop of the alternate exhaust system. This saves about 1000 (I. D. fan) hp.
- The vanes provide a convenient array of spray bars for distributing the quench water uniformly across the duct flow area.
- It is easy to direct the quench water issuing from the vanes in the same direction as the gas flow. The ejector pumping action of the quench water, and the net decrease in specific volume resulting from flow quenching, overcome most of the pressure

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Figure 2-197 Diffuser, Quencher, and Scrubber for ETF Alternate Exhaust

Figure 2-198 Pool Boiling Elbow and Quencher for ETF Alternate Exhaust

drop of the alternate exhaust system, exclusive of the wet scrubber. Table 2-74 summarizes the pressure drops.

TABLE 2-74
ALTERNATE EXHAUST GAS PRESSURE DROPS

Component	Stagnation Pressure Drop "H ₂ O	Comment
1st hot 90° turn with vanes	0.7	8.5 "H ₂ O without vanes
Expanding vertical quench duct	-0.1	Ejector pumping plus cooling
2nd 90° turn with vanes	0.1	
Remaining straight ductwork	-0.6	" " " "
3rd 90° turn	negl.	Omitting vanes adds 0.4 "H ₂ O
Scrubber	19.0	Vendor estimate
(2) 90° elbows, duct, and dump to I. D. fan plenum	0.7	

The turning vanes are spaced approximately one chord length apart and cooled both internally and externally. 200 gpm of water enters each of the 7 hollow vanes at 100 - 150 psig from a manifold at both ends. It leaves the leading and trailing edges from (24) spray nozzles spaced at 6 inch intervals. The trailing edge spray nozzles discharge in a square pattern which assures complete coverage of the duct cross section.

The spray nozzles were selected to have relatively large orifices to avoid possible clogging by dirty quench water.

The nozzle vendor estimates drop size to be 600 microns or smaller. A simple heat transfer calculation for a single drop (neglecting diffusion) yielded Figure 2-199. This shows that 600 micron drops should evaporate in 50 ft of ductwork. The smaller drops evaporate sooner.

A cylindrical outer water cooling jacket joins a straight 12 ft diameter circular duct which forms a gas-tight connection with a second 90°

Figure 2-199 Evaporation Distance as Function of Drop Size ETF Alternate Exhaust Quench

elbow. 500 gpm of water is introduced tangentially past the horizontal outer surfaces of the square gas inlet. Water fills the jacket up to the top of the vertical transition duct (joining the top of the first 90° turn). It flows over the top and joins the main gas stream which is already carrying 1400 gpm introduced by the spray nozzles on the turning vanes.

The remaining ductwork and wet scrubber are conventional. Preliminary specifications for the scrubber are given below.

Scrubber Specifications

Combustion gas conditions at scrubber inlet:

Mass flow rate = 143 lbm (dry gas)/sec + 183 lbm/sec quench water

Specific volume = 49.7 ft³/lbm of dry gas

Gas temperature = 193°F

Gas pressure = 1.0 atm

Composition by mass of water-quenched gas

H₂O: 58%

N₂: 29%

CO₂: 12%

other: 1%

Dust loading - 3.01 grains/acft of dry gas, or 11,000 lbm/hr

consists of K₂CO₃: 1.79 grains/acft

K₂SO₄: 0.89 grains/acft

ash: 0.33 grains/acft

Particle size distribution per enclosed figure.

Gas velocity - 193 ft/sec

Allowable emission: The scrubber removes 99.6% or more of the particulate matter in the gas so that no more than 37 lbm/hr of particulate matter is emitted to the atmosphere with the exhaust gas from the scrubber.

Preliminary scrubber proposals for the above specifications have been received from four manufacturers contacted. Major proposed data are listed below:

	Air Pol.	Chemico	Peabody (Lurgi)	Swemco
Specs. agreed to	Yes	Yes	Yes	Yes
ΔP, "H ₂ O	35-40	18-19	12-14	25
QH ₂ O, gpm	9800	7100	6400	2800
Ht.	41'	81 1/2'	48'	~40'

	Air Pol.	Chemico	Peabody (Lurgi)	Swemco
Max. Length or diameter	37 1/2	47'	20 1/2'	32'
Wt. Mat'l	110 K lbm C. S.	134 K lbm C. S.	- 316 L S. S.	- 316 ELC S. S.

The Chemico carbon steel scrubber was tentatively selected on the basis of cost and pressure drop.

2. 18. 3 Auxiliaries for Alternate Exhaust

2. 18. 3. 1 Water Supply and Drainage

The water supply for the alternate exhaust is covered by Section 2. 4. 6 on Heat Rejection and Cooling Water Systems. Interface requirements for the pumps are:

	Flow	Discharge Pressure
Main	10, 000 gpm	at 20 psig
Quench, taken from main flow	2, 000 gpm	at 150 psig

Drainage is from the bottom of the first quencher elbow and from the bottom of the scrubber demister.

	Temp.	Flow
Demister	170°F	9000 ⁺ gpm
Quencher	212°F	600 ⁻ gpm
Evaporation loss	--	400 ⁺ gpm

2. 18. 3. 2 Controls and Instrumentation

Pump controls will probably be on-off. Water level control in the quencher sump and cooling jacket can be either by hand or by float or other suitable sensor-operated valve. Provision for turndown depends on cost savings, if any. This is appropriate for detail design.

A tentative list of instrumentation is given by Table 2-75.

TABLE 2-75

LIST OF INSTRUMENTATION, ETF ALTERNATE EXHAUST

Component	Device	Number	Measurement	Range
Alternate Exhaust Gas System	Transducer	1	Overall pressure drop	0-30" H ₂ O
	Indicator	1	Overall pressure drop	" " "
	DAS channel	1	" " " "	" " "
	Sensor	1	Scrubber inlet temp.	40-1000°F
	Indicator	1	" " " "	" " "
	DAS Channel	1	" " " "	" " "
	CO monitor	1	CO partial pressure	0-0.1 atm
	Indicator	1	" " " "	" " "
	DAS channel	1	" " " "	" " "
	NO _x monitor	1	NO _x partial pressure	0-0.1 atm
Alternate Exhaust Quench Water	indicator	1	" " " "	" " "
	DAS channel	1	" " " "	" " "
	Transducer	2	Supply pressure	0-150 psig
	Indicator	2	" " "	" " "
	DAS channel	2	" " "	" " "
	Sensor	1	Supply temp	40-200°F
	Indicator	1	" " "	" " "
	DAS channel	1	" " "	" " "
	Sensor			
	Indicator	3	Outlet temp.	" " "
	DAS channel			
	Flowmeter	1	Water inlet flow rate	0-2000 gpm
		1	" " " "	0-1000 gpm
	Indicator	2	" " " "	0-2000 gpm
	DAS channel	2	" " " "	0-2000 gpm
	Transducer	1	Supply pressure	0-25 psig
	Indicator	1	" " "	" " "
	DAS channel	1	" " "	" " "
	Sensor	1	Supply temp.	40-200°F
	Indicator	1	" " "	" " "
	DAS channel	1	" " "	" " "
	Flowmeter	1	Water inlet flow rate	0-8000 gpm
	Indicator	1	" " " "	" " "
	DAS channel	1	" " " "	" " "

2.19 BALANCE OF PLANT

2.19.1 Oxygen System

An oxygen storage facility will be included to provide oxygen enrichment during the progressive testing and operation of the MHD topping cycle components when the high temperature air preheater system is not being used, or in the event of a malfunction in the preheater system. Based on the preliminary test program schedule, sufficient oxygen supply for eight hours of operation at rated flow was chosen as the storage basis. Eight hours of operation will require 380,000 lbs of oxygen (40,000 gal of liquid oxygen). Although the Design Criteria Document had shown 10 hrs of operation, an eight hour run is now deemed adequate for providing meaningful data and operation.

Various oxygen storage schemes were investigated and, because of the volume required, liquid oxygen storage in four, standard size, 11,000 gal vertical tanks was selected. This provides 44,000 gal of liquid oxygen storage vs the 40,000 gal required and, therefore, allows some margin for boil-off during storage while maintaining the minimum liquid volume necessary.

Also based on the preliminary test program schedule, the large oxygen storage requirement will be necessary only during the first two years of ETF operation, with a smaller storage supply for emergency operation in the event of a malfunction required thereafter. Therefore, it was determined that it is economically desirable to lease rather than buy the equipment. The leasing of a single, horizontal, 50,000 gal storage tank was investigated since it is an available size; however, the more common 11,000 gal tanks were chosen. The 11,000 gal tanks can be obtained with a more favorable leasing arrangement since they would be considerably easier for the lessor to lease again after the two year period. One 11,000 gal tank is considered adequate following the first two years of operation.

Vaporizers will be used to convert the stored liquid oxygen to a gas before delivery to the burner. Considering the maximum required oxygen flow of $\sim 572,000$ SCFH, and the availability of steam, steam vaporizers were chosen instead of electric or air types. Six 100,000 SCFH steam heated vaporizers will be required in parallel in order to vaporize the maximum flow rate. The steam required at the maximum flow will be $\sim 8,600$ lb/hr (saturated). The oxygen will be heated to approximately ambient temperature.

As noted, the storage facility will initially consist of the four (4) 11,000 gal liquid oxygen tanks and six (6) steam vaporizers, and also the necessary piping, valves, instrumentation, controls, etc. The four tanks will be connected in parallel to the six vaporizers which will also be connected in parallel to a single oxygen supply line running to the HTAH. The liquid oxygen will be stored at ~ 100 psig (150 psig maximum) in order to provide the required pressure at the burner. The oxygen storage facility with vaporizers will be located outdoors within a fenced area at least 10 ft from any other facility.

Delivery of liquid oxygen to the ETF can either be by truck or rail depending on the gas supplier selected. If delivery is by rail, a transfer pump station will be provided or supplied as part of the leased equipment. The oxygen trucks have integral transfer pumps. Within 24 hr notice, delivery of the liquid oxygen can be provided from vendors in Washington, California, Colorado or other Western States depending on the vendor chosen.

2.19.2 Fuel Oil Storage and Supply

A fuel oil storage and supply system will be provided for receiving, storing, and forwarding the No. 2 distillate. The distillate will be primarily used for firing the high temperature air heaters. Secondary uses of the distillate will be for the house heating boiler, the auxiliary boiler, waste heat boiler startup and the diesel engine. Distillate will be consumed at a maximum rate of ~3500 gph during the by-pass mode and 2460 gph while operating with the bottoming plant without the gasifiers. The system is based on railroad delivery of the distillate to the plant, with railcar capacities of 20,000 gal/car.

A fuel oil transfer station, located on a spur track, will be used for transferring fuel from the railroad cars to the storage tanks. Two fuel forwarding skids will be provided. One skid will supply distillate to the high temperature air heaters and the other skid will supply distillate to the house heating boiler, the auxiliary boiler, and the diesel engine. Each skid will include two 100% capacity fuel oil pumps. Heaters in the fuel oil lines will raise the temperature of the distillate, to provide fuel with the required viscosity, for proper atomization, if required by the auxiliary boiler manufacturer(s).

The distillate will be stored in tanks designed to meet API standards. The tanks will be built inside a diked area designed to accommodate any oil spills. The distillate storage tank sizes and proposed delivery schedules are based on the ETF test program schedule. The storage tanks will hold enough distillate for one month of continuous plant operation. The high temperature air heaters will be oil fired through the middle of the fourth year of the test program.

2.19.3 Waste Removal Systems

Waste collection systems will be provided to collect both solid and liquid wastes and transport them to their proper storage areas. Solid wastes will include slag, ash, mill rejects, seed, and gypsum from the seed regeneration process. Liquid wastes will come from the seed regeneration process, makeup and polishing demineralizers, boiler blowdown, and miscellaneous floor drains and cooling water flows.

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

The Montana Rosebud coal is 8.7% ash and the Illinois #6 is 11.4% ash. From the coal delivered to the combustor, 75 to 90% of the ash will be removed as slag from the combustor with the majority of the balance removed at the radiant section of the boiler. The small amount of remaining ash will be collected in the downstream sections of the boiler or precipitator with the seed. During the bypass mode, seed, ash and slag, normally collected at the boiler and precipitator, will be removed from the combustion gases by a scrubber. Six gasifiers will provide fuel for the high temperature air heaters. Montana coal will be used as the fuel for the gasifiers and ash from the gasifiers will be collected and transported by truck to the waste storage area.

Specifics of the various waste collection systems are as follows:

Mill Rejects - Mill rejects will be collected dry from the bowl mill in the coal preparation area using standard equipment of proven design. The solids collected from the mill will be ~ 0.4% of the coal flow. The rejects from the mill will collect in a hopper having a storage capacity of ~ 18 ft³ or

10 hrs of continuous operation. This hopper will be emptied once per shift by an eductor. The eductor will have a capacity of 10 tph and thus will be able to empty the hopper in seven minutes.

Gypsum - Gypsum will be collected at the seed regeneration plant and held in a hopper. Trucks will be used to transport gypsum to the solid waste storage area.

Combustor Slag - Slag will be removed continuously from the combustor, which operates at 5.5 atm and 4600^oF. This removal system will be unique in two aspects. First, most present day slag tap boilers operate at or near atmospheric pressure and below 4600^oF. Second, the MHD combustion chamber is at 15,000 to 20,000 V above ground potential. Two of the larger companies involved with ash handling equipment were asked to present conceptual designs for handling the slag from the combustor. The result was a series of quench and storage tanks to lower the pressure and temperature of the slag-water slurry for sluicing to the waste area. The basic components of the system are shown in Figure 2-200. Its operations and a discussion of the electrical problem is discussed in the following paragraphs.

Slag falling from the combustor will pass to the refractory lined quench tank which will cool the slag. Nozzles below the water level in the quench tank will add water to cool and fracture the hot slag. The desired water level in the quench tank is maintained by providing an outlet to the overflow tank. Filtered water from the overflow tank is cooled by circulating water system and pumped back to the quench tank. Makeup to the system is added to the overflow tank. Blowdown from the system is taken from the overflow tank. The slag then passes through a section of pipe to the first storage tank. This section of pipe contains a valve and space for a crusher if required. Since the flow of slag is so small, it is felt that the slag will solidify in sizes which won't require crushing. Slag will fall through the first collection tank and settle in the second tank. When the second tank is full, the valve below the first tank is closed. The second tank is depressurized by venting to the atmosphere and the valve at the bottom of the tank is opened. Slag is sluiced to the dewatering bins by means of an eductor. When empty, the tank will be filled with water and pressurized by opening a small valve between the first and second storage tanks. After equalizing the pressure the gate valve between the first and second storage tanks is opened.

Figure 2-200 Combustor Slag Collection System

The second storage tank will have 1140 ft³ of storage volume which will accommodate 90% of the ash. This will be the maximum amount of slag deposited during ten hours of continuous operation. The eductor capacity will be 15 tph and will thus be able to empty the full capacity of the second tank in ~ 2 hrs. The first storage tank will have a storage capacity of 230 ft³ and will thus be able to store the slag produced while the second tank is being emptied. An adequate amount of cooling water will be supplied to maintain the water temperature in the quench tank at 140°F. This temperature is compatible with standard ash collection equipment. Also, its vapor pressure is below that of the vapor pressure in the combustor thus eliminating the possibility of water being added to the combustion gases.

The high electrical potential at the combustor can be handled in two ways. One is to electrically isolate the slag collection system from the combustor. The second is to have the quench tank and first and second storage tanks at the same potential as the combustor. Both methods have their own merits. Electrical isolation eliminates the possibility of stray electrical currents from tank connections. However, it also presents the possible problems associated with arcing between dripping slag and the water surface. Figure 2-200 indicates electrical isolation between the combustor and slag collection system. More information concerning slag and ash sluice water electrical conductivity is necessary to evaluate the pros and cons of each method.

Boiler Slag - Ash, as molten slag, will be collected continuously from the radiant section of the boiler, using standard equipment of proven design. The slag will leave the boiler through a circular opening in the radiant section bottom, falling to the wet slag tank through a refractory lined throat section hung from the boiler. A water cooled swiper arm will be used to keep the throat area free of stalactities. Slag falling into the tank will be agitated and fractured by water jets in the tank. A water seal trough will be located between the boiler throat and slag tank to permit downward expansion of the boiler. The slag will then flow by gravity to a clinker grinder and is then sluiced by means of an eductor to dewatering bins.

The slag tank will have 317 ft³ of storage volume. This volume will accommodate 25% of the ash contained in the coal during ten hours of continuous operation. The eductor, used for removing slag from the clinker

grinder, will have a capacity of 15 tph and will thus be able to empty the slag tank in 40 minutes.

Boiler Seed and Ash - With the steam bottoming plant in operation, ash and seed will be collected from the three chambers in the boiler which are downstream of the primary radiant section, and from the precipitator. The first two sections, the seed recovery and final oxidation furnaces, will have long rectangular slits at the boiler bottom. The slits which run perpendicular to the gas flow, are formed by front and back water walls sloping toward the center of each boiler section, thus forming a hopper. In the second boiler pass, the seed recovery furnace, the ash may contain some dripping wet slag. Ash from the third pass, the final oxidation furnace, from the economizer sections and from the precipitators will be dry. To eliminate problems caused by solidifying slag at the bottom of the seed recovery furnace, a water cooled screw will convey the ash, seed and slag continuously and deposit in a holding hopper. A water cooled conveyor will also collect ash and seed below the final oxidation furnace and deposit it in the same hopper. This hopper and hoppers below the economizer and precipitator will be emptied by a pneumatic vacuum system which discharges to a storage silo. The silo will have 140 ft³ of storage volume and thus be able to store the ash and seed from 10 hrs of continuous operation. A pneumatic pressure system will be used to convey a portion of the recovered ash and seed to the seed regeneration area for processing and the remainder to the seed injection system which is discussed in Section 2.16.3, Seed Feeding.

Bypass Wastes - During the bypass operating mode, the ash and seed, normally removed from the boiler and precipitator, will pass through a quench duct and be separated from the combustion gases in a scrubber, as discussed in Section 2.18. The seed, ash, and quench water slurry will be pumped from the scrubber outlet to the sedimentation basin located adjacent to the storm water and wastewater holding basin. Water from the sedimentation basin will flow to the storm water and wastewater holding basin. From here, it can be pumped back to the quench duct and scrubber. During the bypass mode, the sedimentation basin will provide the residence time required to settle out the seed and ash collected in the scrubber, and both basins will provide adequate residence time to cool the water to the temperature required at the quench duct inlet. When the bypass mode is discontinued,

the sedimentation basin will be used to treat water transferred from the storm water and wastewater holding basin to the clean water holding basin. The storm water and wastewater holding and sedimentation basin will have storage volumes of 760,000 ft³ and a minimum of 25,000 ft³, respectively.

Gasifier Ash - Ash from each of the six gasifiers will be collected in their own individual hoppers. The hoppers will be emptied sequentially, once a shift, and conveyed pneumatically by a vacuum system to a large holding bin. The holding bin will be 2,700 ft³ and will thus have the capacity to store gasifier wastes for 64 hrs of continuous operation. Ash will be transported from the holding bin to the storage area by truck with six truck loads required to empty the entire bin.

Dewatering Bins - The dewatering bins noted earlier will be located between the plant island and waste storage area. Mill rejects and slag will be sluiced to one of the two dewatering bins, while the contents of the other bin are being dewatered. The water will be drained to a settling tank which overflows to a storage tank. The storage tank will provide suction for the ash sluice pumps. Each dewatering bin will have a wet storage capacity of 9,000 ft³ and thus be able to hold the wastes generated during 64 hrs of continuous operation. After dewatering, the solids will be trucked to the waste storage area.

The solids waste storage area will be located on the perimeter of the site, adjacent to the settling pond. Solid wastes generated over the life of the plant will occupy 7,300,000 ft³.

2.19.4 Auxiliary Boilers and Auxiliaries

Three auxiliary boilers will be required. Two will be primarily for building heating and the other will be primarily for supplying steam to the combustion air compressor turbine drive. The boilers will also service various auxiliaries.

The two half-size, building heating, water tube boilers will be rated at 3450 lb/hr each saturated steam at 212°F with feedwater at 212°F (200 Boiler hp). The skid mounted boiler package will include fuel oil air atomizing equipment, and a forced draft fan for the combustion air. Their overall dimensions will be ~ 14-ft long, 7-ft wide, and 8-ft high. Feedwater will be supplied to each boiler from one of the two full service 13 gpm

feed pumps. The feed pumps will take suction from, and will be mounted on a common skid with a deaerator. Feedwater from the deaerator will be pumped through water softeners. Condensate and system makeup will be fed to the deaerator.

In addition to building heating, this boiler will supply steam for vaporizing oxygen that is to be used for combustion, and deaerator pegging steam.

The second auxiliary boiler will supply steam to the combustion air compressor drive turbine during startup and the bypass mode. This auxiliary boiler will also supply steam that is essential for various plant startup functions. The boiler will be rated at 145,000 lb/hr, 1250 psig, and 900°F outlet steam conditions. A steam temperature of 900°F was chosen to match the initial steam temperature from the bottoming plant steam generator during startup. The auxiliary boiler will be oil fired. It will be shop assembled in modules for field assembly, bottom supported, and the following will be included with: combustion air fan, motor and ductwork, combustion gas breeching and stack, combustion and feedwater controls, structural steel, and miscellaneous platforms and stairways. The boiler dimensions will be ~ 35-ft long, 20-ft wide, and 13-ft high. The location of the auxiliary boiler is shown on Figure 4-1.

The condensate and feedwater systems will be the same as that used for the bottoming plant discussed in Section 2.14.5. In this manner, the MHD generator, burner, and diffuser will receive adequate cooling water and will provide heat to the auxiliary boiler feedwater during the bypass mode and startup. Feedwater leaving the diffuser, in excess of that required for the auxiliary boiler, will be diverted to the condenser hotwell.

2.19.5 Water and Wastewater Treatment Systems

Water treatment equipment 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.

Pretreatment equipment will be installed for reducing alkaline hardness and removing organic solids in the makeup demineralizer influent and will process 30 gpm (net) of well water or a mixture of well water and

treated wastewater from the clean water holding basin. The equipment will consist of a 10-ft diameter by 16-ft high cold process softener, two 4-ft diameter by 12-ft high gravity filters, a 4-ft diameter by 12-ft high clearwell, transfer pumps, chemical feed equipment, instrumentation and controls, and the associated valves and piping. This equipment will be housed in the water treatment building located between the clean water holding basin and the plant island.

The makeup demineralizer train will include a 4-ft diameter by 6-ft straight activated carbon purifier, a 2-ft 6-in. diameter by 6-ft straight primary cation exchanger, a 2-ft by 6-in. diameter by 7-ft straight primary anion exchanger, and a 2-ft by 8-ft straight mixed bed polishing unit. The demineralizer system will be completely assembled on skids, including the automatic controls, regeneration system, and associated valves and piping. The processed makeup from the demineralizer will be discharged to the condensate storage tank.

The chemical feed equipment for feedwater quality control will be assembled on a single skid. The equipment will consist of one morpholine feed tank and metering pump system, one hydrazine feed tank and metering pump system, and one emergency phosphate feed tank and metering pump system. Hydrazine and morpholine injection rates will be controlled by automatic adjustment of the respective metering pump discharge rates and the pH analyzers will monitor hydrazine residual and feedwater pH at the inlet to the economizer. Phosphate injection rates will be controlled by manual adjustment of the phosphate feed pump discharge rate.

Three 50% high rate, mixed bed polishing vessels, equipped with an external regeneration system, will be installed in a parallel arrangement for condensate polishing. A full flow condensate bypass will also be included as part of the system. When in operation, two polishing units will be in service while the third unit will be freshly regenerated and kept in a standby position. Each unit will be 4-ft 6-in. diameter by 4-ft 6-in. straight having a minimum resin bed depth of 3-ft. A 2:1 cation-anion resin ratio will be used to establish resin volumes for each unit. The polishing units will operate in the hydrogen-hydroxide cycle with service runs terminated by high cation conductivity.

Cooling tower water treatment will be accomplished by acid treatment of makeup water for scale control, and chlorination of the recirculated water to restrict the formation of bacterial slime, organic growths and marine life. Acid feed equipment will consist of a 10,000 gal sulfuric acid storage tank, acid metering pumps, mixing tee, pH control instrumentation, and the associated valves and piping. Chlorination equipment will be provided for twice daily, shock chlorination treatment of the cooling tower water. Each treatment period will be 30 min in duration. The chlorination equipment will consist of a 2,000 lb/day evaporator chlorination system equipped with a portable scale, and the associated piping, controls, and valves. Chlorine will be supplied from 150 lb capacity cylinders with an estimated consumption rate of 13 cylinders/month. The chlorination and acid feed equipment will be located in the pump house, adjacent to the cooling tower structure. Chlorine cylinders will be enclosed in a shed, built against the pump house wall. The acid storage tank will be located in the yard, adjacent to the pump house.

Storm drainage and plant waste waters, discharged from the storm water and wastewater holding basin to the clean water holding basin, will be treated as necessary to maintain the pH of the water within acceptable limits. Chemical feed rates will be controlled by a pH controller with sampling point location in the discharge of the waste transfer pump. Chemical injection will be to the transfer pump suction well. Chemical feed equipment will consist of a chemical feed tank, a metering pump, a pH controller and the associated valves, instrumentation, controls and piping with the materials of construction suitable for handling either acid or caustic depending on the pH requirements of the water. The chemical feed equipment and chemicals will be housed in a weather proof enclosure, adjacent to the wastewater discharge pump.

A water quality control panel for the bottoming cycle will be located in the water sampling room, on the first floor of the control building. Sample coolers, pressure regulators, valves, tubing, a sampling sink and other parts comprising the sample collection portion of the system will be installed in one section of the control pane. The analytical testing apparatus, accessory instrumentation, electrical components, and face mounted analyzers and recorders will be installed in the second section of the panel. Instrumentation

and sampling point locations will be provided to maintain the feedwater pH and hydrazine residuals, in the preboiler piping, within acceptable limits for corrosion control. They will also ensure the protection of the bottoming cycl against condenser in leakage, condensate polisher over runs, and boiler water solids carryover.

2.19.6 Miscellaneous Mechanical Systems and Equipment

Miscellaneous mechanical equipment will include pumps, tanks, and all other auxiliary mechanical equipment required for complete systems, that are not included under the other major categories.

The condensate and feedwater pumps are discussed in paragraph 2.4.5.5.

A fire protection system will be provided to meet the requirements of NFPA, local and state codes for electrical equipment, fuel storage and handling areas and chemical storage areas. Deluge systems will be of the dry type wherever freezing can occur. Two 100% capacity pumps will be provided for fire protection. One will be motor driven and the other will be an emergency diesel driven pump. Both pumps will take suction from the clean water holding basin and will be housed in the water treatment building adjacent to the basin.

One 60,000 gal expoxy-lined carbon steel storage tank will be provided for condensate makeup. The demineralized water from the condensate storage tank will be transferred by gravity for normal makeup or by a condenser. The size of the tank will be based on the amount of water required for cycle replacement.

Compressed air equipment, complete with receiver tanks, automatic controls, driers, etc., will be furnished for general plant requirements and control air. The equipment will be of the reciprocating type and designed for 125 psig service.

Compressed air equipment, complete with receiver tanks, automatic controls, blowoff valve, lube oil equipment, etc., will be furnished for soot blowing air requirements. The equipment will be of the centrifugal type and designed for 200 psig service.

One hogging ejector will be provided to remove air from the main condenser during cold startups. The single stage steam jet will lower the

pressure in the condenser to ~ 10 in. HgA, at which time the twin stage, twin element steam jet air ejector will be started. 1950 lbs/hr of 200 psig steam will be supplied to the hogging ejector during startup from the auxiliary boiler.

A nonpotable service water system will be included for the plant and coal handling area. This system will supply water for washdown of equipment and floors and miscellaneous equipment cooling requirements in remote locations. The source of the water will be wells. The well water will be stored in a 20,000 gal steel elevated tank.

An air exhauster with dust separators and accessories will be installed to provide a centralized vacuum cleaning system in the test facility. For remote areas, portable vacuum cleaning equipment or alternate means to maintain cleanliness will be used as noted in other sections of the report.

2.19.7 Electrical Equipment

The electrical equipment proposed for the MHD ETF will employ standard commercial designs utilizing the National Electric Manufacturers Assoc. (NEMA), Illuminating Engineers Society (IES), National Electric Code (NEC) and other applicable standards in determining detailed design applications.

The major components of the electrical equipment have been broken down and are listed below.

- Power Distribution Equipment
- Electric Motors
- Control Power Equipment
- Emergency Power Equipment
- Lighting
- Communications
- Cable and Raceways
- Cathodic Protection and Grounding

The proposed Auxiliary Electrical System is diagrammed on the one line diagrams. The drawings are Figure 2-201 "Unit One Line Diagram," Figure 2-202 "Auxiliary Electric One Line Diagram - Figure 2-203 "Auxiliary Electric One Line Diagram - Sheet 2."

Figure 2-201 Unit One Line Diagram

Figure 2-203 Auxiliary Electric One Line Diagram - Sheet 2

2.19.7.1 Power Distribution Equipment

The station auxiliary power will be fed from the low voltage windings of the Station Auxiliary Transformers and will be three phase, sixty Hertz, 4160 V, resistance grounded.

4160 V Switchgear and Buses

The incoming feeders to the metal-clad 4160 V switchgear will be fed through cable bus through main power breakers to two lineups of switchgear with a tie breaker. The switchgear will be located indoors on the ground floor of the control building.

All 4160 V circuit breakers will be drawout air type with 125 Vdc operating and monitoring power. Breakers and buses will be sized in accordance with the loads carried with sufficient capacity for future additional loads. Each breaker and instrument compartment will contain space heater elements that are fed from a 120/208 V distribution panel.

Each breaker will contain current transformers, protective relays, disconnect devices, control power fuses, ammeters and control test switches, door mounted. The bus will have potential transformers, low voltage relays, and voltmeters mounted in instrument cubicles in the switchgear.

The 4160 V switchgear will provide power to motors larger than 200 hp and 4160-480 V transformers.

480 V Power Centers

The 480 V power centers will be comprised of 4160-480 V transformers, dry type throat connected to a main breaker in a lineup of 480 V metal clad switchgear. The 480 power centers will be located on the ground floor of the control building and coal unloading building.

The 480 V circuits breakers will be drawout air type, 125 Vdc operation and will have protective devices located in each breaker compartment. The 480 V bus will have potential devices for remote and local monitoring and relays, as required, for equipment and personnel protection.

The 480 V power centers will provide power to 125 hp through 200 hp motors, nonmotor loads from 101 kW through 300 kW, and 480 V motor control centers. The power centers will have electric space heaters fed from a 120/208 V distribution panel.

480 V Motor Control Centers

The 480 V motor control centers will be metal-clad, free standing vertical and horizontal bus configuration. The motor control centers will be located indoors as near as possible to the loads serviced.

The motor control centers will consist of air circuit breakers, 100 A through 400 A frame size, combination starters size 1 through size 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 three 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.

2.19.7.2 Electric Motors

Motors will be sized and designed to fit the driven equipment characteristics, environmental requirements and the following parameters.

Motors larger than 200 hp will operate on a three phase, 4160 V, sixty Hertz system. Each motor will have bearing thermocouples, six stator RTD's, two grounding points, oversized conduit boxes, space heater (120 V or 208 Vac operation), and will have a service factor of 1.15. The motor design hp will not utilize the service factor.

Motors 25 hp through 200 hp will operate on a three phase, 480 V sixty Hertz system. Each motor will have a space heater (120 Vax operation), oversized conduit box and two ground connection points. The motors will have a service factor of 1.15. The motor design hp will not utilize the service factor.

Motors, 1/2 through 20 hp, will operate on a three phase, 480 V, sixty Hertz system. Motors will have oversized conduit boxes and two grounding points.

Motors less than 1/2 hp, except valve operators, will operate on a single phase, 120 V, sixty Hertz system.

Motor operated valve motors will be designed to meet the valve operating characteristics. Motor operated valves 1/10 hp and larger will operate in a three phase, 480 V, sixty Hertz system, and smaller motors on a single phase, 120 V, sixty Hertz system.

Motors driving equipment that are required for the safe shut down of major equipment in an emergency will be designed to operate on a 125 Vdc system.

2.19.7.3 Control Power Equipment

The major control voltages will be 125 Vdc and 120 Vac, single phase, sixty Hertz, 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 125 Vdc control power will be fed through one or more dc distribution panels with two-pole breakers supplying the various control loads. This dc system will provide control power for the 4160 V switchgear, 480 V

power centers, critical motor control, protective relaying, fire protection, emergency diesel generator and emergency motor controls. The battery will also furnish power to the vital ac inverter.

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

A solid state battery charger will be furnished which will be supplied by a breaker from the essential 480 V motor control center. The charger will be designed to be capable of recharging the battery, in eight hours, from a voltage level of 1.75 V/cell to full voltage while maintaining normal control requirements.

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

Vital ac System

A 120 V single phase, sixty Hertz vital ac system will be furnished. This system will consist of an inverter, bypass transformer, 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 required during detailed design.

The Vital ac System will be designed with a minimum of 25% spare capacity. A maintenance bypass transformer with voltage regulating equipment will be installed to provide vital ac control power during maintenance of the inverter system.

The Vital ac System will be located on the mezzanine floor of the control building.

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 contact voltage will be 125 Vdc transformed from the power supply.

The power supplies and logic cabinets for the operation alarm system will be located on the mezzanine floor of the control building with the light panels located in the control room. All local annunciator systems will have power supplies, logic cards and windows in self-contained enclosures for mounting on local control panels. See paragraph 3.5 for a discussion of the operation alarm system.

Small Motor Control

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

Miscellaneous Control Power

Dry type, 480 V - 120/208 V, four wire transformers and distribution panels will be furnished for control power for various nonessential systems which require 120 V, single phase, sixty Hertz, power from sources other than starters or the vital ac system.

These transformers and distribution panels will be located indoors near the loads to be supplied.

2.19.7.4 Emergency Power Equipment

Emergency Diesel Generator

An Emergency Diesel Generator, rated at 1600 kW, 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 diesel generator will furnish three phase, 4160 V, sixty Hertz, power to the 4160 V switchgear.

The Emergency Diesel Generator will be remotely operable by operator action, locally by operator action or started automatically by a low voltage relay initiated by low voltage on the 4160 V buses.

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 RTF 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.

2.19.7.5 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.

Area Lighting

Mercury vapor street lighting, parking area lighting and floodlight fixtures mounted on poles or on buildings will be installed to provide station yard and street lights. These lights will be supplied from 480 V, three phase, sixty Hertz, air circuit breakers in various motor control centers.

Building Lighting

The administration building, steam turbine generator building, inverter housing, MHD building, coal handling control house, and the control building will have fluorescent fixtures for normal lighting. The lighting will be 120 V, single phase, sixty Hertz, supplied from local distribution panels.

Hazardous Area Lighting

Lighting in the coal handling areas, gasifier, oxygen and other areas which meet the NFPA requirements for hazardous locations will be illuminated with explosion proof mercury vapor or incandescent fixtures operating on 120 V single phase, sixty Hertz, power supplied by local distribution panels.

Steam Generator and Other Area Lighting

The steam generator, seed regeneration, non hazardous coal areas, air preheater, and miscellaneous buildings, will be illuminated utilizing mercury vapor and incandescent fixtures operating on 120 V, single phase, sixty Hertz, power supplied from local panels.

Convenience Outlets

Convenience outlets, two wire, three-pole with ground interrupter protection will be installed throughout the ETF. The outlets in hazardous areas will be explosion proof, as required. In areas of high maintenances, outlets will be located such that an outlet is within 25 ft of any area where maintenance work may be performed. These outlets will be 120 V, single phase, sixty Hertz, and supplied from local distribution panels.

Emergency Lighting

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

For areas remote from the station battery, local emergency lighting will be provided by self-contained battery pack fixtures which include battery, charger, voltage indicator and one to four light fixtures. These fixtures will be powered by 120 V single phase, 60 Hz from local lighting panels.

The emergency lighting system will provide lighting to permit safe egress from any indoor area to any exits out of the buildings, tunnels or other areas. Illuminated exit signs will be provided and continuously lighted.

In addition, the Main Control Room will have a system of emergency incandescent lights which will provide sufficient illumination to permit continued operation of the control panels by the operating personnel when the normal control room illumination is inoperable.

2.19.7.6 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. Loud speakers and horns located throughout the plant will be fed from solid state amplifiers. Muting facilities will be used where applicable. The inherent design will preclude the need for acoustic booths. The system will include one paging and four party line channels.

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 telephone company service to these areas.

Sound Powered Phones

All control panels, transformer panels, and other major maintenance equipment, will be provided with sound powered telephone jacks. These sound

powered jacks will provide readily available means of communications during lengthy maintenance or checkout periods without tying up the intraplant system.

Load Dispatching

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

2.19.7.7 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.

High Voltage Power Cable and Raceways

Power cable for the 4160 V system power will be stranded copper conductors with 5000 V insulation, shielding, and flame resistant jacket construction. The cables will be routed through dedicated ladder type trays or conduits, as required.

Medium Voltage Power Cable and Raceways

Medium voltage power cable will be stranded copper conductors with 600 V insulation and flame resistant jacket construction. The power cables will be routed through dedicated ladder type trays or conduits, as required.

Low Voltage Power and Control Cables

Cables of 120 and 125 V power and control will be stranded copper conductors, single or multiple conductor with 600 V insulation and flame resistant overall jacket. The low voltage power and control cables will be routed through dedicated ladder type trays or conduits, as required.

Signal Cable

Signal cable will be of two types. The first being of stranded copper conductor, 300 V insulation, shielding, copper drain wire, and flame resistant jacket. Cable will be of two or more conductor construction. The other signal cable will be thermocouple extension wire with solid conductors of the proper metals, as required, 300 V insulation, shielding, copper drain wire and flame resistant jacket. Thermocouple cables will be single or multiple pair construction. Signal cables will be routed through dedicated solid bottom trays with covers or in steel conduits, as required.

Communication Cable

Communication cable and local telephone company wires will be routed through dedicated steel conduits, handholes, floor wireways, and junction box raceway systems.

Lighting Wire

Fixtures operated on a 480 V system will be medium voltage cable. Wiring for 120 V fixtures will be solid copper conductors, single wire, 300 V insulation, THHW type. Wiring will be run in dedicated steel conduits in hazardous and outdoor areas and in EMT in indoor areas.

Cable Trays

Cable tray design and cable routing will be such that predetermined cable fills will not be exceeded. High voltage trays will have only one layer of cables with a minimum of one cable diameter between cables. Medium voltage trays will have a 35% fill limit. Signal trays will have a 40% fill limit.

Conduits

Underground conduits in duct banks will be korduct or fiberglass, for power and control cables, and galvanized steel, for signal and communications, encased in concrete, with reinforced concrete at road crossings. Duct banks will terminate at buried manholes or stub-up areas into pull boxes. Buried conduit design will provide that cable pulling tensions will not be excessive.

Individual buried conduit runs will be galvanized steel conduits encased in concrete.

Exposed conduit for all cable types, except lighting, will be galvanized steel conduit. At motors, and on equipment subject to excessive vibrations or movement, a minimum two feet length of flexible conduit will be installed.

2.19.7.8 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 electrical equipment, or equipment with electrical parts within the station area, will be suitably bonded to the station grounding grid or to structural members of the station building, which will serve as a part of

the ground grid in this area. Major members of composite steel structure, such as buildings and all separate towers supporting electrical equipment, as well as electrical equipment or equipment with electrical parts located remote from the station, will be connected to the main copper cable grounding grid. This 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 ETF and the switchyard. The ETF and switchyard ground grids will be interconnected. Grounding will also be provided for the plant perimeter fence and for sections of the fence adjoining the switchyard and passing under overhead electrical conductors.

Joints in the ground grid, and connections to structural steel, will be welded by Cadwelding or Thermowelding in such a manner that the resistance of the weld is less than that of the equivalent length of conductor.

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.

Grounding of the shield of each shielded power cable will be provided at two points. Grounding of control systems, where used, such as for motor starter controls, will be made at only one point.

2.19.8 Combustion Air and Flue Gas System

The combustion air and flue gas system flow diagram is shown in Figure 2-204. This system includes the bottoming cycle boiler, MHD channel components, high temperature air heaters (HTAH), low temperature air heater (LTAH), HTAH air and gas blowers, main air compressor, bypass system, coal drying and feed equipment, stack, auxiliary boiler and all interconnecting piping.

During normal operation all equipment bypass lines are closed. Bypasses are provided as required. HTAH blowdown can be dumped directly to the stack. HTAH recycle gas and air blowers can bypass the intermediate temperature heaters during startup. The main air compressor discharge has a dump valve to assure operation below the compressor surge line. The seed regeneration gas blower preferably takes flue gas from the HTAH discharge. If not available, it will use flue gas from the auxiliary boiler or air.

Figure 2-204 Combustion Air and Flue Gas Flow Diagram

All equipment interconnecting piping will be carbon steel pipe, except as specifically noted in Section 2.11, High Temperature Air Preheater System. The carbon steel pipe will conform to ASTM specification A-155. All pipe will be insulated to prevent heat loss and designed with expansion joints to absorb thermal loads.

2.19.9 Steam Systems

The steam systems flow diagram is shown in Figure 2-205. The major pieces of equipment in the steam system are the waste heat boiler, auxiliary boiler, house heating boilers, ac turbine, air compressor turbine, deaerator and steam jet air ejectors.

During normal integrated plant operation, steam jet air ejectors (SJAЕ), the deaerator and the seed regeneration plant receive steam from the turbine extraction. Below 50% load on the turbine, extraction pressure falls below that required for the SJAЕ. Steam is then supplied from the main steam line. If extraction pressure continues to drop, the seed regeneration plant will begin to receive desuperheated steam from the main steam line. Provision for bypassing the main turbine has been included to facilitate unit startup. During startup, the deaerator will receive pinging steam from the house heating boilers. The SJAЕ, condenser hogger and steam seal system will receive steam from the auxiliary boiler on startup. Oxygen is vaporized with steam from the house heating boilers.

Main steam piping from the bottoming cycle boiler and from the auxiliary boiler to both turbines will be made of 2-1/4 Cr-1Mo alloy steel conforming to ASTM specification A335 Gr P22. Extraction steam and other low temperature piping will be made of carbon steel conforming to ASTM specifications A-106 Gr B and A-53 Gr A or B type S for sizes below 2-in. and above 2-1/2 in., respectively.

Figure 2-205 Steam Systems Flow Diagram

SECTION 2.0

REFERENCES

1. Petty, S., et al., 16th Symposium on Engineering Aspects of MHD, Pittsburgh, 1977.
2. 16th Symposium on Engineering Aspects of MHD, Pittsburgh, 1977.
3. "The Technology Base for Large Superconducting Magnets," Montgomery, D. B., Williams, J. E. C., 15th Symposium on Engineering Aspects of MHD, Philadelphia, PA 1976.
4. Final Technical Report, FE-2285-7, "Design of Superconducting Magnets for MHD Applications," by Avco Everett Research Laboratory, Inc., ERDA Contract E(49-18) 2285 June 1977.
5. Wilson, M. N., Walters, C. R., Lewin, J. D., and Smith, P. F., "Experimental and Theoretical Studies of Filamentary Superconducting Composites-Part I," J. Phys. D. 3, 1518, 1971.
6. Petty, S., Solbes, A., Enos, G. and Dunton, A., "Progress on the Mark VI Long-Duration MHD Generator," Paper IV.5, Proceedings of the 15th Symposium On Engineering Aspects of MHD, The University of Pennsylvania, May 24-26, 1976.
7. Stickler, D. B. and DeSaro, R., "Replenishment Processes and Flow Train Interaction," Paper I.7, Proceedings of the 15th Symposium on Engineering Aspects of MHD, The University of Pennsylvania, May 24-26, 1976.
8. Stickler, D. B., et al., "Coal Combustor Technology Development," 17th Symposium on MHD, Stanford University, March 1978.
9. Teno, J., et al., "A Coal Combustion System for MHD Generators," presented at Intersociety Energy Conversion Engineering Conference, Las Vegas, 1970.
10. Stickler, D. B., et al., "Rapid Devolatilization Modeling of Coal," Combustion Institute Eastern Section Meeting, Johns Hopkins University, Applied Physics Laboratory, November 12-13, 1974.
11. Ubhayakar, S. K., Stickler, D. B., von Rosenberg, Jr., C. W. and Gannon, R. E., "Rapid Devolatilization of Pulverized Coal in Hot Combustion Gases," prepared for presentation at the Sixteenth Symposium on Combustion, M. I. T., Cambridge, Massachusetts, August 15-21, 1976.

12. Lowenstein, A.I. and von Rosenberg, Jr., C.W., Avco Everett Research Laboratory, Inc., Everett, Massachusetts, "Shock Tube Studies of Coal Devolatilization.
13. Lewis, J. A. and Gauvin, W.H., Department of Chemical Engineering, McGill University, Montreal, Quebec, Canada. "Motion of Particles Entrained in a Plasma Jet," September, 1973, pp. 982-990.
14. Stowell, Dennis, E. and Smoot, L. Douglas, Brigham Young University Provo, Utah, "Turbulent Mixing Correlations in Free and Confined Jets." AIAA Paper 73 1194 C.1.
15. Tufts, L.W. and Smoot, L. D. Brigham Young University, Provo, Utah Vol. 8, No. 12, December 1971, "A Turbulent Mixing Coefficient Correlation for Coaxial Jets with and without Secondary Flows."
16. Quarterly Progress Report for the period March 1 - May 31, 1976, "Investigation of Electrode Maintenance Processes and Associated Channel Materials Requirements for Open Cycle MHD Generators," EPRI Contract RP 322-1.
17. Vasil'eva, I., Malyuzhonok, G.P., Nefedov, A.P. and Proberezhsky, A.I., "Joint US-USSR Experimental Studies of the Dependence of Plasma Electrical Conductivity on Plasma Temperature Performed in the Avco Mark VI MHD Facility," Paper IX.1, Proceedings of the 15th Symposium on Engineering Aspects of MHD, The University of Pennsylvania, May 24-26, 1976.
18. Fourth Annual Report of the MHD Generator Development Program. Avco Everett Research Laboratory, Inc., American Electric Power Service Corp. 1964.
19. Sixth Annual Report of the MHD Generator Development Program. Avco Everett Research Laboratory, Inc., American Electric Service Corp. 1964.
20. Runstadler, P.W. and Dolan, F.X., Further Data on the Pressure Recovery Performance of Straight-Channel, Plane-Divergence Diffuser at High Subsonic Mach Numbers, ASME Paper 73-FE, C.I.
21. Runstadler, P.W. and Dean, R.C., Straight Channel Diffuser Performance at High Inlet Mach Numbers, Trans. ASME, Journal of Basic Engineering, September 1969, pp. 397-422.
22. Anonymous, General Electric Heat Transfer and Fluid Flow, Data Book, 1970, Section G406, p. 6.
23. Idzorek, J. J., "MHD Diffuser Model Test Program," Fluidyne Report 1070, July 1976.

24. Doss, Ezzat D., "Subsonic MHD-Diffuser Performance with High Blockage," 16th Symposium, Engineering Aspects of Magnetohydrodynamics, University of Pittsburgh, Pittsburgh, Pa., May 16-18, 1977.
25. Sajben, J., Kroutil, J. C., and Sedrick, A. V., "Conical Diffuser Flows with Natural and Screen-Simulated Inlet Conditions," AIAA Journal, Vol. A, No. 12, December 1976, pp. 1723-1977.
26. Private Communication, Koppers Company, Inc., Pittsburgh, Pa., (1977).
27. Private Communication, Krupp-Koppers GmbH, Essen, W. Germany, (1977).
28. Jakob, M., "Heat Transfer," Volume II, John Wiley & Sons, Prentice Hall, (1967).
29. Razelos, P. and Paschkis, V., "The Thermal Design of Blast Furnace Stove Regenerators," Iron and Steel Engineer Year Book, pp. 523-558, (1968).
30. Hausen, H., "Vervollstaendigt Berechnug des Waermeaustausches in Regenatoren," VDI-Beiheft, Verfahrenstechnik, No. 2, (1942).
31. Rohsenow and Choi, "Heat, Mass and Momentum Transfer," Prentice Hall (1961).
32. Berczynski, F. A., "Recent Improvements in Blast Furnace Stove Design," Ironmaking Conference Proceedings, 27:71-83 (1968).
33. Dancy, T. E., et al., "Principles of Stove Operation," Iron and Steel Engineer Year Book, pp. 506-516, (1963).
34. Butterfield, P., et al., "Hot Blast Stoves," Journal of the Iron and Steel Institute, June 1963.
35. Rehms, F. H., "AIME Blast Furnace, Coke Oven, and Raw Materials Proceedings," Vol. 21, (1962).
36. Hasselman, D. P., "United Theory of Thermal Shock-Structure Initiation on Crack Propagation in Brittle Ceramics," Journal of American Ceramic Society, Vol. 52, No. 11, November 1969.
37. Hals, F. A., et al., "High Temperature Air Preheaters for Open Cycle MHD Energy Conversion Systems," National Heat Transfer Conference (1975).
38. van Laar, J. and Ijmuiden, H., "High Temperature Internal Combustion Chamber Stoves," Ironmaking Conference Proceedings, 33:408-415, (1974).

39. Proceeding of NSF-OCR Engineering Workshop of MHD Materials, Massachusetts Institute of Technology, November 20-22, 1974.
40. Palz, H. and Heuer, A., "Design and Construction of Hot Blast Stove Plants for High Blast Temperatures and High Blast Pressures," Iron-making Conference Proceedings, 32:165-176, April 1973.
41. Goodier, J.N., "Stresses in Domes and Crowns of Circular Kilns," Journal of American Ceramic Society, 16, (5), 220, (1933).
42. "Modern Refractory Practice," Harbison-Walker Refractories Co.
43. McDowell, J.S., "Sprung-Arch Roofs of High Temperature Furnaces, Part III," Blast Furnace Steel Plant, 28, (2), 161, (1940).
44. Maeser, O.J., "Why Blast Furnace Stove Shells Fail," Iron and Steel Engineer, 48:53-60, April 1971.
45. Buhler, H.E., et al., "Types of Stress-Corrosion Cracking on Unalloyed and Low-Alloyed Structural Steels, with Special Consideration of Stress-Corrosion Cracking on Hot Blast Stoves, Part II: Observations Made During Operation and Studies of Damages," Translation from Stahl U. Eisen 95, No. 17, August 1975.
46. Horvay, G., "Stress Analysis of Perforated Plates," General Electric Report 56 RL-1611, (1956).
47. Roark, R.J., Formulas for Stress and Strain, McGraw-Hill, N.Y., Fourth Edition (1965).
48. Schleusener, S.A., Lindberg, J.D., White, K.O., Johnson, R.L., Appl. Opt. 15, 2547-2550 (1970).
49. Patterson, E.M., Gillette, D.A., Stockton, B.H., Paper MC3 in Atmospheric Aerosols NASA CP-2004 (1976).
50. Voltz, F.E., Appl. Opt. 12, 564-568 (1973).
51. Plass, G.N., Mie Scattering and Absorption Cross Sections of Aluminum Oxide and Magnesium Oxide. SSD-TDR-62-127, Vol. VI (Acronutronic Div. of Ford Motor Co., Newport Beach, California, 27 May 1963).
52. Carlson, D.J. and DuPuis, R.A., Alumina Absorption and Emittance, Pub. #U-2627 (Philco, Ford Motor Co., 31 May 1964).
53. Gryvnak, D.A. and Burch, D.E., Optical and Infrared Properties of Al_2O_3 at Elevated Temperatures, Pub. #U-2623 (Philco, Ford Motor Co., 31 May 1964).

54. Mulcahy, M.F.R., Boow, J. and Goard, P.R.G., J. of the Inst. of Fuel, 309, 385-394 (1966).
55. Kivel, B., Hals, F.A., J.Q.S.R.T. 15, 87-105 (1975).
56. Hottel, H.C. and Sarofim, A.F., Radiative Transfer, (McGraw-Hill N.Y., 1967).
57. Bueters, K.A., Combustion 45, 12-18 (March, 1974).
58. Hals, F.A. and Lewis, P.F., "Control Techniques for Nitrogen Oxides in MHD Power Plants," 12th Symposium on Engineering Aspects of MHD, March, 1972.
59. Yavorsky, P.M., et al., "Potassium Formate Process for Removing SO₂ from Stack Gas," Environmental Science and Technology, Vol. 4, No. 9, Sept. 1970; U.S. Patent No. 3,592,850, July 13, 1971, Yavorsky, P.M., et al., "Regeneration of Formate from Thiosulfate."

3.0 INSTRUMENTATION AND CONTROLS

3.1 SCOPE

This section discusses the following aspects of the MHD ETF instrumentation and controls.

For the overall facility as an integrated entity:

Basic features

Type of controls

System configuration

Facility operating system

Data acquisition system (exclusive of sensors and transducers)

Protection system.

Detailed control, operation, and monitoring (including startup, shutdown, normal and emergency operation and protection) of the following major components and subsystems are described in their respective sections of this report:

Gasifier

Low and high temperature heat exchangers

High temperature air heaters

Coal preparation and live storage

Coal processing and feed

Combustor

Dewar

Magnet

Diffuser

Inverter

Switchgear and transformers

Switchyard

Steam turbine generator

Condenser

Condensate and feedwater system

Combustion air and gas system
Scrubber and electrostatic precipitator
Induced draft fans
Auxiliary boilers
Seed regeneration and feed
Waste handling
Water treatment
Cooling towers.

3.2 BASIC FEATURES

The primary objective of the control system and accompanying instrumentation will be to provide for the reliable, safe and economical operation of the MHD facility.

The following principles are incorporated in the design concept:
Operation, control and monitoring of the facility from a central control room.

Inclusion of an optimum of automatic operation capability to minimize required operator participation, while maintaining high system reliability and unit availability.

Inclusion of manual operation capability in subsystems to satisfy the requirements for startup and shutdown operations, and to permit maximum equipment operation in the event of component malfunctions.

Inclusion of multiple control modes to allow determination in operation of optimum system response to changes in operation demand within appropriate stability limits.

Control structure capable of reconfiguration with minimal downtime.

Use of analog and digital systems to obtain the best features of each type.

Incorporation of safety interlocks to provide pre-planned actions when unsafe conditions develop.

System and component operational performance monitored on a real time basis.

Detail analysis of system and component behavior performed off-line.

3.3 TYPE OF CONTROLS

Controls for major systems will be solid state electronic type. Local controls, including final control elements (control valves and control drives) will be either electric or pneumatic, as appropriate. Operational controls will utilize commercially available and proven hardware, avoiding systems or components in a development state. Signal transmissions to and from the control room will employ electric/electronic media. Any required electric-pneumatic converters will be located in close proximity to the associated final control elements.

The Facility Operating System will be a dedicated hardware system with a high degree of flexibility to allow changes in loop configuration with relative ease. Logic systems will be of the dedicated type. Logic systems for control system switching logic and for the plant interlock requirements will be of the solid state type.

The Protection System will be of the hardwired type and designed to limit the consequences of plant upset or accident conditions to acceptable levels. It will be a dedicated system comprised of components of proven reliability for the services involved. The system will be independent of the operating and data acquisition system and will employ hardware redundancy to provide high reliability in combination with minimal false trips. Suitable test features will be incorporated. The system will employ continuous monitoring; sampled data techniques will be excluded.

The Data Acquisition System will be a real time digital computer based system including a backup readout system for all instrumentation readouts by other systems, and additional monitoring and processing capability sufficient to meet the needs of both facility operations and experimenters. It will be capable of recording basic system performance parameters, alarm conditions and operator actions. Software will be modular, standardized, well documented, and readily modifiable by knowledgeable personnel.

3.4 SYSTEM CONFIGURATION

The system configuration is illustrated by the block diagram of Figure 3-1. Illustrated are the Facility Operating System, the Protection System, and the Data Acquisition System. Figure 3-1 denotes a simplified

Figure 3-1 System Configuration

overall configuration of the respective systems and subsystems together with input types and output functions. The Facility Operation System will be comprised of Power Generation Controls and associated subsystem controls, Operator Controls and Displays, Operations Alarm System, and Plant Auxiliaries Operating System. Descriptions of the purpose and function of the various elements of the overall system is included in subsections 3.5, 3.6, and 3.7.

3.5 FACILITY OPERATING SYSTEM

Very little information has thus far been developed on the dynamics of combined MHD/steam power plants. Simulations require the use of simplifying assumptions, hence, differences between predicted and actual dynamic behavior are to be expected. The nature and extent of the differences, however, are not definitely predictable. Therefore, the control system for the MHD ETF must be able to assimilate modifications emanating from actual performance experience acquired from the physical facility.

The control system structure will be conceived utilizing the best possible understanding of the overall process and provide for a high degree of flexibility. The Facility Operating System will provide multiple modes of control including Coordinated Mode, Boiler Following Mode, and various lower level modes of operation. It will also provide flexibility in configuration by selection of a hardware system amenable to ready functional reconfiguring.

A fundamental facet of energy division between the MHD component and the bottoming plant, i. e. , for a given energy input, any change in MHD generation causes an offsetting reaction in bottoming plant generation, provides favorable open loop system response. Although the MHD response is much faster than that of the bottoming plant, transient utilization of boiler energy storage will enhance the responsiveness of bottoming plant generation.

The following major relationships will be maintained to provide balanced steady-state operation at any desired generating point:

Combustor firing rate (coal feed) in accordance with desired total generation (total generation demand).

Optimization of MHD and steam power based on unit generation demand.

Steam turbine admission valve position in accordance with total generation demand minus MHD generation.

Firing rate trimmed from steam pressure error.

Combustor air flow in balance with coal feed and trimmed to maintain desired sub-stoichiometric condition in MHD channel. CO/CO₂ ratio expected to be used for this purpose.

Boiler combustion air flow controlled as a percentage of coal feed and trimmed to maintain stack O₂ at desired value.

The Facility Operating System will be comprised of the following major elements:

Generation Controls and associated subsystem controls

Operator Controls and Displays

Operation Alarm System

Plant Auxiliaries Operating System.

3.5.1 Generation Controls

The Generation Controls subsystem requirements are depicted in the conceptual simplified block diagram form as shown in Figure 3-2 and also presented earlier in Section 1.4.4. The variables shown are conceptual and are subject to change as additional studies and research require. Further definition of the subsystem design is shown on the functional control system diagrams of Figure 3-3 and 3-4. These diagrams show the relationship of the required inputs and the controlled functions.

The major modes of unit control are the coordinated mode and the boiler following mode. The coordinated mode applies the generation demand to the MHD generation control subsystem, the combustion system and the main steam turbine admission valves. In the boiler following mode, generation demand is applied to the main steam turbine admission valve and the combustion system is controlled to maintain throttle steam pressure. For this report the coordinated mode is discussed as the normal or most desired mode of unit control

The amount of generation desired at any point in time from the facility is established via an Automatic Load Control System (not within the scope of the ETF) or by the ETF operator (Desired Generation).

Figure 3-2 MHD Simplified Model - Block Control Diagram

Figure 3-3 Conceptual Functional Control Diagram - Sheet 1

Figure 3-4 Conceptual Functional Control Diagram - Sheet 2

The Desired Generation will be processed through the Generation Demand Control network which includes high and low limits and maximum rate-of-change limit on the Generation Demand signal being processed. The measured generation (MW Generated) will be compared to the processed (limited) Desired Generation value, and the difference (error) will be acted upon by proportional and integral control action. Measured electrical frequency will be utilized in the form of Frequency Bias to modify the Generation Demand signal to counteract deviations of system frequency. Feed-forward control will be utilized to process changes in demand immediately in order to reduce response delays inherent in systems developing control signals through error detection only. Limits and runbacks will be applied to the developed demand signal to keep system demand within the limits of the capabilities of the plant equipment.

The Generation Demand Signal developed by the Generation Demand Controls will be applied in parallel to the MHD Burner combustion controls, to the steam turbine controls and to the MHD generation controls. The demand on the steam turbine will be for the generation required of the steam turbine generator, not that of the entire unit. Thus, the steam turbine demand signal will be attained by subtracting MHD generation from the total Generation Demand signal. Trim controls will restrict throttle steam pressure error to predetermined limits during the process of borrowing and storing energy in the boiler during load changes.

The subsystems illustrated each use the measured process variable in a closed loop feedback arrangement. Primary air flow control for the MHD will employ a trim control, utilizing the measured CO/CO_2 ratio of the MHD generator exhaust gas before afterburning to provide the desired sub-stoichiometric condition in the Burner and MHD channel. Boiler secondary combustion air flow, required for afterburning and complete oxidation of the MHD generator exhaust gas, will be provided by the secondary air blower. The air blower will be controlled from a demand obtained by scaling the Generation Demand signal to provide an air flow demand signal and then trimming this signal from measured stack O_2 .

Seed Feed demand will be developed from measured MHD generation trimmed by combustion gas conductivity. The control requirements for some of the major independent control loops are shown in Figure 3-4.

3. 5. 2 Digital Logic System

The Generation Controls Subsystem will encompass a digital logic system which will provide the necessary logic associated with manual and automatic transfers of control stations, transfer of setpoints, and other digital logic associated with the analog controls of the Generation Control Subsystem. The logic system will be solid-state electronic using either a hardwired system or a programmable controller approach.

3. 5. 3 Operator Controls and Displays

The Operator Controls and Displays Subsystem will encompass the manual devices for adjustments and switching functions available to the operator and the recorders, indicators, status lights, and other intelligence associated with operation of the facility. The devices comprising this subsystem will largely be located on appropriate sections of control boards in the central control room. Devices not required in the daily operation of the facility may be located in proximity to the equipment being controlled. Controls will include control switches, pushbuttons, automatic-manual transfer and setpoint stations, hand loaders, etc. Indicators will generally be vertical-scale type. Recorders will generally be small-scale, strip chart, nominal speed type. High speed recorders and X-Y plotters will be provided for use by experimenters.

3. 5. 4 Operation Alarm System

The Operation Alarm System is conceived as a combination alarm and events recording system. It will utilize a colored CRT to provide an alphanumeric entry for each individual alarm condition as it occurs. It will also provide a window display employing groups of alarms per individual window. The groupings in the window display will be by systems, subsystems, and major equipment, providing a summary picture to the operator of the distribution of existing alarms among the facility elements. All alarms will be recorded upon occurrence, and upon clearing, on an alarm printer (events recorder). The alarm printer will record all events (occurrence and clearance) by time, event identification and alphanumeric description. Time resolution of events will be ~ 3 msec.

Each alarm, upon occurrence, will be presented in distinctive color at the top of the list on the CRT, and by distinctive visual presentation on the group window display, as well as recorded individually on the alarm printer. Clearance of each alarm will be evidenced as a distinctive visual presentation on the group window display and recorder and as an individual return-to-normal on the alarm printer. The clearing alarm condition will automatically eliminate the corresponding entry from the CRT alarm complement.

The Operation Alarm System will be actuated from analog inputs (converted to digital representation at a specific value), and from digital inputs directly from individual devices and from the Data Acquisition System. The DAS alarm printer will identify the analog values of the individual alarm (low, low-low, high, high-high, etc.) outputted to the Operation Alarm System.

3.5.5 Plant Auxiliaries Operating System

The Plant Auxiliaries Operating System will be comprised of the analog subloop controls for the various plant auxiliaries subloops and the digital logic system encompassing the permissive and protection functions for the elements of the respective subloops. The analog subloop controls will be of the electronic solid-state type or of the pneumatic type, as appropriate to the application. Requisite operator control functions will be provided in the complement of central control room facilities. The digital logic system functions will be provided by a hardwired solid-state logic system as contrasted to a relay-type logic system. This arrangement is intended to provide high reliability together with flexibility for accommodation of functional requirements as initially determined and as ultimately developed.

3.6 PROTECTION SYSTEM

The Protection System will be completely independent of the Facility Operating System and the Data Acquisition System. The Protection System will utilize components of proven design and high reliability to provide tripping of major system components in a manner that is designed to protect the integrity of the vital constituents of the facility. Redundancy will be employed in sensor and protective devices to preclude unnecessary

false trips of the unit. The system will employ independent sensing and will be hardwired in order to maintain its independence of operating and monitoring systems.

3.7 DATA ACQUISITION SYSTEM

The Data Acquisition system will be a digital computer capable of being used for data gathering, monitoring and operator guidance. The system will be solid-state using integrated circuits and using card mounted plug-in construction. The system will operate in an air-conditioned environment. The system will include the major equipment listed below:

- Input/Output cabinets

- Central Processor (main frame)

- Programmer's console and desk with programmer's input/output printer

- Reader and punch at programmer's console

- Unit operator's console with CRT for display

- Output printer for periodic log

- Output printer for digital trend printout

- Output printer for alarm printout

- Analog trend recorders

- Interconnecting plug-in cabling between all equipment of the system.

3.7.1 Input/Output Cabinets with Provision for the Following Type Units

- Low level dc (current or voltage) signal inputs

- Thermocouple inputs

- Contact inputs

- Pulse inputs

- RTD inputs.

The cabinets will contain the required multiplexers, analog to digital converters, thermocouple linearization and automatic reference junction compensation, signal filtering, amplifiers, and any other required signal conditioning.

3.7.2 Central Processor

The Central Processor will be a real-time high speed computation and data processing unit.

3.7.3 Analog Input Hardware

All analog inputs will be fully buffered.

3.7.4 Operator's Console

An operator's console will be provided for communication between operator and computer. The console will have all pushbuttons, selector switches, indicating lights, address switches, digital display and other items necessary for manual entry to request output via the printers, trend recorders, and digital displays.

3.7.5 Programmer's Console

A programmer's console will include programmer's input/output printer, a reader and punch, and other controls and/or displays to provide a suitable interface for the programmer.

3.8 ARRANGEMENT OF INSTRUMENTATION AND CONTROLS

Control and displays, required by the operator in daily operation and monitoring of the total plant, will be mounted on control boards located in a central control room. Process transmitters, in general, with associated local indicators and alarm initiating devices based on function, will be group mounted in instrument racks located throughout the plant. The control relays and logic equipment associated with control room operation will be mounted in enclosed metal racks located in an electronics room.

The data acquisition system main frame, programmer's console and input/output racks will be located in an electronics room. The printers for alarm, digital trend and periodic logging will be located in the central control room. The central control room and electronics room will be air-conditioned, including humidity control, as required, for the electronic equipment.

The control boards will contain the necessary switches for start-stop of plant equipment, manual/auto selector stations for remote manual control capability for various components, indicating lights, indicators, recorders, and annunciators. All equipment will be strategically located based on function. The control boards for the physical cycle system located in the control room shall be of the vertical type with a bench section. The proposed control room layout is shown on Figure 3-5.

DRW.	CHK.	ENG.
DES.	SOL.	CH. DISC. ENGR.
AVCO EVERETT RESEARCH LABORATORY, INC.		
DOE		
M H D ENGINEERING TEST FACILITY		
MHD ETF		
PROPOSED CONTROL ROOM LAYOUT		
MAIN		SCALE
BOSTON • CHARLOTTE • DENVER • PORTLAND		DATE
CLIENT JOB NO.		DWG. NO.
3240-1-404M		

Figure 3-5 Proposed Control Room Layout

It is proposed that a mimic display be used for indicating status and physical parameters for the fuel, air and gas flow systems, as a minimum to provide the operators who will be unfamiliar with these systems with a diagrammatic operational guide.

Control boards required for electrical generation monitoring, protective relaying, substation control and monitoring and turbine supervisory instrumentation shall be of the vertical type architecture. The controls and monitoring instruments shall be arranged for easy operator viewing and access.

Table 3-1 shows the recommended monitoring and control function locations as required for major equipment components and systems. The final design phase will further define the function locations.

TABLE 3-1
CONTROL & MONITORING LOCATIONS

EQUIPMENT COMPONENT OR SYSTEM	MONITORING LOCATION			CONTROL LOCATION	
	LOCAL	CONTROL ROOM	DATA ACQUISITION SYSTEM	LOCAL	CONTROL ROOM
A. Plant Auxiliaries					
1. Instrument Air System	X	X	X	X	
2. Service Air System	X	X	X	X	
3. Cooling Water Supply System	X	X	X		X
4. Fire Protection System	X	X	X	X	
5. Cryogenic Supply Systems	X	X	X	X	
6. Service Water Supply System	X	X	X	X	
7. Low Pressure Auxiliary Boilers	X	X		X	
8. High Pressure Auxiliary Boilers	X	X	X	X	X
9. Condensate Make-up System	X	X	X	X	X
10. Water Treatment System	X	X	X	X	
11. Waste Water Treatment System	X	X	X	X	
12. Plant Security System	X	X		X	X
B. Fuel Supply Systems					
1. Gasifier System	X	X	X	X	X
2. Coal Unloading & Storage	X	X	X	X	
3. Coal Distribution System	X	X	X		X
4. Fuel Oil Unloading & Storage	X	X	X	X	
5. Fuel Oil Supply System	X	X	X		X
C. Combustion Air Supply Systems					
1. Auxiliary Steam Turbine & Auxiliaries	X	X	X	X	X
2. Air Compressor & Auxiliaries	X	X	X	X	X
3. HTAH Press/Depress Compressor		X	X		X

TABLE 3-1
CONTROL & MONITORING LOCATIONS (CONTINUED)

	MONITORING LOCATION			CONTROL LOCATION	
	LOCAL	CONTROL ROOM	DATA ACQUISITION SYSTEM	LOCAL	CONTROL ROOM
4. Combustion Air Blower		X	X		X
5. Low Temperature Air Heater		X	X		X
6. Air Flow Control System		X	X		X
D. High Temperature Air Heaters					
1. HTAH Gas & Air Controls		X	X		X
2. HTAH Combustion Controls		X	X		X
E. MHD & Auxiliaries					
1. Burner Controls		X	X		X
2. Channel (Gas Path)		X	X		X
3. Diffuser (Gas Path)		X	X		
4. Transition (Gas Path)		X	X		
5. Cooling Water System	X	X	X		X
6. Cryogenics Systems	X	X	X	X	
7. Seed Injection System	X	X	X		X
8. Seed Regeneration System	X	X	X	X	X
9. Slag Removal System	X	X	X	X	
10. Gas Scrubber System (Temporary)	X			X	
F. Steam Generator & Auxiliaries					
1. Warm-up Burners	X	X	X		X
2. Steam Cycle	X	X	X		X
3. Steam Temperature	X	X	X		X
4. Feedwater Cycle	X	X	X		X
5. Deaerating Heater	X	X	X		X
6. Furnace Monitoring	X	X	X		X
7. Induced Drat Fan		X	X		X
8. Air Flow Systems		X	X		X
9. Precipitators	X	X	X	X	

TABLE 3-1
CONTROL & MONITORING LOCATIONS (CONTINUED)

	MONITORING LOCATION			CONTROL LOCATION	
	LOCAL	CONTROL ROOM	DATA ACQUISITION SYSTEM	LOCAL	CONTROL ROOM
10. Stack Monitoring	X	X	X		X
11. Soot Removal System	X	X	X		X
12. Ash Removal System	X	X	X	X	
G. Steam Turbine & Auxiliaries					
1. Steam Turbine & Auxiliary Systems	X	X	X		X
2. Condenser	X	X	X		X
3. Condensate System	X	X	X		X
4. Steam Jet Air Ejectors	X	X	X	X	X
5. Gland Steam Seal System	X	X	X	X	X
6. Circulating Water System	X	X	X	X	X
7. Cooling Water System	X	X	X		X
H. Generator & Auxiliaries					
1. Generator		X	X		X
2. Hydrogen & Seal Oil Systems	X	X	X	X	
3. Cooling Water System	X	X	X		X
4. Projective Relay System		X	X		X
I. Substation & Unit Aux. Electrical Systems					
1. Substation		X	X		X
2. Unit Auxiliary Electrical		X	X		X
3. DC & Vital AC Power Systems	X	X	X	X	
J. MHD Electrical Generation					
1. MHD Consolidation		X	X		X
2. Magnet	X	X	X		X
3. Inverters	X	X	X		X
4. Protective Relaying		X	X		

4.0 PLANT LAYOUTS, MAINTENANCE AND SERVICE

4.1 EQUIPMENT ARRANGEMENT AND TRADEOFF ANALYSIS

The Plot Plan and Plant Island General Arrangement are shown in Figures 4-1 and 4-2, respectively. Plant Island Sections and Details A through E are shown in Figures 4-3 through 4-7, respectively.

The Plot Plan has been arranged such that all areas service the power plant in an orderly and efficient manner. Proper Consideration has been given to minimizing land use wherever possible and to providing an aesthetically pleasing site. The site orientation was chosen such that prevailing winds will move the cooling tower plume away from the plant. The site will basically be composed of three sections. The first and most westerly section will be the plant entrance, the plant island and switchyard. The second or intermediate area will be comprised of the materials handling equipment. In this area, fuel, seed and plant wastes will be received, processed and sent to their respective points of use or disposal. The third area will be the material storage area for fuel and solid and liquid wastes. Each of the three areas will be serviced by a branch line of the railroad.

The Plant Island arrangement will provide accessibility for maintenance of all the major components. The centerline of the burner, channel, diffuser and transition section are on a straight horizontal line at the center of the plant island. As shown in Figure 4-3, the HTAH outlet is at the same elevation as the burner inlet and the boiler inlet and transition section outlet center lines are at the same elevation. The refractory lined duct from the HTAH to the burner is horizontal to eliminate problems that occur from bends, and is kept short to minimize heat loss.

The channel center line elevation was chosen to minimize excavation and also to keep the equipment close enough to grade elevation so as to be easily maintained. As a result, the HTAH and combustor slag collection equipment will be located in a 30 foot deep pit. The boiler elevation provides adequate height below seed recovery hoppers for maintenance trucks if necessary.

Figure 4-1 Plot Plan

Figure 4-3 Plant Island Sections and Details

Figure 4-4 Plant Island Sections and Details

DES. V.D.G.	CHK. SAM	ENG. SAM
DES.	SOL.	CR. DISC. ENGR.
AVCO EVERETT RESEARCH LABORATORY, INC.		
DOE		
MHD ENGINEERING TEST FACILITY		
PLANT ISLAND		
SECTIONS AND DETAILS		
MAIN		SCALE 1" = 20'-0"
CHAS. T. MAIN, INC.		DATE 5-15-78
BOSTON • CHARLOTTE • DENVER • PORTLAND		CLIENT JOB DWG. NO.
		3240-1-404G

Figure 4-5 Plant Island Sections and Details

Figure 4-6 Plant Island Sections and Details

Figure 4-7 Plant Island Sections and Details

The remainder of the power plant components are suitably located around the MHD and steam generator buildings. The coal and seed feed systems are as close as possible to the burner to minimize long response times. The steam turbines and low temperature heat recovery equipment are each located adjacent to their respective sources. The stack is situated so as to be equally accessible to both the main and bypass I. D. fans, the auxiliary boiler and exhausts from the HTAH and coal drying equipment. Electrical leads from the steam turbine-generator and inverter subsystem boiler leave the building at the same location. The control building is centrally located for convenience and ready access to the plant. Also accessibility of each component and adequate laydown and maintenance areas have been provided. The MHD building, as part of its laydown area, will include within it a space where the magnetic field is above 200 G. This space will be considered an unsafe work area.

5.0 BUILDINGS AND STRUCTURES

All buildings and structures will be designed to resist zone 3 seismic forces as specified in the Uniform Building Code. Materials of construction will be chosen to implement conservation of energy. All buildings will be properly ventilated, adequately heated, and certain areas will be airconditioned. For facility heating, an outdoor design temperature of -24°F dB will be used. For summer ventilation and airconditioning, an outdoor design dry bulb temperature of 86°F (18% RH) will be used for critical areas, and 83°F (18% RH) will be used for noncritical areas. The facility will be designed for an outdoor ambient temperature range of 95°F dB (15% RH) to minus 30°F dB.

5.1 FOUNDATIONS

All major equipment and structural loads will be supported by piles of 60 ton capacity at minimum spacing of 3 ft - 6 in. or spread footings at maximum allowable net bearing pressure of 1.5 tons/sq ft. The hypothetical site is in a valley containing alluvium to depths of 500 ft or more, underlain by bedrock of moderate relief. The alluvium is heterogeneous and highly permeable, varying from silty clay to boulders and conglomerates.

It has been assumed, in the absence of detailed subsurface information, that piles 100 ft long will be required to develop 60 ton capacity. It is possible that the reported boulders will prevent the driving of piles to the required depth. In that event, deep spread footings or mat foundations might be required in lieu of piles.

Exterior footings and grade beams will be founded a minimum of 6 ft below plant grade to preclude frost heave.

The foundation pit of the HTAH and combustor slag system, 140 ft by 110 ft in plan and 30 ft deep, is considered as a high contingency item at this stage of project development. The possibility of highly pervious soil and a high water table is assumed, until detailed site information is available. These assumed conditions dictate special construction measures and design provisions that are discussed below. The pit design will provide for membrane

water proofing, mass sufficient to overcome buoyancy with the water table assumed at 10 ft below plant grade, and heavy, reinforced concrete pit walls capable of withstanding the high lateral pressures of the saturated surrounding earth.

5.2 STRUCTURES

5.2.1 Administration and Office Building

The administration and office building will be a 130 ft by 60 ft, three storied steel frame building with insulated metal siding and a built up roof. This building will provide space for plant supervisory personnel including the director of engineering, support engineering, scientific and research staff, purchasing, and accounting personnel. The building will include a cafeteria, locker rooms, lavatories and showers, conference hall, and spaces with sleeping accommodations. The materials of construction will be chosen with conservation of energy in mind. The necessary building heating, ventilating and airconditioning will be included. A covered walkway at the second floor will connect to the control building. The parking space provided in front of this building will facilitate easy access and necessary convenience.

5.2.2 Maintenance Building

The maintenance building will be located east of the administration and office building, as shown on the Plot Plan, Figure 4-1. The building will be 130 ft long, 90 ft wide, and 60 ft high. Direct road access will be provided at the north side of the building. Railroad access will be provided through the Air Preheater 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 include a 45 ft span bridge crane (as described in Paragraph 5.3), and heating and ventilation.

5.2.3 Air Preheater Building

The air preheater building will be located south of the gasifier building adjoining the MHD and maintenance buildings. It will be a 260 ft long, 110 ft wide and 150 ft high. This building will house the four high temperature air heaters, low temperature heat recovery equipment, the coal crusher and

miscellaneous support equipment. The high temperature air heaters will be in a pit 30 ft deep. The rest of the building floor is at grade elevation. The building will have a steel frame covered with metal siding and a built up roof.

Intermediate platforms will be provided at different levels to facilitate maintenance and operation of equipment. A bridge crane (as described in Section 5.3) spanning the width of the building will be provided to service the high temperature air heaters and other equipment that is housed in the building. Adequate ventilation will be provided in the building. The railroad spur passing through the building will facilitate installation and maintenance of equipment.

5.2.4 MHD Building

The MHD building will be located in the center of the plant island surrounded by the maintenance building, air preheater building, inversion building, etc. It will be a 145 ft long, 125 ft wide, and 104 ft high, steel frame building covered with insulated metal siding and a built up roof. A 140 ft span bridge crane located below the roof (as described in Section 5.3) will facilitate maintenance and erection of equipment. The railroad track inside the building will facilitate transportation of different equipment that is to be tested and also ease of maintenance of equipment in an outside facility when required. The building will be provided with adequate heating and proper ventilation.

5.2.5 Coal and Seed Feed Building

A 110 ft by 40 ft, steel frame coal and seed feed building will be located east of the MHD building. The steel structure will support equipment at different levels. Platforms will be provided at various locations to facilitate operation of the system and ease of maintenance. The building will be covered with insulated metal siding and a built up roof. Adequate heating and proper ventilation will be provided.

5.2.6 Cryogenic Systems Building

A 50 ft by 40 ft, steel frame two storied Cryogenic System building will be located adjacent to the MHD and coal and seed feed buildings. The building will be covered with insulated metal siding and a built up roof and will be provided with adequate heat and ventilation.

5.2.7 Control Building

The control building will be located adjacent to the MHD and steam turbine-generator buildings. It will be a five level steel frame building, 65 ft by 40 ft in plan. The control room will be located at the operating floor level and 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 will be at the mezzanine level. One level above the control room will be the plant laboratory. The top floor of the control building will be office space for plant operating personnel and test engineers.

Within the control building stairwells will run from the ground floor to the fifth floor. An enclosed walkway will connect the administration building with the control building.

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

5.2.8 Steam Turbine-Generator Building

The 65 ft wide by 100 ft long, steel frame steam turbine-generator building will be located adjoining the control building. The building will house the steam turbine-generator unit, condenser, air compressor and the auxiliaries for these units.

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

A bridge crane (as described in Section 5.3) located under the roof of the building, runs along the length of the building.

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

Adequate entrance and egress will be provided through service and man doors located on the west and south sides of the building.

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

5.2.9 Steam Generator Building

A 50 ft by 140 ft steel frame building will be provided to house the boiler. The building will be covered with metal siding and a roof. An elevator located in the northwest corner of the building will service all elevations in the steam generator building.

5.2.10 Gasifier Building

A 30 ft by 95 ft steel frame building will be provided to support and house gasifiers and related equipment. The building will be located north of the Air Preheater building. Platforms will be provided at various levels for facilitating proper maintenance and operation of equipment. The building will be covered with metal siding and a roof.

5.2.11 Water Treatment Building

A 50 ft by 50 ft, one storied, steel frame water treatment building with insulated aluminum siding, containing an air conditioned water treatment laboratory, demineralizing and chemical facilities, toilet and space for miscellaneous storage will be provided. This building, which also houses the clarifier and chemical storage tanks, will be located south of the plant island and north of the cooling tower.

5.2.12 Coal Handling Structures

Located on the coal conveying railroad track will be a steel frame coal car thaw shed 300 ft long. The heating coils housed in this aluminum sided shed will thaw any frost or ice that is present in the delivered coal. East of the thaw shed will be a steel receiving hopper. The hopper will be located in a reinforced concrete pit which is covered with a steel frame structure with aluminum siding. After being dumped, the coal will be conveyed to a telescopic type stacker chute. A steel hopper in a reinforced concrete pit will reclaim the coal to a conveyor which then delivers the coal to the crusher silo that is located in the east end of the HTAH building.

5.3 CRANES AND HOISTS

Cranes and hoists will be provided in the test facility at different locations to facilitate ease of installation, testing, operating and maintenance of equipment. These are described in the following paragraphs.

5.3.1 Air Preheater Building Crane

A 110 ft span 50 ton capacity (50 ton main hook and 10 ton auxiliary hook) bridge crane with total hook travel of ~ 160 ft, will be located below the roof level.

5.3.2 MHD Building Crane

A 140 ft span, 150 ton capacity (150 ton main hook and 10 ton auxiliary hook) bridge crane with total hook travel of ~ 140 ft will be located below the roof level. It will provide for the handling of the MHD generator, magnet, slag system, combustor and diffuser components.

5.3.3 Maintenance Building Crane

A 45 ft span, 150 ton capacity (150 ton main hook and 10 ton auxiliary hook) bridge crane with total hook travel of ~ 35 ft will be located in the maintenance building. The crane will extend into the Air Preheater building and will conveniently handle any equipment components that are to be serviced within the facility.

5.3.4 Miscellaneous Hoists and Trolleys

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

5.4 CHIMNEY

An 8 ft diameter, 250 ft high, steel stack will be located east of the steam generator building as shown on the Plot Plan, Figure 4-1. The design features of the stack will include two free standing steel shells, an outer load bearing structural member and an inner flue gas liner. Each shell will be a solid unitary welded member. There will be no sections, joints or flanges. A combination of fiberglass insulation and dead air will fill the annular space between the shell walls. The shells will be independent of one another with no direct contact between the shells walls. This type of stack will provide overall economy as the costs of foundation and installation will be considerably lower than other stack installations using different types of material and construction.

6.0 SITE AND SITE DEVELOPMENT

6.1 GENERAL SITE DESCRIPTION AND DEVELOPMENT

The site is located in western Montana. The region is characterized by mountain ranges (elevation 8,000-10,000 ft ASL) separated by relatively wide (5-40 mi) flat valleys. The relief from valley to peak varies from 2,000-4,000 ft. The foothills, located between the valleys and mountains, are widely dissected by streams and consequently have strong local relief. The streams, mostly intermittent, leave the foothills and cut into the valley floors causing streamside relief of 5-50 ft. In contrast, streamless areas of the valley floors are quite flat and relatively large.

The valley in which the site is located is generally oriented north-south, relatively large and flat, and located ~10 mi east of the nearest large city. The valley stretches 50 mi southward and is 8-10 mi wide in most places. A small stream, which flows southward from a spot near the center of the valley, enters a creek that crosses the south end of the valley. Relatively flat areas of up to 500 acres are found in the southern half of the valley and it is in this vicinity that the site is located. The site for the proposed facility is ~2,800 ft long and 1,500 ft wide, or about 97 acres.

The site location contains a well developed transportation system, composed of two railroads, an airport, and federal and state highways. Access to the site will be provided by constructing an access road which connects to a major federal highway that is located adjacent to the site. Railroad access will be provided by constructing a spur line to a major railroad line, which crosses the eastern edge of the site valley within 5 mi of the site location. All plant shipments for both construction and operation, including fuel delivery, are assumed to be overland.

Power for construction will be available at the site from the local electric utility. Water for construction activities will be obtained by drilling wells into the aquifer at the site.

The site location has a continental climate. Cold winter temperatures are seasonably followed by substantially warmer summer temperatures. For example, in the nearest large city, the mean normal temperature for January is near 15°F , while in July, this temperature increases to about 62°F . Wintertime low temperatures often fall to -20°F or -40°F , while summertime highs often reach 80°F to 90°F . Total precipitation is low, averaging about 20" per year. June is normally the wettest month, receiving 2.5" of precipitation. Water evaporation from Class A pans is estimated to be 35" per year, with 80% of this evaporation occurring between May and October. Average relative humidity varies from summer daytime lows of 25-50% to year round nighttime highs of 60-70%. Severe weather in the region includes summer thunderstorms (sometimes with damaging hail), strong winds, rare tornadoes, and sub-zero temperatures.

The meteorological investigations of the area have been at the regional levels and are predominantly theoretical. In the general area of the hypothetical site, the effects of local topography may contribute to air pollution problems. The mountain terrain surrounding the site and its valley are known to cause air flow channelization and inversion effects. Early morning inversions commonly occur in the valleys of western Montana during all months. However, they are more pronounced in fall and winter and have a longer duration.

In the vicinity of the hypothetical site, it has been found that calm wind periods account for nearly one third of the observation during the morning and early afternoon, and for one fourth of all observations. The remainder of the time, the wind blows from all sectors with a similar frequency of occurrence. Average wind speeds are ~ 20 mi/hr during unstable conditions and 4 mi/hr during stable conditions. On an annual basis, wind blows generally in the southeast direction.

The design meteorological history for the ETF site will be the historical data collected by the weather station at Cut Bank, Montana, as recorded in the "Air Force Manual 88-8 Chapter 6, Engineering Weather Data" and as listed in Table 6-1. Although Cut Bank is located 180 mi north of Butte, its elevation is 3,751 ft ASL, lower than the ETF design elevation of 5,000 ft ASL. The differences in latitude and elevation are deemed offsetting and, therefore, the data can be considered typical for the ETF site.

TABLE 6-1
WEATHER DATA

<u>Dry Bulb Range °F</u>	<u>Hrs/Year</u>	<u>Mean Wet Bulb- °F</u>
100-104	1	64
95-99	3	63
90-94	17	61
85-89	68	60
80-84	147	57
75-79	224	55
70-74	312	53
65-69	422	50
60-64	552	48
55-59	659	46
50-54	820	43
45-49	828	40
40-44	829	37
35-39	852	34
30-34	802	29
25-29	603	25
20-24	436	21
15-19	282	16
10-14	212	11
5-9	173	7
0-4	140	2
-5 to -1	133	-3
-10 to -6	103	-8
-15 to -11	71	-13
-20 to -16	36	-18
-25 to -21	22	-23
-30 to -26	11	-27
-35 to -31	1	-33

The data will be used for performance design of evaporative type cooling tower.

The valley of the hypothetical site contains fill to depths of 500 ft or more. The fill rests on an irregular bedrock of moderate relief. This alluvium is a poorly sorted mixture, ranging from fine silty clay to boulders and conglomerates. The alluvial fill at the base is highly permeable; however, it presents no serious problems either for site preparation by grading or for construction of facilities.

A chain-link type fence, topped with three strands of barbed wire, will be erected around the plant perimeter and grounded in certain areas. Selected areas will be seeded with grass and additional landscaping will be provided at the administration building. Exterior surfaces of the dikes for different water holding basins and solid-waste storage area will be seeded with grass to prevent erosion and provide an aesthetically pleasing atmosphere.

6.2 ROADS AND PARKING

The main plant entrance road will enter on the west side of the site, parallel to the railroad access line to the site. The road will then subdivide, with one branch extending to the parking lot and the other branch connecting to the plant island loop road. The plant island loop road will be extended to provide access to the cooling tower, clean water holding basin, storm water and wastewater holding basin, settling basin, solid waste storage area, thaw sheds, and coal dumping hopper. The plant island loop road will branch off at a number of locations in order to provide full access to the switch yard, administration building, maintenance building, warehouse, water treatment building, waste handling area, coal preparation area, and seed regeneration plant. Provision will be made for parking one hundred cars in the area adjoining the administration building. All roadways and parking areas will be constructed out of asphalt on a 6" base material.

6.3 RAILROADS

Railroad access to the plant will be provided by constructing a spur line to the major railroad line, which is ~ 5 mi west of the site boundary. A spur line will be constructed off the main access track, ~ 150 ft from the entrance to the site. This spur line will subdivide into two branches. One

branch will extend through the Air Preheater building and the MHD building. During construction, this track will be utilized to transport construction materials and heavy equipment that is located in the Gasifier building, Air Preheater building, MHD building, Turbine building, Inversion building, and Steam Generator building. Overhead cranes will be provided in the Air Preheater building and MHD building to allow direct access to the railroad cars and to facilitate erection of equipment in these areas. Once the test facility is in operation, this track can be utilized to haul different components that are to be tested. Further, this line will provide flexibility in transporting equipment and equipment components to the Maintenance building or to any other outside maintenance facility that is required. When the test facility is in operation, the second branch will serve the oil loading and transfer station, and the seed regeneration plant. During construction, this branch could be utilized to transport construction materials and equipment in the seed regeneration plant, waste handling area, etc.

The main access track will continue in an east-west direction parallel to the boundary of the site, through the thaw sheds, and over the bottom dump unloader. The spur line, north of the main access track, will provide flexibility for train movement when the line west of the thaw sheds is occupied by cars awaiting unloading. Details of coal delivery are included in Section 2.14.1, Coal Receiving, Storage and Reclaiming.

In addition to the site land requirements, an additional 91 acres are required for the assumed 5 mi of access track that connects to the main line. A 150 ft wide right-of-way is assumed for this track.

6.4 BASINS AND DRAINAGE

Surface runoff from the plant island area, coal storage area, and solid waste storage area will be collected and emptied into the storm water and wastewater holding basin. In the plant island, catch basins and storm sewers will be located as required with ultimate discharge into the storm water and wastewater holding basin. Inside the plant island buildings, water that is collected from the equipment and floor drains, will be first treated in oil separators and then pumped from a station pump to the storm water and wastewater holding basin. Surface runoff from the coal storage area and solid waste storage area will be collected through a system of open ditches and transferred to the storm water and wastewater holding basin.

Where feasible, the surface runoff from the areas other than those mentioned above will be collected through a system of catch basins and storm water piping and transferred to the clean water holding basin.

All the basin dikes will be constructed from the alluvial fill at the site. All basins will be lined with Hypalon or any other suitable material. Exterior surfaces of the dikes will be seeded to prevent erosion and provide a pleasing atmosphere. On top of the dikes around basins, a chain link fence, 4 ft high, will be provided to safeguard animals and human beings against accidentally falling into the basins, as a result of the slippery basin liners.

The storm water and wastewater holding basin will be sized to accommodate scrubber wash water and storm water.

6.5 WASTE DISPOSAL AREAS

The solid waste generated in this facility will be collected, managed, and stored in an area located near the east boundary of the plant site. Details of this system are described in Section 2.10.3.

The area designated will be 11.4 acres, which includes low level dikes around the area. The area will be lined with low cost lining material to prevent leechate from the area entering the aquifer.

Sewage disposal facilities will consist of a packaged primary and secondary treatment system with effluent chlorination.

6.6 WATER SUPPLY

Clean surface runoff from the area will be collected in the clean water holding basin. Contaminated storm water and other wastewater, stored in the storm water and wastewater holding basin, will be transferred to the clean water holding basin after adequate chemical treatment and sedimentation. The clean water holding basin will be a lined basin surrounded and protected by earthen dikes and will be the primary water supply source. Any additional water that is required will be supplied by a system of wells driven into the aquifer in the area.

Water for the cooling tower makeup will be supplied from the clean water holding basin. The evaporative mechanical draft cooling towers will be situated in an area adjoining the clean water holding basin.

Service water, including sanitary and potable water, will be supplied by pumps located at well heads. All potable and sanitary water will be chlorinated.

APPENDIX A
EQUIPMENT LIST

The following is a list of the major pieces of plant equipment. The numbering system used corresponds to the account numbers in Table 1-23, ETF Cost Estimate.

MAJOR-EQUIPMENT LIST

312. BOILER PLANT

	<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
312.1	<u>Coal Handling</u>			
312.11	<u>Unloading and Yard Storage</u>			
	Receiving Hopper	1	200 Tons	Receive and handle 6" nominal size coal
	Reciprocating Feeders	2	1250 TPH	
	Belt Conveyor	1	1250	Receiving hopper to live storage
	Belt Scale	2	1500 TPH	
	Metal Detector	1		
312.12	<u>Reclaim and Delivery</u>			
	Reclaim Belt Conveyor	1	285 TPH	
	Crusher Silo	1	660 Tons 65' high, 28' diam. w/sloping bottom	Storage for 10 hours combustor and 15 hours gasifier coal supplies
	Vibrating Feeder	1	300	Above Crusher

MAJOR-EQUIPMENT LIST

(contd)

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Crackers	2	285 TPH	Below Reclaim Hopper
Apron Feeders	2	285 TPH	Below Crackers
Crusher	1	300 TPH	Rolling Ring Type
Bucket Elevator	2	180 TPH	Combustor Coal
Bucket Elevator	1	120 TPH	Gasifier Coal
Belt Conveyor	1	180 TPH	Combustor Coal
Belt Conveyor	1	120 TPH	Gasifier Coal
Pulverizer Storage Silo	1	360 Tons, 60' high, 20' diam, w/sloping bottom	10 hours coal storage for gasifier
Reclaim Hopper	2	200 Tons	
Dust Control System			
Instruments and Controls		Local pressure, temperature monitoring instruments. Weight and flow measuring and transmitting instruments.	
312.2 <u>Slag and Ash Handling</u>			
Eductors	1	10 TPH	Mill rejects
Eductors	2	15 TPH	Combustor and boiler slag
Feeder Valves	18	2 TPH	Economizer Hoppers
Water Cooled Screw Conveyors	2	1.75 TPH	
Gasifier Ash Storage Silo	1	2760 ft ³ , 30' high, 14' diam.	
Recovered Seed Silo	1	500 ft ³ , 15' hg. 5' diam.	From screw conveyors
Recovered Seed Silo	1	1400 ft ³ , 25' high, 10' diam.	All recovered seed
Mechanical Exhauster with Filter	2		Ash and seed removal from gasifiers, boiler and precipitator.

MAJOR-EQUIPMENT LIST
(contd)

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Primary and Secondary Collectors and Bag Filter	2		Seed and ash removal from vacuum collection system.
Dewatering Bins and Settling Tanks	2	9000 ft ³	
Ash Sluice Pumps	2		Both full size
Sump Pumps	2	10,000 GPM @ 25 ft. TDH	Bypass quench water collection
Bypass Supply Pumps	2	10,000 GPM @ 82 ft. TDH	Storm water holding basin suction
Bypass Supply Pumps	2	2,000 GPM @ 360 ft. TDH	Suction from bypass supply pumps
Radiant Boiler Slag Collection System	1	317 ft ³	
Instruments and Controls			Local pressure and temperature monitoring instruments. Weight and flow measuring and transmitting instruments.
312.4 <u>Steam Generator</u>			
312.41 Steam Generator	1	Balanced draft FW in at 218°F controlled circulation, 523,000 lb/Hr 1250 psig, 950°F, 31' wide x 138' deep x 110' high	
312.42 <u>Intermediate Temperature Air Heater</u>			
Intermediate Temperature Air Heater Section of Boiler		LTAH - Air I; 10 panels, 1-7/8" tube, 22.5" transverse spacing, 1-7/8" longitudinal spacing. LTAH - Air II; 8 panels 1-7/8" OD tube, 14.75" transverse spacing, 1-7/8" longitudinal spacing	

MAJOR-EQUIPMENT LIST

(contd)

	<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
312.43	<u>Instrumentation and Controls</u>		Control systems for furnace draft, steam temp., FW flow and combustion (warm-up) Instrumentation for steam/water and air/ gas temp., press. and flows. Environ- mental impact instru- mentation and corro- sion and metal temps. Instruments used are listed below.	

312.43 (contd)

<u>Flows</u>	<u>Instrument or Method</u>	<u>Indication/ Number⁽¹⁾</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Equivalent Range</u>
<u>Steam and Water</u>				
Feedwater	Differential Pressure Transducer	0/1/1	Feedwater Flow Nozzle	0-1500 gpm
Superheater Desuperheat Spray	Calculated	--	Heat Balance	----
Circulating Water	Differential Pressure Transducer	2/0/0	Downcomer Pitot Tubes	0-2.5 mpph
Waterwall Absorption Test Loops	Differential Pressure Transducer	0/0/2	Flow Nozzles; Slag Furnace and Seed Recovery Furnace Calorimeters	----
<u>Air and Gas</u>				
Total Flue Gas	Pitot Traverse	1/0/0	Duct to ESP	0-150,000 scfm
Air to MHD Combustor	Laser Spectrophotometer to Measure CO/CO ₂	1/0/1	Diffuser Exit	----
Total Air	Calculated	--	From Fuel Flow and Composition plus Oxygen Meas.	----
Burnout Air	Differential Pressure Transducer	0/1/1	Venturi Meter	0-75,000 pph
Burnout Air	Calculated	--	O ₂ Measurement of Gas at Economizer Outlet	----

(1) Indication of test measurement values is required at the following:
 # Local Ind/# Control Room Ind/# Data Acquisition Sys. Ind.

312.43 (contd)

<u>Temperatures</u>	<u>Instrument or Method</u>	<u>Indication/ Number⁽¹⁾</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Range (°F)</u>
Steam and Water	Calibrated CR-C Well Thermocouples	0/1/1	•Economizer Inlet	0- 500
		0/1/1	•Economizer Outlet	0- 500
		0/1/1	•Superheater Outlet	0-1500
		0/1/1	•Superheater Desuperheater Inlet	0-1500
		0/1/1	•Superheater Desuperheater Outlet	0-1500
		0/1/1	•Superheater Desuperheater Spray Water	0- 500
		0/1/1	•Transition Outlet	0-1000
		0/0/2	•Downcomers	0-1000
		0/0/60	•Furnace Calorimeters	0-1000
Metal	Calibrated Stainless Steel Sheathed CR-C Chordal TC's	0/0/200	•Furnace Waterwall Tubes - Slag Furnace; Vertical strips, 20 each x 4 walls; Horizontal strips, 10 each x 4 walls x 3 elevations.	0-1000
	C-A Button TC's	10/10/10 20/20/20	•LTAH Panels - 3rd Chamber •Superheater Sections - 2nd and 3rd Chambers	0-2000 0-2000
Air and Gas	CR-C Thermocouples	0/2/2	•LTAH Inlet (Air and Recycle Gas)	0-1000
		0/2/2	•LTAH Outlet (Air and Recycle Gas)	0-1500
		0/1/1	•Economizer Inlet (Gas)	0-1000
		0/2/2	•Ljungstrom Gas In and Out	0-1000
	Shielded Aspirated Water Cooled Probes with Appropriate TC's (e.g., Platinum/ Platinum 10% Rhodium)	14/0/0	•Slag Furnace Outlet, Finishing Superheater Outlet, LTHA Inlet/ Outlet, Intermediate SH Points	0-3000

(1) Indication of test measurement values is required at the following:
 # Local Ind/# Control Room Ind/# Data Acquisition Sys Ind

312.43 (contd)

<u>Flows</u>	<u>Instrument or Method</u>	<u>Indication/ Number⁽¹⁾</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Equivalent Range</u>
<u>Air and Gas (Cont'd.)</u>				
Coal Fan Gas Flow	Differential Pressure Transducer	0/1/1	Venturi Meter	0-60,000 acfm
Flue Gas Flow Distribution	Pitot Traverse	1/0/0	Sections in Steam Generator Convective Pass	----
<u>Solids</u>				
Slag to Ash Pit	Load Cell	0/1/1	Ash Bins	0-7,000 pph
Solids from Hoppers	Load Cell	0/3/3	Ash Bins	0-5,000 pph
Coal to Combustor	Calibration of Petrocarb ΔP	0/1/1	Primary Injector/Combustor ΔP	0-70,000 pph
Coal to Pulverizer Coal Bin	Techometer	0/1/1	Coal Feeder RPM	0-90,000 pph

(1) Indication of test measurement values is required at the following:
 # Local Ind/# Control Room Ind/# Data Acquisition Sys. Ind.

312.43 (contd)

<u>Temperatures</u>	<u>Instrument or Method</u>	<u>Indication/ Number (1)</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Range (°F)</u>
Air and Gas (Cont'd.)	Radiation Pyrometer	3/0/0	•Intermediate Points in Primary Radiant Furnace	0-4000
	CR-C Thermocouples	0/2/2 0/2/2	•Mill Inlet and Outlet •Baghouse Inlet and Outlet	0-1000 0 500
Refractory (Absorption)	Calibrated Stainless Steel Sheathed C-A Thermocouples	40/0/40	•Slag Furnace	0-2000
Refractory (Monitoring)	Calibrated Stainless Steel Sheathed Thermocouples	0/40/0	•Slag Furnace, Vertical Strips, 10 each	0-2000
Pulverized Coal	Calibrated Stainless Steel Sheathed Thermocouples	0/12/0	•Prepared Coal Storage Bin; Storage Injector; Primary Injector	0- 700

(1) Indication of test measurement values is required at the following:
 # Local Ind/# Control Room Ind/# Data Acquisition Sys Ind

312.43 (contd)

<u>Samples/Levels</u>	<u>Instrument or Method</u>	<u>Indication/ Number⁽¹⁾</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Equivalent Range</u>
<u>Flue Gas Constituents</u>				
Nitrogen Oxides-NO _x	Chemiluminescence Analyzer	2/2/2	•Economizer gas outlet and stack monitor.	
		3/0/3	•1st radiant furnace chamber at inlet, ½ elevation and at transition to 2nd radiant furnace chamber.	
Carbon Monoxide-CO	Infrared Analyzer	2/2/2	•Economizer gas outlet and stack.	
		1/1/1	•Gas leaving finishing superheater.	
		1/1/1	•Gas to LTAH.	
Total Hydrocarbons-THC	Flame Ionization Analyzer	2/2/2	•Economizer gas outlet and stack	
Oxygen-O ₂	Paramagnetic Analyzer	1/1/1	•Economizer gas outlet.	0-21%
	Paramagnetic Analyzer	1/1/1	•Coal System Cyclone Outlet	
Sulfur Dioxide-SO ₂	Wet Chemistry	2/0/0	•Economizer Gas outlet and stack.	
		1/0/0	•Flue gas comp. inlet.	
Carbon Dioxide-CO ₂	Calculated		•Economizer gas outlet and stack.	
Particulates	ASME Dust Collector	2/0/0	•Economizer gas outlet and stack.	
		0/1/0	•ESP outlet.	

(1) Indication of test measurement values is required at the following:

Local Ind/# Control Room Ind/# Data Acquisition Sys Ind

312.43 (contd)

<u>Samples/Levels</u>	<u>Instrument or Method</u>	<u>Indication/ Number⁽¹⁾</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Equivalent Range</u>
Particulates (Cont'd.)	Opacity Meter	0/1/0	•Stack Gas	
Solids Levels	Load Cells	1/1/1	•Pulverized coal storage bin.	200,000#
		1/1/1	•Coal storage injector bin.	100,000#
		1/1/1	•Coal primary injector bin.	100,000#
Moisture Content	Dewpoint Hygrometer and	1/0/0	•Gas to mill.	
Slag Deposits	Visual Observation	1/0/0	•Petrocarb gas inlet.	
		1/0/0	•Slag furnace.	
Water Level	Gage Glass	1/2/0	•Drum	
Coal Samples	Grab Sample	1/0/0	•Grav. coal feeder.	
	Cyclone Sampler	1/0/0	•Mill outlet.	
	Grab Sample	1/0/0	•Prepared coal bin.	

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(1) Indication of test measurement values is required at the following:
 # Local Ind/# Control Room Ind/# Data Acquisition Sys Ind

312.43 (contd)

<u>Measurement</u>	<u>Instrument or Method</u>	<u>Indication</u>	<u>Location</u>	<u>Equivalent Range</u>
<u>Temperature</u>				
Gas	C-CR T.C.	0/2/2	Mill Outlet; Inlet	0-1000 F
	C-CR T.C.	0/2/2	Baghouse Inlet; Outlet	0-500 F
Coal	C-CR T.C.	0/16/0	4 each in Pulverized Coal Storage Bin and Petrocarb Injectors	0-1000
<u>Flow</u>				
Coal	Petrocarb	0/1/1	Petrocarb ejectors	0-80,000 lbm/hr
	Gravimetric Feeder	0/1/1	Gravimetric Feeder	0-80,000 lbm/hr
Gas	Differential Pressure Transducer	0/1/1	Coal Fan Inlet	0-60,000 acfm
<u>Level</u>				
Coal	Load Cell	0/1/1	Pulverized Coal Storage Bin	0-200,000 lbm
	Load Cell	0/2/2	Petrocarb Injectors	0-100,000 lbm
<u>Pressure</u>				
Gas	Pressure Transducer	0/2/2	Petrocarb Injectors	0-200 psig
Air	Pressure Transducer	0/1/1	Petrocarb Ejectors	
Oxygen	O ₂ Analyzer	0/1/1	Coal Fan	0-20%
Power	Ammeter	0/1/0	Mill Motor	0-700 KVA

312.43 (contd)

<u>Measurement</u>	<u>Instrument or Method</u>	<u>Indication</u>	<u>Location</u>	<u>Equivalent Range</u>
<u>Temperature</u>				
Gas	C-CR T.C.	0/1/0	Ljungstrom Inlet	0-1000 F
	C-CR T.C.	0/1/1	Recycle Fan Outlet	0-1000 F
	C-CR T.C.	0/1/1	Ljunstrstrom Outlet to Stack	0-1000 F
Air	C-CR T.C.	0/1/1	F.D. Fan Outlet	0-1000 F
<u>Pressure</u>				
Air	Pressure Transducer	0/1/1	F.D. Fan Outlet	0-10 psig
Gas	Pressure Transducer	0/1/1	Recycle Fan Outlet	0-10 psig

<u>Pressures</u>	<u>Instrument or Method</u>	<u>Indication/ Number⁽¹⁾</u>	<u>Location of Measurement or Calculation Procedure</u>	<u>Range psig</u>
Steam and Water	Calibrated Bourdon	1/1/1	Economizer Inlet	0 - 2000
	Gauges and Strain	1/1/1	Economizer Outlet	0 - 2000
	Gauge Pressure	1/1/1	Drum	0 - 2000
	Transmitters	1/1/1	Superheater Outlet	0 - 2000
		1/1/1	Superheater Spray Water	0 - 2000
Air and Gas	Water Manometers and Pressure Transmitters	3/3/3	Furnace	-10" to 10" H ₂ O
		1/1/1	Economizer Inlet (Gas)	-20" to 0" H ₂ O
		1/1/1	Economizer Outlet (Gas)	-20" to 0" H ₂ O
		1/1/1	Precipitator Outlet	-20" to 0" H ₂ O
		2/2/2	HTAH Blower Outlet (Air and Recycle Gas)	0 - 10
		2/2/2	LTAH Inlet (Air and Recycle Gas)	0 - 10
		2/2/2	LTAH Outlet (Air and Recycle Gas)	0 - 10
	Magnehelics	4/4/4	Across Superheater Sections (Gas)	0" to 10" H ₂ O
		3/3/3	Across All Chambers	0" to 10" H ₂ O
	Strain Gauge Pressure Transmitters	0/1/1	Coal Storage Injector	0 - 200
		0/1/1	Coal Primary Injector	0 - 200
		0/1/1	Petrocarb Ejectors	0 - 200
		0/1/0	Flue Gas to Mill	-20" to 0" H ₂ O
		0/1/0	Flue Gas from Mill	-20" to 0" H ₂ O
		0/1/0	Flue Gas to Cyclone	-20" to 0" H ₂ O
		0/1/0	Flue Gas to Coal Fan	-30" to 0" H ₂ O
		0/1/0	Flue Gas from Coal Fan	0" to 10" H ₂ O
		0/1/0	Flue Gas from Baghouse	0" to 10" H ₂ O

(1) Indication of test measurement values is required at the following:
 # Local Ind/# Control Room Ind/#Data Acquisition Sys Ind

312.43 (contd)

<u>Power Consumption</u>	<u>Instrument</u>	<u>Indication/ Number⁽¹⁾</u>	<u>Location</u>	<u>Equivalent Range</u>
Electric Motor	Wattmeter-Ammeter	0/1/1	Pulverizer	0 - 500 KW
		0/2/2	HTAH FD Fans	0-1500 KW
		0/2/2	HTAH GR Fans	0 - 500 KW
		0/1/1	Coal Processing Fan	0 - 300 KW
		0/1/1	CPS Flue Gas Compressor	0 - 800 KW
		0/2/2	Boiler Circ. Pumps	0 - 200 KW
		0/1/1	Electrostatic Precipitator	0 - 200 KW
		0/1/1	ID Fan	0 - 700 KW

(1) Indication of test measurement values is required at the following:
 # Local Ind/# Control Room Ind/# Data Acquisition Sys Ind

Systems Test/Instrumentation
Cross-Reference

312.43 (contd)

FLOWS

Steam and Water

Feedwater	S1, S8
Superheater Desuperheat Spray	S1
Circulating Water	S1, S8
Waterwall Absorption Test Loops	S2, S8

Air and Gas

Total Flue Gas	S1, S8
Air to MHD Combustor	S1, S8
Total Air	S1, S8
Burnout Air	S1, S8
Coal Fan Gas Flow	C2, S8
Flue Gas Flow Distribution	S7

Solids

Slag to Ash Pit	S4, S8
Solids from Hoppers	S4, S8
Coal to Combustor	S1, C3
Coal to Pulverizer Coal Bin	C2, S8

TEMPERATURES

Steam and Water	S1, S8, S2
Metal	S2
Air and Gas	S1, S8, S3, C2
Refractory (Absorption)	S2
Refractory (Monitoring)	S6
Pulverized Coal	

SAMPLES/LEVELS

Flue Gas Constituents

Nitrogen Oxides - NO _x	S1, S3
Carbon Monoxide - CO	S1, S3

Cross-Reference (Cont'd.)

312.43 (contd)

SAMPLES/LEVELS (Cont'd.)

Total Hydrocarbons - THC	S1, S3
Oxygen - O ₂	S1, S3, C2
Sulfur Dioxide - SO ₂	S1, S3, C4
Carbon Dioxide - CO ₂	S1
Particulates	S3, P1, C2, C3
Moisture Content	C2, C3
Slag Deposits	S1
Water Level	
Coal Samples	S1, C2

PRESSURES

Steam and Water	S1
Air and Gas	S1, C3, C2

Key

Steam Generator	S1 - Thermal Performance
	S2 - Waterwall Heat Absorption
	S3 - Emission Levels
	S4 - Bottom Solids Analysis
	S5 - Pressure Parts Corrosion
	S6 - Refractory Corrosion
	S7 - Convective Pass Heat Profiles
	S8 - Cell Heat and Material Balances
	S9 - Sootblower Evaluation and Sequencing
Coal Processing	C1 - Coal Sampling and Analysis
	C2 - Raymond System Component Performance
	C3 - Petrocarb System Component Performance
	C4 - Flue Gas Press. System Component Performance
HTAH Waste Heat Recovery	H1 - Fan Systems Performance
	H2 - HX Thermal Performance
Precipitator	P1 - Collection Efficiency

MAJOR EQUIPMENT LIST

(contd)

	<u>DESCRIPTION</u>	<u>REQUIRED NUMBER</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
312.44	<u>Auxiliaries</u>			
	Warm-Up Oil Guns	6	Firing #2 oil at 34 x 10 ⁶ Btu/hr ea.	
	ID Fan	1	116,500 scfm at -24" wg.	
	Air Nozzles	6	9,000 lb/hr. ea. at ΔP = 4" wg.	
	Sootblowers	10	Wall deslaggers	Seed Recov. Furn.
	All Blowers:	7	Full retract/20 ft. travel	
	Automatic manual override sequen- tial air blowing,	12	Wall deslaggers	Air Heater Chamber
	motor operated	7	Full retract/20 ft. travel	
	system suitable for 200 psig.	13	Full retract/20 ft travel	Superheaters
		8	Multiple nozzle rotary blowers spanning width.	Economizer
	Circulation Pumps	2	6,600 gpm, 25 psi head	
	Duct Burner	1	Firing #2 oil at 34 (10 ⁶) Btu/hr ea.	
312.5	<u>Effluent Control</u>			
312.51	<u>Precipitator and Breeching</u>			
	Electrostatic Precip- itator	1	Designed for 173, 000 SCFM @ 275 ^o F, 99.26% eff., 5.57 gr/acf inlet load- ing .04 gr/act out- let loading	

MAJOR-EQUIPMENT LIST

(contd)

	<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
312.52	<u>Chimney</u>			
	Chimney	1	250 Ft. high steel, 8' OD with inner gas liner.	
312.53	<u>Bypass System</u>			
	90° Elbow	2	90° water cool- ed elbow with water cooled turning vanes	
	Expanding, vertical quench duct	1	12 Ft. OD, 18 Ft. length	
	Venturi Scrubber and demister	1	Design conditions; 143 lb/sec. dry gas plus 183 lb/ sec quench water, gas temp. 193° F, Dust loading 3.01 gr/acft, 99.6% particu- late removal	
	Ductwork		36 Ft. of 10 Ft. diameter steel duct. 100 Ft. of 4 Ft. x 12' rectangular duct	
	ID Fan		160,000 ICFM	
312.6	<u>Auxiliary Boiler System</u>			
	Auxiliary Boilers	2	Rated 3450 pph saturated steam at 212° F. Oil fired, 14 long X 7' wide X 8' high	Package house heating boilers.

MAJOR-EQUIPMENT LIST
(contd)

	<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
	Auxiliary Boiler	1	Rated @ 145, 000 pph, 1250 psig/900° F steam outlet. Oil fired. 35' long x 20' wide x 13' high	Shop sub-assemblies. Primary use to supply steam for compressor drive turbine. FD fan included.
312.7	<u>Other Boiler Plant Systems</u>			
312.71	<u>Condensate and Feedwater Systems</u>			
	Startup hogging ejector	1	150 pph air equiv- alent capacity with 1950 pph steam @ 200 psig	
	Polish Demineral- izers	3	50% capacity high rate, mixed bed type with external re- generation 4'6" diameter.	
	Deaerator	1	Vertical spray type, Design operating 10 psig, Max. press. 50 psig.	
	Condensate Pumps	2	Vertical canned type 575 GPM @ 290 Ft. TDH	
	Boiler Feed Pump	1	Horizontally split, multi- stage, 1230 GPM @ 3730 Ft. TDH	

MAJOR-EQUIPMENT LIST
(contd)

	<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
312.72	<u>Water Treatment System</u>			
	Cold Process Softner	1	10 Ft. diam. x 16 Ft. high	Pretreatment equipment for demineralizer.
	Gravity Filters	2	4Ft. diam. X 12 Ft. high	Pretreatment equipment for demineralizer.
	Clearwell	1	4 Ft. diam. X 12 Ft. high	Pretreatment equipment for demineralizer.
	Transfer Pumps	10	30 GPM	Pretreatment equipment for demineralizer.
	Demineralizer Train			
	Activated Carbon Purifier	1	4 Ft. diam. X 6 Ft. High	
	Straight Primary Cation Exchanger	1	2 Ft. 6 in. diam. X 7 Ft. high	
	Chemical Feed Equip- ment			
	Morpholine Feed tank and meter- ing pump system	1		Skid mounted, Condensate Treatment,
	Hydrazine Feed tank and meter- ing pump system	1		Skid mounted, Condensate Treatment
	Emergency Phosphate Feed Tank and Metering Pump System	1		Boiler drum water treatment
	Acid Feed Tank and Metering Pumps	1		Circulating water system treatment
	Evaporator	1	2000 lb/day	C.W. system chlorination
312.73	<u>Water Supply System</u>			
	Well Water Pumps	2	150 GPM	
	Hydropneumatic Tank	1	250 ft ³	Well water tank & control.
	Transfer Pumps	4	200 GPM	Storm water to clean Water basin

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Feed Tank and Metering Pump	1		To control pH of flow to clean water basin.

MHD-ETF MAJOR EQUIPMENT LIST

314. Steam Turbine Generator and Auxiliaries

314.1 Steam Turbine and Auxiliaries

Steam Turbine	1	55 MW, 1250 psig/ 950° throttle conditions, design flow 427,532 pph.	Multi-stage, single flow straight condensing, with one uncontrolled extraction
Generator	1	58,000 kVA	
Auxiliaries		Lube oil and steam seal systems, inlet stop valve, insulation and lagging, EHC speed governing system and instrumentation	

314.2 Condenser and Auxiliaries

Surface Condenser	1	Heat load 469,563,770 Btu/hr 8708 - 3/4" 19 BWG 90/10 CuNi Tubes, 48292 ft. ² surface area, TTD = 5.1° F	Two pass
Steam Jet Air	1	1575 pph steam @ 95 psig and 900 GPM cooling water. Air capacity 56.2 pph, water vapor capacity 123.6 pph	Two stage, twin element with inter and after condensers

MAJOR-EQUIPMENT LIST
(contd)

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
314.3 Circulating Water System			
314.31 Pumps, Valves, Piping & Struc.			
Circulating Water Pumps	2	19,000 GPM @ 62 ft. TDH	Vertical circulating type.
Cooling Water Pumps	2	1900 GPM @ 87 ft. TDH	Vertical circulating type.
314.32 Cooling Towers			
Cooling Tower	1	Heat loads 469, 563,770 Btu/Hr., 4 cell, 43, x 43' ea. cell, design S.B. = 59°F, Range = 26.6°F Approach = 18°F	Mechanical draft counter flow
314.5 <u>Other Turbine Plant and Mechanical Equipment</u>			
Condensate Storage Tank	1	60,000 Gal.	Epoxy-lined carbon steel
Service Air Compressors	2	1000 SCFM @ 125 psig ea.	
Instrument Air Compressors	2	150 SCFM @ 125 psig ea.	
Soot Blowing Air Compressors	1	3750 SCFM @ 200 psig	
Soot Blowing Air Compressor	1	6000 SCFM @ 200 psig	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
<u>315 Accessory Electric Equipment</u>			
<u>315.1 Station and Auxiliary Transformer</u>			
Station/Startup Transformer	1	12/16/20 MVA OA/FOA/FOA Oil-Filled Transformer 115kV to 4.16kV, WYE-WYE with HV Bushing CT's, Grounding Resistor, Control Cabinet and Protective and Indicating Devices.	
Unit Auxiliary Transformer	1	12/16/20 MVA OA/FOA/FOA Oil-filled Transformer, 13.8kV to 4.16kV, Delta-WYE with HV Bushing CT's Grounding Resistor Control Cabinet and Protective and Indicating Devices.	
<u>315.2 Miscellaneous Motors</u>			
		4160 Volt 3 phase, Motors, with Bearing Thermocouples, Six Stator Winding RTDs, Two Grounding Points, Oversized Conduit Boxes, Space Heaters, Bearings as Required for Service. Mounting, Speed, Enclosure and Service Factor to be Determined Later.	
SC Magnet Helium Compressor	1	350HP	
Air Preheater Compressor	1	500HP	
Circulating Water Pump	2	400HP	
Sootblowing Air Compressor	1	2500HP	
Hi-Temp Air Heater F.D. Fan	2	1750HP	
Hi-Temp Air Heater G.R. Fan	2	500HP	
Cooling Tower Fan	4	250HP	
Boiler Induced Draft Fan	1	1300HP	
Boiler Feed Pump	1	1750HP	
Coal Pulverizer	1	600HP	
Flue Gas Compressor	1	900HP	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
			480V 3 Phase, Motors Over 100HP, Fed From ACB's in Station Power Centers. Motors will have Oversized Conduit Boxes, Bearing Thermocouples and Apace Heaters. Mounting, Enclosures, Service Factor and Speed to be Determined By Driven Equipment and Location.
Service Air Compressor	2	200HP	
Boiler Circulating Pump	2	150HP	
Coal Fan	1	200HP	
Auxiliary Cooling Pump	1	125HP	
	LOT		480V 3 Phase Motors $\frac{1}{2}$ - 100HP, Fed From 480V Combination Starters in Station Motor Control Centers. Services Inculde Fans, Pumps, Cranes, Valves, Conveyors and Other.
	LOT		120V Single Phase Motors, Fractional HP for louvers, Valves, Exhaust Fans.
	LOT		125V DC Motors For Emergency Services, Fed Through D-C Starters Which are Supplied from the Main D-C Distribution Panel
<u>315.3 Switchgear and Motor Control Centers</u>			
Switchgear Assembly	2	5000V Metal Clad, Indoor, 3000 Main Bus, 350 MVA 3000 Incoming ACB, 12-1200A 250 MVA ACB's, 1 Cubicle for Instruments. Switchgear will Include 1 set of 1600A tie Bus Between Assemblies.	
Power Centers	3	Metal Clad 600V Swtichgear with 4000A Incoming ACB, 600A or 1600A Feeder ACB's, Throat Connection to Dry Type 2,500kVA 4.16kV to 480V Delta-WYE Transformer, with Grounding Resistor Power Center will Contain Instruments for Protection and Indication.	
480V Metal Clad Motor Control Center	7	Indoor, with 100A and 225A Frame Circuit Breakers, Combination Motor Starters-FVNR Sizes 1-4, FVR Sizes 1 & 2 and space For Future Expansion. Buses will be sized to fit Loads.	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
<u>315.4 Conduit, Tray, Cable and Busswork</u>			
Ladder Type Cable Tray	LOT	4 Inch & 6 Inch Deep, 6 to 24 Inches Wide, Aluminum. To be Utilized For 125V DC & 120V AC Control, 480V Power, 120/208V Power, 4 16kV Power and Lighting Cables. Tray includes elbows fittings, covers, cover clamps and accessory hardware	
Solid Type Cable Tray	LOT	4 Inch Deep, 6 to 24 Inches Wide, Aluminum. To be utilized for Signal Cables (0-10 MV, 4-20 ma), Thermocouple and Communications Cables. Tray to include covers (complete), elbows, fittings, clamps and accessory hardware.	
Conduit and Fittings	LOT	½ Inch - 1 Inch EMT (Lighting); ¾ Inch - 4 Inch Rigid Steel; ¾ Inch - 4 Inch Alum.; 1½ Inch - 4 Inch Fiber or Korduct	
Isolated Phase Bus	1 Set	Metal Clad, Self Cooled for Steam-Turbine-Generator Leads. Bus to be 2,500A, 15kV with Neutral Grounding Equipment, PT's and Support Structures. Bus will have a 1000A Tap to the Unit Aux. Transformer including supports, elbows, and connecting hardware	
Control Cable	LOT	Cu Conductors 600V Flame Resistant, Multi-Conductor, Color Coded Per IPCEA. Cable assemblies will be: 2/c-19/#25AWG Unshielded 3/c-19/#25AWG Unshielded 5/c-19/#25AWG Unshielded 7/c-19/#25AWG Unshielded 9/c-19/#25AWG Unshielded 12/c-19/#25AWG Unshielded 2/c - #14AWG, 7 Strand, Unshielded 5/c - #14AWG, 7 Strand, Unshielded 3/c - #14AWG, 7 Strand, Shielded 2/c - 19/#22AWG, Shielded 4/c - 19/#22AWG, Shielded 7/c - 19/#22AWG, Shielded	
Signal Cable	LOT	Cu Conductors 300V Flame Resistant, Multi-Conductor Color Coded Per IPCEA with Shield and Drain Wire. Cable assemblies will be: 2/c #16 AWG, 7 Strand 3/c #16 AWG, 7 Strand 2 Pair # 16 AWG, 7 Strand 4 Pair # 16 AWG, 7 Strand 8 Pair # 16 AWG, 7 Strand	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Thermocouple Extension Cable	LOT	300V, Single or Eight Pair, Color Coded Per ISA, Overall Flame resistant jacket, copper drain wire	
Lighting Wire	LOT	Flame Resistant, 300V, Single Conductor Solid No. 12 AWG and 10 AWG.	
5000V Power Cable	LOT	Stranded Cu Conductors, EPR Insulation, Shield, Flame Resistant Jacket, Single Conductors- Factory Triplexed. Conductors, Cross-Linked Polyethylene Insulation, Flame Resistant Jacket. Cable construc- tion to be:	
		1/c - 6 AWG 1/c - 10 AWG 3/c - 12 AWG 3/c - 10 AWG 3/c - 6 AWG 3-1/c 2 AWG Factory Triplexed 3-1/c 2/0 AWG Factory Triplexed 3-1/c 250 MCM Factory Triplexed 3-1/c 500 MCM Factory Triplexed	
Set of 5000V Cable Bus	2	3000A, Including Tray, Supports and Terminating Hardware, (From Station Startup XFMR to 4.16 kV SWGR and From Unit Aux. XFMR to 4.16kV SWGR)	
<u>315.5 Miscellaneous Electrical Equipment</u>			
Grounding Equipment	LOT	Including Ground Rods, Rod Extensions, Clamps, Thermoweld Molds, Thermoweld Cartridges, Soft Drawn Copper Ground Cable (Bare or Insulated Dependant on Conditions). Ground Pads, and Misc. Hardware.	
Lighting For Indoor Areas	LOT	Fixtures to be Mercury Vapor, Fluorescent or Incandescent Dependant on areas; illuminated and Environment. MV and Fluorescent Fixtures to include ballasts. Mounting brackets, lamps and switches to be included.	
Outdoor Lighting Equipment	LOT	Including Poles, Brackets, Fixtures, Ballasts, Foundations and Photoelectric Control.	
Uninterruptible Power Supply	1	Inverter System 125V to 120V 10 a-c including Transfer Switches to Bypass Transformer and Distribution Panel	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Lighting & Control Transformers	LOT	Dry type 9 kVA-7kVA.480V 3 Wire to 120/208V 4 Wire	
Lighting & Control Distribution Panels	LOT	Wall Mount, Main Lugs, Single, Double or Three Pole Circuit Breakers.	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
315.6 Integrated Control System			
Balance of Plant Analog and Digital Control Systems	1 Lot		Required to complete an integrated control system for plant Control
Control Room Control Panels	1 Lot		Complete with annunciators, indicators, recorders, control inserts, control switch indicating lites required. The control and monitor plant operation from the remote control room.
Hardware Cabinets	1 Lot		For Analog Control Systems and Digital Logic System to be located in the Electronics Room.
Primary Sensing Elements and Signal Generating Devices	1 Lot		Necessary to provide input signals to control systems for balance of plant.
Final Control Drive Devices	1 Lot		To control plant variables.
315.7 Data Aquisition System			
Central Processing Unit (Main Frame)	1 Lot		Complete with Software Programs
Input/Output Cabinets	1 Lot		Containing required terminations, multiplexers, analog to digital converters, signal conditioners, amplifiers and buffers.
Output Printers	4 Each		For periodic logs, digital trends, alarm printouts and post trip or incident reviews.
Analog Trend Recorders	1 Lot		

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Interconnecting Cables	1 Lot		Between major equipment components.
Operator's Console	1 Each		Mounted on a desk complete with all required pushbuttons, selector switch, indicating lights, address switches, reduced size CRT for operator messages and other items necessary for output devices.
Programmer's Console	1 Each		With input/output printer. Tape reader and punch and necessary other controls and devices to provide a suitable interface for the programmer.
Large Screen Display CRT	1 Each		To display alarms and opera- tional graphic displays.
Primary Sensing Elements and Signal Generating Devices	1 Lot		To provide input intelligence.

315.8 Emergency Power Systems

Emergency Diesel Generator	1	2500kVA, 4160V with Complete Air Start Package, Built in Fuel Tank, Battery, Battery Charger, Control Panel, Protective Instruments and Weatherproof Enclosure.
60 Cell Station Battery	1	800 AMP-Hour Lead-Calcium, Mounted on Racks with Portable Test Devices.
Battery Charger	1	480V to 125V D-C.

MAJOR-EQUIPMENT LIST

316. Miscellaneous Power Plant Equipment

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
316.1 Fuel Oil Handling System			
Fuel forwarding skid with two 100% capacity pumps	1	45 GPM ea.	Supply HTAH
Fuel forwarding skid with two 100% capacity pumps	1	60 GPM ea.	Supply Aux. boiler house htg. boiler and diesel.
316.2 Fire Protection System			
Motor Driven Fire pump	1	1000 GPM @ 75 psi	
Diesel Driven Fire Pump	1	1000 GPM @ 75 psi	

317. MHD Topping Cycle

317.1 Combustion Equipment

317.11 Coal Drying

<u>Coal Processing System</u>			
Bulk Material Valve	1	72,000 lbm/hr	S-E-CO 8" Valve
Gravimetric Coal Feeder	1	72,000 lbm/hr	S-E-CO
Mill	1	#863 RS Bowl Mill	500 HP
Cyclone Filter	1	Raymond #16 Cyclone Separator 72,000 lbm/hr coal, 133,000 lbm/hr gas	
Fan	1	N.Y.B. Series 60 #1500 - 133,000 lbm/hr gas, 24 inwg	
Baghouse	2	Ray Jet 9 MW-50 Dust Collectors 133,000 lbm/hr gas	
Airlock	1	16" Airlock 72,000 lbm/coal/hr	
Storage Bin	1	15; Diam, 20' High w/sloping bottom	2½ hrs fuel storage.

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
<u>317.11 Coal Drying (cont.)</u>			
Bin Activator	1	Vibrascrew 8' Bin Activator	
Feeder	1	Vibrascrew 12" Heavy Duty Feeder	
Scalping Screen	1	C-E Tyler Hummer Screen	
<u>317.12 Coal Injection</u>			
Petrocarb System	1	72,000 lbm/hr coal to combustor at 6 atm pressure.	Equipment from Petrocarb Company.
Flue Gas Press- izing System	1	3,000 scfm flue gas at 200 psig to Petrocarb System	Equipment from Ingersoll- Rand includes positive displacement reciprocating compressor with 900 HP motor gas scrubber, intercoolers, and aftercoolers.
<u>317.13 Combustor</u>			
Combustor	1	Design operating conditions; 6 atm; 15.87 lb/sec. Montana Rosebud Coal @ 5% H ₂ O, 126.1 lb/ sec air @ 3000°F. Heat Loss=16.8 MWt	Single stage water wall cooled with 4/1 turndown ratio
<u>317.14 Slag Collection System</u>			
Combustor Slag- Collection Equipment			
1st collection tank	1	230 ft ³	
2nd Collection tank	1	1140 ft ³	
Quench Tank	1	20 ft ³	
Heat Exchanger	1		

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.14 <u>Slag Collection System (cont.)</u>			
Pumps	2	300 GPM @ 50 ft. TDH	
Instruments and controls		Local pressure and temperature monitoring devices. Weight and flow measuring and transmitting instrument.	
317.2 MHD Generator			
317.21 Nozzle	1	Design Flow 516.5 (10 ³) lb/hr at 4570 ⁰ F	Subsonic nozzle designed for slagging operation. Fabricated from 3 sections ETP copper 4in. thick and drilled for cooling water.
317.22 Channel (3000 ⁰ F)	1	Design flow 516.5 (10 ³) lb/hr at 4570 ⁰ F, 5.4 atm. inlet stagnation pressure. Inlet Mach No.=.85. Power output = 45.6 MWe. Heat loss=15.5 MWt.	Slagging type, constant velocity channel.
317.23 Diffuser & Transition Sections	1	Design flow 516.5 (10 ³) lb/hr at 3677 ⁰ F 1.193 atm. inlet conditions. Pressure recovery factor is .46. Heat loss is 14.5 MWt.	Construction is of water cooled steel walls.
317.3 Magnet Subsystem		Super conducting 6 Tesla.	Active length 9m.
317.31 Structure	1		Trusses, tension plates and support legs

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.32 Winding Assembly			Two sealed containers. each holds super- conducting windings & insulation
317.33 Dewar			Vacuum tank, warm bore and seals
317.34 Refrigeration System			
Refrigerator/compressor	1	400 W of refrigera- tion	
Liquid Helium Storage Tank	1	5000 gallons	
Liquid Nitrogn Storage Tank	1	5000 gallons	
Gaseous Helium Storage Tank	1	5300 gallons	

MAJOR-EQUIPMENT LIST

317.4 Inversion System

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.41 ¹² Inverters			
DC Bridges	44+2 spares	3-phase, 6-pulse, three thyristors in series per leg, each 3000 volts peak inverse, for bridge rating of 1350 A dc continuous and 10% overload capability. Surge withstand capability 12 kilo amps. Assembled on trays for "slide-in" mounting into enclosed forced-air ventilated cubicle. Complete with heat sinks and ancillary components; voltage dividing circuits, damping circuits, zener diode and arrester protection, gate drive and pulse transformer supplied from bridge potential, connections to gate drive circuits at ground potential using fiber optics signal channels (or equivalent). Also with monitoring indicating lamps for each thyristor, and with bridge voltage and current transducers Normal bridge operating voltage 2500 volts dc. Insulation to withstand 25kV dc to ground continuously (clean indoor atmosphere). Bridges may be operated as individual inverter units; or in series for a total voltage of 25 kV dc Maximum.	
DC Smoothing Reactions	44+2 spares	Inductance 4 millihenry Rated 1350A dc continuous with average 10% ripple. Short time overload 3500A for 5 cycles of 60H power frequency. may be magnetic with air gap to limit saturation to dc currents of not more than 2 times rated. Insulated same as dc bridges. To be mounted in same forced-air ventilated cubicles.	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
DC By Pass Switches	44+2 spares	<p>Vacuum bottle type similar to HBDC converter bypass switches. To divert up to 3500A dc from dc bridge, or close into 3500A short circuit from MHD output, within 2 cycles of power frequency and carry this current for up to 15 cycles. To open in 3 cycles with up to 3500A until the inverter commutates current out of switch. Recovery voltage withstand on opening of 5000 volts dc.</p> <p>Insulated same as dc bridges and mounted in same forced-air ventilated cubicles.</p>	
DC Power Cubicles	44	<p>Indoor metal-clad with front and rear access; with air exit louvers back, sides and top; filtered blower air entrance from duct underneath cubicles.</p> <p>Each to contain 4 thyristor bridge assemblies, associated smoothing reactors and bypass switches and firing control gate drive unit for 4 bridges.</p> <p>AC connections to each bridge with exit from bottom rear into underground cable trench to outdoor converter transformers.</p> <p>DC busbar connections arranged to allow individual bridge operation, or connections to other cubicles and to MHD output leads via front bottom cable trench.</p> <p>Cable tray entrance at top for control and sensor secondary wiring.</p>	
DC Control Cubicles	6	<p>Indoor metal-clad with front and rear access. To contain all control circuitry on plug-in circuit boards for all modes of inverter operation (constant extinction angle control, current regulator control, automatic start-up and shut-down, etc.) to deliver firing signals to gate drive units in the dc Power Cubicles. Also to contain all protective relays for converter transformers, dc commutation failure, arc-through, overvoltage and overcurrent, etc.</p>	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
DC Control Cubicles (cont.)	6	<p>Top entrance for wiring to power cubicles in same room, and to dc master control board in remote main control room.</p> <p>One control cubicle to have front benchboard to contain monitoring iscillescope, and limited manual control to be specified later with permissive interlock from master control board.</p>	
DC Master Control Board	1	<p>In main control room. To contain switches pots etc. to allow manual setting of extinction angles, current references, commutation resistance, etc. for each of the 44 dc bridges individually or in predetermined common modes for series-parallel operation. Also switched point meters for ac and dc voltages, ac and dc currents, ac and dc power, and indicator of main tap-changer position. Automatic and manual start-up and shut-down. Alarms for all protection operations and air temperature of power cubicles. Open-Close control of ac breakers for converter transformers filters and capacitor banks.</p> <p>Optional simplified mimic board permitting visual display of connections of dc bridges for MHD load circuit arrangement in operation.</p>	
Convertor Transformers	11 as:	<p>6-10/12.5 MVA OA/FA 3 phase outdoor</p> <p>5-5.6/7 MVA OA/FA 3 phase outdoor</p>	<p>Primary 13.8kV, four secondaries each 1.60 kV, two connected ungrounded wye, two delta. Leakage reaction between primary and each secondary not to exceed 15%.</p> <p>Manually switched no-load taps on primary; as per Fig. 2-170</p> <p>Superimposed ac harmonics total 10% rms of fundamental.</p>

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Convertor Transformers (cont.)	11 as:	With bushing current transformers for differential protection and current monitoring.	Insulation compatible with 25 kV dc to ground continuous of bridges on secondary low-voltage side. BIL's later.
AC Harmonic Filters		Single tuned series R,L,C filters for 11th and 13th harmonic and hi-pass second order filter tuned to 20th harmonic and above. Each separately switched with fault protection.	Size of filters: 11th - 1.3 MVAR per phase at 60H _z , 1.4 MVAR with harmonic 13th - 1.3 MVAR per phase at 60H _z , 1.4 MVAR with harmonic Hi-Pass-2.0 MVAR per phase at 60H _z , 2.0 MVAR with harmonic Inductances, Air Core 11th-1.07 MilliHenry per phase 13th - 0.77 MilliHenry per phase Hi - Pass - 0.21 MilliHenry per phase Quality factors Q, not less than 35 corresponding to equivalent frequency deviation not greater than 2% Insulation for 13.8 kV, BIL later.
Static Capacitor Banks		Three 7 MVAR 3-phase each at 13.8 kV, separately switched, with fused units and bank overcurrent protection.	
Auxiliary supplies		One uninterruptible first grade supply consisting of controlled rectifier charger, 3-phase, 60H _z ; 125V heavy duty battery; output inverter, 120V, single-phase, 60H _z . Power capacity 20 kW (est.). For converter controls, dc sensors, fault recording. Battery capable of full load for about 5 minutes on loss of 3-phase supply.	Secondary dc power for relay panels, dc monitoring, etc. from station changers battery (dual source).

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
Auxiliary Supplies (cont.)			Cooling air supply for dc power cubicles, 40 kva (est.). Four blowers. On loss of main auxiliary supply, this cooling required for 15 minutes (est) from emergency generator.
317.42 Electric Consolidation Circuitry			
Diodes	64	80A, 500V	
Diodes	32	160A, 500V	
Diodes	16	320A, 500V	
Diodes	8	640A, 500V	
SCRS	4	1280A, 500V	
Commutation Caps	2	1uf, 500V	
Auto Transformers	32	80A, 20mH	
Auto Transformers	16	160A	
Auto Transformers	8	320A	
Auto Transformers	4	640 A	
Heat Smks			
Gating Circuitry			For 4 SCR
Cabinet and Isolation			
Instrumentation			

MAJOR-EQUIPMENT LIST
(contd)

	<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.5	<u>Oxidizer Preheat System</u>			
317.51	<u>Air Compressor and Drive</u>			
	Air Compressor	1	7566.7 ppm @ 71.2 psia 18270 BHP, 5564 RPM	Seventeen Stage Axial Flow with variable stator vane control.
	Mechanical Drive	1	18270 BHP, 5564 RPM, 2.7 in HgA back pressure, 1250 psig/950°F throttle condi- tions	Air Compressor Drive, multi-stage, condensing turbine
317.52	<u>Combustion Air and Gas Fans</u>			
	<u>HTAH Waste Heat Recovery System</u>			
	FD Fan	2	70,100 scfm at 5 psig	
	GR Fan	2	20,300 scfm at 5 psig	
317.53	<u>Low Temperature Air Heater</u> <u>Lungstrom Air Heater</u>	1	Duty = 23.3(10 ⁶) Btu/hr	Effectiveness = 58%
317.54	<u>High Temperature Air Heater</u>			
317.541	Vessels	4	Refractory lined Steel shells, 130 high x 19.25' diam. Matrix height 85' diam. 15'	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.542 Reheat Burner	4	Refractory Lined Steel shells, 70' high x 16.04'diam. Burners rated at 340 M Btu/Hr.	
317.544 Auxiliary Equipment Compressor			Pressurization/Depres- surization system.
Air Accumulator		Spherical, 21 ft. diameter, 3900 lb. air at 250 psi	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.6 Seed Subsystem			
317.61 Seed Regeneration Process			
Coke Storage Silo	1	25 ton capacity (1000 cu ft.)	200 hrs fuel storage
Coke Silo Airveyor	1	1000 lb/hr	
Coke Silo Airveyor Compressor Motor	1	5 HP	
Coke Feeder	1	Acrison Model 203B-105Z grav- imetric feeder, 50-500 lb/hr	
Coke Feeder Drive Motor	1	10-1 variable speed drive motor 1 HP	
Coke Feeder Hopper	1	50 cu. ft.	
Coke Bucket Elevator	1	500 lb/hr	
Bucket Elevator Drive Motor	1	5 HP	
Gasifier	1	60 in. dia. Wellman-Galusha, refractory lined, coke feed/ air blown gasifier 5 TPD	
Gasifier Airblower	1	5 HP	
Gas/Water Cooler	1	Gas/water 500 SCFM 1 x 10 ⁶ Btu/hr	
Compressor Booster	1	Ingersoll-Rand Type ESH 13 in. dia. cylinder, 5 in. stroke	
Compressor Booster Drive Motor	1	40 HP	
Compressor Second Stage	1	Ingersoll-Rand Type ESH 6 in. dia. cylinder, 7 in. stroke	Tandemly driven with third stage
Compressor Third Stage	1	Ingersoll-Rand Type ESH 4 in. dia. cylinder, 7 in. stroke	Tandemly driven with second stage

<u>ITEM</u>	<u>NO. REQ'D</u>	<u>DESCRIPTION</u>	<u>REMARKS</u>
Compressor Second & Third Stage Drive Motor	1	75 HP	
CO Pressure Tank	1	100 cu. ft./500 psia	
Scrubber	1	Ethanolamine scrubber, CO ₂ removal system 500 SCFM/500 psia	
Regenerator	1	Ethanolamine regenerator, CO ₂ removal system 500 SCFM/500 psia	
CO ₂ Scrubber Pump	1	20 GPM	
CO ₂ Scrubber Pump Motor	1	3 HP	
CO Reserve Storage Tanks	1	Aggregate volume 1000 cu. ft. 2000 psia	
CO Heat Exchanger	1	Gas/steam 500 SCFM .2 x 10 ⁶ Btu/hr	
Reactor	1	42 in. i.d. x 26 ft. long jacketed, multi-section continuous reactor, working vol. 170 cu. ft. co- current or countercurrent flow, sectional gas injection, multiple turbine mixers, 300 gal/500 psia/ 500 F	
Reactor Mixer Drive Motor	1	20 HP	
Lime Storage Silo	1	50 ton capacity (1500 cu. ft.)	200 hrs storage
Lime Silo Airveyor	1	1500 lb/hr	
Lime Silo Airveyor Compressor Motor	1	5 HP	
Lime Feeder	1	Acrison Model 203B-105Z grav- imetric feeder, 100-1000 lb/hr	
Lime Feeder Drive Motor	1	10-1 variable speed drive motor 1 HP	
Lime Feeder Hopper	1	10 cu. ft.	
Virgin K ₂ SO ₄ Silo	1	50 ton capacity (1500 cu. ft.)	

ITEM	NO. REQ'D	DESCRIPTION	REMARKS
Virgin K_2SO_4 Silo Airveyor	1	3000 lb/hr	
Virgin K_2SO_4 Silo Airveyor Compressor Motor	1	10 HP	
Recovered Seed Ballast Silo	1	5 ton capacity (300 cu. ft.)	20 hrs storage
Recovered Seed Ballast Silo Airveyor	1	3000 lb/hr	
Recovered Seed Ballast Silo Airveyor Compressor Motor	1	10 HP	
K_2SO_4 Feeder	1	Acrison Model 203B-105Z grav- imetric feeder 300-3000 lb/hr	
K_2SO_4 Feeder Drive Motor	1	10-1 variable speed drive motor 1 HP	
K_2SO_4 Feeder Hopper	1	30 cu. ft.	
Dissolving Tank	1	1000 gallons	
Dissolving Tank Mixer	1	1000 gallons	
Dissolving Tank Mixer Drive Motor	1	15 HP	
Reactor Slurry Feed Pump	1	Moyno Model 9P6 type SSQ, 316 stainless steel positive pressure slurry pump, .5-15 GPM/500 psia	
Reactor Slurry Feed Drive Motor	1	27-1 variable speed drive motor 15 HP	
Reactor Feed Heat Exchanger	1	Liquid/steam 15 GPM 2×10^6 Btu/hr	
Filter Slurry Feed Pump	1	Moyno Model 9P6 type SSQ, 316 stainless steel positive pressure slurry pump .5-15 GPM/500 psia	
Filter Slurry Feed Drive Motor	1	27-1 variable speed drive motor 15 HP	
Flash Tanks	2	50 cu. ft.	

ITEM	NO. REQ'D	DESCRIPTION	REMARKS
Rotary Pressure Filter	1	Bird-Young 2 ft. diam. x 3 ft. face, pressurized rotary drum filter, 1500 lb/hr	
Rotary Pressure Filter Drive Motor	1	35 HP	
Rotary Pressure Filter Compressor	1	500 CFM/15 lb differential	
Rotary Pressure Filter Compressor Drive Motor	1	50 HP	
Filter Rotary Valve	1	1500 lb/hr	
Filter Rotary Valve Motor	1	1 HP	
Wash Water Feed Pump	1	20 GPM	
Wash Water Feed Pump Drive Motor	1	10-1 variable speed drive motor 15 HP	
Wash Water Heat Exchanger	1	Liquid/steam 1×10^6 Btu/hr	
Wash Water Removal Pump	1	20 GPM	
Wash Water Removal Pump Drive Motor	1	10-1 variable speed drive motor 15 HP	
Spray Drier Feed Pump	1	20 GPM	
Spray Drier Feed Pump Drive Motor	1	10-1 variable speed drive motor 15 HP	
Spray Drier	1	Swenson stainless steel unit 5 ft. 3 in. dia. x 42 ft. 22000 SCFM	
Cyclone	1	Swenson stainless steel unit 3 ft. 8 in. dia. x 36 ft. 22,000 SCFM	
Dust Collector	1	Swenson stainless steel unit 5 ft. dia. x 16 ft. 22,000 SCFM	
Spray Drier Exhaust Fan	1	Swenson, 150 CFM, 15 in. s.p.	

<u>ITEM</u>	<u>NO. REQ'D</u>	<u>DESCRIPTION</u>	<u>REMARKS</u>
Spray Drier Exhaust Fan Motor	1	75 HP	
Spray Drier Airveyor	1	3000 lb/hr	
Spray Drier Airveyor Compressor Motor	1	10 HP	
Flue Gas Reheater	1	Flue gas/steam 1 x 10 ⁶ Btu/hr	
Potassium Formate Ballast Silo	1	9 ton capacity (300 cu. ft.)	
Potassium Formate Ballast Silo Airveyor	1	3000 lb/hr	
Potassium Formate Ballast Silo Airveyor Compressor Motor	1	10 HP	
Potassium Formate Storage Silo	1	50 ton capacity (1500 cu. ft.)	
Potassium Formate Storage Silo Airveyor	1	3000 lb/hr	
Potassium Formate Storage Silo Airveyor Compressor Motor	1	10 HP	
Portable Pneumatic Rail Car Unloader	1	10 tons/hr	
Portable Pneumatic Rail Car Unloader Compressor Drive Motor	1	50 HP	

PRELIMINARY INSTRUMENT LIST
SEED REGENERATION PLANT

<u>ITEM</u>	<u>NUMBER REQ'D</u>	<u>APPLICATION</u>	<u>LOCATION</u>
TRC	1	Steam Flow Control of Reactor Slurry Feed (350°F - 450°F)	Heat Exchanger X-1
TRC	1	Steam Flow Control to Reactor (350°F - 450°F)	Reactor
TRC	1	Cooling Water Flow Control to Gasifier (1000°F - 1500°F)	Gasifier
TRC	1	Cooling Water Flow Control to Gas Cooler (100°F - 200°F)	Gas Cooler
TRC	1	Steam Flow Control to Heat Exchanger X-2 (350°F - 450°F)	Heat Exchanger X-2
TRC	1	Steam Flow Control to Flue Gas Reheater (200°F - 600°F)	Flue Gas Reheater
TRC	1	Cooling Water Flow Control to Dissolver (180°F - 240°F)	Dissolving Tank
TC	1	Steam Flow Control to CO ₂ Removal System (240°F - 340°F)	CO ₂ Removal System
LC	1	K ₂ SO ₄ Level Control of Dissolver Feed Hopper	K ₂ SO ₄ Feed Hopper
LC	1	Lime Level Control of Dissolver Feed Hopper	Lime Feed Hopper
LC	1	Coke Level Control of Gasifier Feed Hopper	Coke Feed Hopper
LC	1	Liquid Level Control of Reactor	Reactor
FRC	1	Liquid Flow Control of Reactor Slurry Feed and Dissolver Recycle	Dissolving Tank Discharge
FRC	1	Liquid Flow Control of Dissolver Water Feed	Dissolver
FRC	1	Solid Flow Control of Coke Feed to Gasifier	Gasifier
FRC	1	Solid Flow Control of Lime Feed to Dissolver	Dissolver

PRELIMINARY INSTRUMENT LIST
(contd)

<u>ITEM</u>	<u>NUMBER REQ'D</u>	<u>APPLICATIONS</u>	<u>LOCATION</u>
PRC	1	Pressure Control of Reactor Off Gas to Bottoming Plant or Flare (250-550 psia)	Reactor
CRC	1	CO Analyzer and Flow Control of Gas Feed to Reactor (50-500 lb/hr CO)	Scrubber
PRV	1	Pressure Control of Reactor Gas Output (500-15 psia)	Reactor
PRV	1	Pressure Control of Filter Slurry Feed (500-210 psia)	Flash Tank 1
PRV	1	Pressure Control of Filter Wash Water Feed to Dissolver (250-15 psia)	Filter
PRV	1	Pressure Control of Spray Drier Feed and Dissolver Recycle Feed (250-15 psia)	Flash Tank 2

LEGEND:

LC	-	Level Controller
TRC	-	Temperature Recorder/Controller
TC	-	Temperature Controller
FRC	-	Flow Recorder/Controller
PRC	-	Pressure Recorder/Controller
PRV	-	Pressure Reducing Valve
CRC	-	Concentration Recorder/Controller

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.62 Seed Injection System			
Seed Feed System	1	11500 lb/hr	Includes injector storage and primary injector tank.
Gravimetric Feeder	1	10000 lb/hr	K ₂ SO ₄ feeder to mixing screw conveyor
Gravimetric Feeder	1	1800 lb/hr	KCO ₂ H and K ₂ CO ₃ feeder to mixing screw conveyor
Mixing Conveyor	1	13000 lb/hr	

MAJOR-EQUIPMENT LIST

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
317.7 Other MHD Topping Equipment			
317.71 O ₂ System			
Liquid Oxygen Storage Tanks	4	11,000 gallons	Stored at 100 to 150 psig.
Oxygen Vaporizers	6	Rated at 100,000 SCFH of oxygen each. 8600 pph steam required.	
317.72 Gasifier System			
Gasifiers	6	Wellman-Galusha process coal feed rate 448T/D, at 5% moisture, Air feed rate 100.4 (10 ³) pph. Product Gas HHV=139.8 Btu SCF at 630 to 680°F.	

MAJOR-EQUIPMENT LIST

318 Research Equipment

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
318.1 MHD Channel for 2500° F Air Preheat	1	Designed for 517,400. pph mass flow at inlet conditions of 4360° F, and a stagnation pressure of 48,8 psia. Channel output 35.5 MWe	Subsonic, constant velocity, slagging type channel.
318.2 Changel nozzle for 2500 F Air Preheat	1	Design Flow 517,400 pph mass flow at 4360° F.	Subsonic nozzle de- signed for slagging operation. Frabri- cated from 3 sections of ETP copper 4 in. thick and drilled for cooling water. milled grooves are provided for slag collection.
318.3 Research Equipment		Channel instrumentation not considered necessary for operation of a commercial plant. An example of which is the visual readout meters for channel electrode currents or voltages.	

MAJOR-EQUIPMENT LIST

319 Simulation Equipment

<u>DESCRIPTION</u>	<u>NUMBER REQ'D</u>	<u>SIZE AND/OR CAPACITY</u>	<u>NOTES</u>
319.1 DC Resistive Load Bank			
Load Banks	12	Resistance 4.42 ohms; 1 load bank consists max. dissipation of 10 resistor tubes 4 MW, Max. Current arranged hydraulically 950 amps; Voltage in parallel and elect- Drop 4200 V (above trically in series. values pre for ea Resistor tube is 18' load bank) long stainless steel tube of ½" OD and .01 wall. Flow is 18.4 GPM per tube.	

350. TRANSMISSION PLANT

MHD-ETF Major Equipment List

350.1 STRUCTURES & IMPROVEMENTS

<u>Description</u>	<u>No. Req.</u>	<u>Size and/or Capacity</u>	<u>Notes</u>
Substation Structural Steel System	1	Four circuit Ring Bus, 115 kV	
Foundation System	1	Four circuit Ring Bus, 115 kV	Includes 3 Transf. & 4 OCB's.
Control House	1	115 kV Substation	Includes Control & Relaying for 3 Transf. & 1 Commercial Feeder

350.2 MAIN TRANSFORMERS

<u>Description</u>	<u>No. Req.</u>	<u>Size and/or Capacity</u>	<u>Notes</u>
Main Turbine Generator Step Up Transformer	1	40/53/66 MVA, 115/13.8 kV	
Main MHD Inverter Transformer	1	40/53/66 MVA, 115/13.8 kV	
Start-Up Transformer & Constr. Power Transformer	1	12/16/20 MVA, 115/4.16 kV	
Inverter Step-Up Transformers	6	6/7.5 MVA Inverter Voltage/13.8 kV	
Inverter Step-Up Transformers	2	8/10 MVA Inverter Voltage/13.8 kV	
Inverter Step-Up Transformers	3	10/12.5 MVA Inverter Voltage/13.8 kV	

350.3 SUBSTATION

Main Circuit Breakers	4	115 kV, 1200 Ampere, 5000 MVA I.C.	
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350.3

SUBSTATION (Con't.)

<u>Description</u>	<u>No. Req.</u>	<u>Size and/or Capacity</u>	<u>Notes</u>
Inverter Circuit Breakers	16	15 kV, 600 Ampere	
Disconnect Switch	12	115 kV, 1200 Ampere Manually Operated	
Cable & Conduit System	1	115 kV Switchyard	
Grounding & Bus System	1	115 kV Switchyard	
Relay & Control System	1	4 - OCB Ring Bus System	

PRELIMINARY-EQUIPMENT LIST

SEED REGNERATION PLANT

<u>ITEM</u>	<u>NO. REQ'D</u>	<u>DESCRIPTION</u>	<u>REMARKS</u>
Coke Storage Silo	1	25 ton capacity (1000 cu ft.)	200 hrs fuel storage
Coke Silo Airveyor	1	1000 lb/hr	
Coke Silo Airveyor Compressor Motor	1	5 HP	
Coke Feeder	1	Acrison Model 203B-105Z gravimetric feeder, 50-500 lb/hr	
Coke Feeder Drive Motor	1	10-1 variable speed drive motor 1 HP	
Coke Feeder Hopper	1	50 cu. ft.	
Coke Bucket Elevator	1	500 lb/hr	
Bucket Elevator Drive Motor	1	5 HP	
Gasifier	1	60 in. dia. Wellman-Galusha, refractory lined, coke feed/air blown gasifier 5 TPD	
Gasifier Airblower	1	5 HP	
Gas/Water Cooler	1	Gas/water 500 SCFM 1×10^6 Btu/hr	
Compressor Booster	1	Ingersoll-Rand Type ESH 13 in. dia. cylinder, 5 in. stroke	
Compressor Booster Drive Motor	1	40 HP	
Compressor Second Stage	1	Ingersoll-Rand Type ESH 6 in. dia. cylinder, 7 in. stroke	Tandemly driven with third stage
Compressor Third Stage	1	Ingersoll-Rand Type ESH 4 in. dia. cylinder, 7 in. stroke	Tandemly driven with second stage

PRELIMINARY-EQUIPMENT LIST
(contd)

ITEM	NO. REQ'D	DESCRIPTION	REMARKS
Compressor Second & Third Stage Drive Motor	1	75 HP	
CO Pressure Tank	1	100 cu. ft./500 psia	
Scrubber	1	Ethanolamine scrubber, CO ₂ removal system 500 SCFM/500 psia	
Regenerator	1	Ethanolamine regenerator, CO ₂ removal system 500 SCFM/500 psia	
CO ₂ Scrubber Pump	1	20 GPM	
CO ₂ Scrubber Pump Motor	1	3 HP	
CO Reserve Storage Tanks	1	Aggregate volume 1000 cu. ft. 2000 psia	
CO Heat Exchanger	1	Gas/steam 500 SCFM .2 x 10 ⁶ Btu/hr	
Reactor	1	42 in. i.d. x 26 ft. long jacketed, multi-section continuous reactor, working vol. 170 cu. ft. co-current or countercurrent flow, sectional gas injection, multiple turbine mixers, 300 gal/500 psia/500 F	
Reactor Mixer Drive Motor	1	20 HP	
Lime Storage Silo	1	50 ton capacity (1500 cu. ft.)	200 hrs storage
Lime Silo Airveyor	1	1500 lb/hr	
Lime Silo Airveyor Compressor Motor	1	5 HP	
Lime Feeder	1	Acrison Model 203B-105Z gravimetric feeder, 100-1000 lb/hr	
Lime Feeder Drive Motor	1	10-1 variable speed drive motor 1 HP	
Lime Feeder Hopper	1	10 cu. ft.	
Virgin K ₂ SO ₄ Silo	1	50 ton capacity (1500 cu. ft.)	

PRELIMINARY-EQUIPMENT LIST
(contd)

<u>ITEM</u>	<u>NO. REQ'D</u>	<u>DESCRIPTION</u>	<u>REMARKS</u>
Virgin K ₂ SO ₄ Silo Airveyor	1	3000 lb/hr	
Virgin K ₂ SO ₄ Silo Airveyor Compressor Motor	1	10 HP	
Recovered Seed Ballast Silo	1	5 ton capacity (300 cu. ft.)	20 hrs storage
Recovered Seed Ballast Silo Airveyor	1	3000 lb/hr	
Recovered Seed Ballast Silo Airveyor Compressor Motor	1	10 HP	
K ₂ SO ₄ Feeder	1	Acrison Model 203B-105Z grav- imetric feeder 300-3000 lb/hr	
K ₂ SO ₄ Feeder Drive Motor	1	10-1 variable speed drive motor 1 HP	
K ₂ SO ₄ Feeder Hopper	1	30 cu. ft.	
Dissolving Tank	1	1000 gallons	
Dissolving Tank Mixer	1	1000 gallons	
Dissolving Tank Mixer Drive Motor	1	15 HP	
Reactor Slurry Feed Pump	1	Moyno Model 9P6 type SSQ, 316 stainless steel positive pressure slurry pump, .5-15 GPM/500 psia	
Reactor Slurry Feed Drive Motor	1	27-1 variable speed drive motor 15 HP	
Reactor Feed Heat Exchanger	1	Liquid/steam 15 GPM 2 x 10 ⁶ Btu/hr	
Filter Slurry Feed Pump	1	Moyno Model 9P6 type SSQ, 316 stainless steel positive pressure slurry pump .5-15 GPM/500 psia	
Filter Slurry Feed Drive Motor	1	27-1 variable speed drive motor 15 HP	
Flash Tanks	2	50 cu. ft.	

PRELIMINARY-EQUIPMENT LIST

(contd)

ITEM	NO. REQ'D	DESCRIPTION	REMARKS
Rotary Pressure Filter	1	Bird-Young 2 ft. diam. x 3 ft. face, pressurized rotary drum filter, 1500 lb/hr	
Rotary Pressure Filter Drive Motor	1	35 HP	
Rotary Pressure Filter Compressor	1	500 CFM/15 lb differential	
Rotary Pressure Filter Compressor Drive Motor	1	50 HP	
Filter Rotary Valve	1	1500 lb/hr	
Filter Rotary Valve Motor	1	1 HP	
Wash Water Feed Pump	1	20 GPM	
Wash Water Feed Pump Drive Motor	1	10-1 variable speed drive motor 15 HP	
Wash Water Heat Exchanger	1	Liquid/steam 1×10^6 Btu/hr	
Wash Water Removal Pump	1	20 GPM	
Wash Water Removal Pump Drive Motor	1	10-1 variable speed drive motor 15 HP	
Spray Drier Feed Pump	1	20 GPM	
Spray Drier Feed Pump Drive Motor	1	10-1 variable speed drive motor 15 HP	
Spray Drier	1	Swenson stainless steel unit 5 ft. 3 in. dia. x 42 ft. 22000 SCFM	
Cyclone	1	Swenson stainless steel unit 3 ft. 8 in. dia. x 36 ft. 22,000 SCFM	
Dust Collector	1	Swenson stainless steel unit 5 ft. dia. x 16 ft. 22,000 SCFM	
Spray Drier Exhaust Fan	1	Swenson, 150 CFM, 15 in. s.p.	

PRELIMINARY-EQUIPMENT LIST

(contd)

<u>ITEM</u>	<u>NO. REQ'D</u>	<u>DESCRIPTION</u>	<u>REMARKS</u>
Spray Drier Exhaust Fan Motor	1	75 HP	
Spray Drier Airveyor	1	3000 lb/hr	
Spray Drier Airveyor Compressor Motor	1	10 HP	
Flue Gas Reheater	1	Flue gas/steam 1 x 10 ⁶ Btu/hr	
Potassium Formate Ballast Silo	1	9 ton capacity (300 cu. ft.)	
Potassium Formate Ballast Silo Airveyor	1	3000 lb/hr	
Potassium Formate Ballast Silo Airveyor Compressor Motor	1	10 HP	
Potassium Formate Storage Silo	1	50 ton capacity (1500 cu. ft.)	
Potassium Formate Storage Silo Airveyor	1	3000 lb/hr	
Potassium Formate Storage Silo Airveyor Compressor Motor	1	10 HP	
Portable Pneumatic Rail Car Unloader	1	10 tons/hr	
Portable Pneumatic Rail Car Unloader Compressor Drive Motor	1	50 HP	

PRELIMINARY INSTRUMENT LIST

SEED REGENERATION PLANT

<u>ITEM</u>	<u>NUMBER REQ'D</u>	<u>APPLICATION</u>	<u>LOCATION</u>
TRC	1	Steam Flow Control of Reactor Slurry Feed (350°F - 450°F)	Heat Exchanger X-1
TRC	1	Steam Flow Control to Reactor (350°F - 450°F)	Reactor
TRC	1	Cooling Water Flow Control to Gasifier (1000°F - 1500°F)	Gasifier
TRC	1	Cooling Water Flow Control to Gas Cooler (100°F - 200°F)	Gas Cooler
TRC	1	Steam Flow Control to Heat Exchanger X-2 (350°F - 450°F)	Heat Exchanger X-2
TRC	1	Steam Flow Control to Flue Gas Reheater (200°F - 600°F)	Flue Gas Reheater
TRC	1	Cooling Water Flow Control to Dissolver (180°F - 240°F)	Dissolving Tank
TC	1	Steam Flow Control to CO ₂ Removal System (240°F - 340°F)	CO ₂ Removal System
LC	1	K ₂ SO ₄ Level Control of Dissolver Feed Hopper	K ₂ SO ₄ Feed Hopper
LC	1	Lime Level Control of Dissolver Feed Hopper	Lime Feed Hopper
LC	1	Coke Level Control of Gasifier Feed Hopper	Coke Feed Hopper
LC	1	Liquid Level Control of Reactor	Reactor
FRC	1	Liquid Flow Control of Reactor Slurry Feed and Dissolver Recycle	Dissolving Tank Discharge
FRC	1	Liquid Flow Control of Dissolver Water Feed	Dissolver
FRC	1	Solid Flow Control of Coke Feed to Gasifier	Gasifier
FRC	1	Solid Flow Control of Lime Feed to Dissolver	Dissolver

PRELIMINARY INSTRUMENT LIST
(contd)

<u>ITEM</u>	<u>NUMBER REQ'D</u>	<u>APPLICATIONS</u>	<u>LOCATION</u>
PRC	1	Pressure Control of Reactor Off Gas to Bottoming Plant or Flare (250-550 psia)	Reactor
CRC	1	CO Analyzer and Flow Control of Gas Feed to Reactor (50-500 lb/hr CO)	Scrubber
PRV	1	Pressure Control of Reactor Gas Output (500-15 psia)	Reactor
PRV	1	Pressure Control of Filter Slurry Feed (500-210 psia)	Flash Tank 1
PRV	1	Pressure Control of Filter Wash Water Feed to Dissolver (250-15 psia)	Filter
PRV	1	Pressure Control of Spray Drier Feed and Dissolver Recycle Feed (250-15 psia)	Flash Tank 2

LEGEND:

LC	-	Level Controller
TRC	-	Temperature Recorder/Controller
TC	-	Temperature Controller
FRC	-	Flow Recorder/Controller
PRC	-	Pressure Recorder/Controller
PRV	-	Pressure Reducing Valve
CRC	-	Concentration Recorder/Controller

APPENDIX B

TEST AND EVALUATION OF STEAM GENERATOR, COAL PROCESSING SYSTEM AND ELECTROSTATIC PRECIPITATOR

A. TEST SUMMARY

B. PROCESS VARIABLES

Each test unit is supplied with the necessary equipment and controls to vary the excess air, unit load, and furnace wall deposits.

C. EMISSIONS DETERMINATION

Operation of the test units in the planned modes as specified in the baseline test programs will produce variations in the flue gas emission levels. The effect of these changes on NO_x , SO_x , CO, THC, and unburned carbon will be determined. The emission control instrumentation and sampling system and the method for calculating emission levels on a weight basis are described in Section J of this appendix.

D. UNIT PERFORMANCE

Operation of these units as proposed in this study will produce variations in unit operation and thermal performance. The following process measurements are required to properly assess the impact of these changes on new unit design.

1. Furnace Absorption

Variations in load or operating parameters of the MHD burner will result in changes in the average and peak absorption rates and the absorption profiles. The furnace waterwall absorptions will be calculated using chordal drilled thermocouples as described in Section K. of this appendix.

2. Superheat, Low Temperature Air Preheater and Economizer Section Absorptions

Variations in the gas temperature and gas flow leaving the furnace envelope and entering the convective sections of the unit will affect the total heat pickup of each section. The absorption rates for each section will be determined.

3. Air Heater Performance

Air and gas temperatures and gas side oxygen concentrations entering and leaving the air heater are required to calculate air heater performance, unit efficiency, heat losses and air and gas flow rates.

4. Furnace Waterwall Corrosion

Unit operation with oxygen-deficient flue gas will result in reducing atmosphere within the furnace envelope, resulting in accelerated waterwall corrosion rates. To ascertain the effect of this mode of operation on waterwall wastage, furnace corrosion probes will be utilized as described in Section L of this appendix.

5. Fuel and Ash Analysis

During each test a representative fuel sample must be obtained for later analysis. The fuel analyses are required to perform the combustion calculations necessary to determine excess air levels and unit gas and air flow rates. For calculation of the emission levels on a weight basis, the fuel analyses are also necessary. The coal and ash samples will be analyzed by the ASTM procedures listed in Section M of this appendix.

6. Pressure Parts and Refractory Corrosion

Alkali-metal sulfates have normally been recognized as the aggressive compounds in waterwall tubes and refractory wastage. The first step in the overall corrosion mechanism involves transport of the alkalis to tube or refractory surfaces. Alkalies, as they exist in coal mineral matter, are to a large degree sublimated and carried to tube and refractory surfaces as a vapor where they condense. Here they combine with sulfur oxides to form alkali sulfates. One possibility is that with low excess air, iron pyrites may be deposited on tube or refractory surfaces without undergoing significant oxidation. Oxidation of the pyrites would then occur at the tube surface providing sufficient sulfur oxides to react with alkalis forming either pyrosulfates or alkali-iron-trisulfates. In addition, the required high localized levels of SO_3 would be produced to maintain stability of the alkali-iron-trisulfates.

Another possibility, although less likely than the previous mechanism, is that free sulfur from deposited pyrites can attack iron directly. This is not too likely because enamel deposits (alkalies) will usually shield the tube from sulfur attack.

Experience with the Draft recovery furnaces indicated that extensive repairs and replacement of refractories are required after a few years of operation.

The quantity and distribution of pyrites in the subject coal will have an influence on the behavior of the sulfur in the furnace. Coal containing pyrites that are not well disseminated throughout the coal would be more likely to result in coarse particles reaching the tubes. In cases such as this, particular attention should be given to coal fineness.

E. TEST MEASUREMENTS

The following measurements will be required in support of the test program.

F. STEAM GENERATOR TESTS

1. Thermal Performance

Flows: Feedwater, superheater-desuperheater spray, circulating water, air to MHD combustor, total air, burnout air, low temperature air and recycle gas, flue gas.

Temperatures: Feedwater, superheater, drum, air to MHD combustor, total air, secondary air, low temperature air and gas recycle, flue gas leaving economizer.

Pressures: Feedwater, superheater, drum, furnace, air to MHD combustor, total air, burnout air, low temperature air and recycle gas.

Samples: Flue gas constituents, coal, and slag deposits.

2. Waterwall Heat Absorption

Flows: Test loop, circulating water, feedwater, flue gas, and burnout air.

Temperature: Test loop, circulating heater, feedwater, flue gas, burnout air and refractory.

Pressure: Test loop, circulating heater, feedwater, flue gas and burnout air.

3. Emission Level

Samples/Levels: NO_x, CO, THC, O₂, SO₂, CO₂ and solids levels.

4. Bottom Solids Analysis

Sample/Levels: Chemical and physical analysis of slag and seed.

5. Pressure Parts Corrosion

Sample: Material wastage, analysis of the deposits, and visual observations.

Temperature: Coupon

6. Refractory Corrosion

Sample: Material wastage, analysis of deposits and visual observation.

Temperature: Refractory

Convective Pass Heat Profiles

Flows: Flue gas, flue gas distribution, low temperature air and gas recycle, steam and economizer.

Temperature: Flue gas, low temperature air and gas recycle, steam and economizer.

Pressure: Flue gas, low temperature air and gas recycle, steam and economizer.

7. Cell Heat and Material Balances

Measurements should be the same as for thermal performance.

8. Sootblower Evaluation and Sequencing

Measurements should be the same as for thermal performance.

G. COAL PROCESSING

1. Coal Sampling and Analysis

2. Raymond System Component Performance

Flow: Flue gas, recycle gas and coal.

Temperature: Flue gas and recycle gas.

Pressure: Flue gas.

Samples: Coal and dust loading.

3. Petrocarb System Component Performance

Flow: Coal, flue gas and air.

Temperature: Flue gas and air.

Pressure: Flue gas, storage and primary injector and air.

Sample: Flue gas and coal.

4. Flue Gas Pressure System Component Performance

Flow: Flue gas.

Temperature: Flue gas.

Pressure: Flue gas.

5. HTAH Waste Heat Recovery

a. Fan System Performance

Flow: Air

Temperature: Air

Pressure: Air

Power: Motor

b. HX Thermal Performance

Flow: Gas and air

Temperature: Gas and air

Pressure: Gas and air

H. PRECIPITATOR

a. Collection Efficiency

Flows: Flue gas and seed.

Temperature: Flue gas.

Pressure: Flue gas

Sample: Flue gas

I. MHD-ETF SYSTEMS TEST/INSTRUMENTATION CROSS-REFERENCE
FLOWS

Steam and Water

Feedwater S1, S8

Superheater Desuperheat Spray S1

Circulating Water S1, S8

Waterwall Absorption Test Loops S2, S8

Air and Gas

Total Flue Gas S1, S8

Air to MHD Combustor S1, S8

Total Air S1, S8

Burnout Air S1, S8

Coal Fan Gas Flow C2, S8

Flue Gas Flow Distribution S7

Solids

Slag to Ash Pit S4, S8

Solids from Hoppers S4, S8

Coal to Combustor S1, C3

Coal to Pulverizer Coal Bin C2, S8

TEMPERATURES

Steam and Water	S1, S8, S2
Metal	S2
Air and Gas	S1, S8, S3, C2
Refractory (Absorption)	S2
Refractory (Monitoring)	S6
Pulverized Coal	

SAMPLES/LEVELS

Flue Gas Constituents

Nitrogen Oxides - NO _x	S1, S3
Carbon Monoxide - CO	S1, S3
Total Hydrocarbons - THC	S1, S3
Oxygen - O ₂	S1, S3, C2
Sulfur Dioxide - SO ₂	S1, S3, C4
Carbon Dioxide - CO ₂	S1
Particulates	S3, P1, C2, C3
Moisture Content	C2, C3
Slag Deposits	S1
Water Level	
Coal Samples	S1, C2

PRESSURES

Steam and Water	S1
Air and Gas	S1, C3, C2

Key

Steam Generator	S1 - Thermal Performance
	S2 - Waterwall Heat Absorption
	S3 - Emission Levels
	S4 - Bottom Solids Analysis
	S5 - Pressure Parts Corrosion
	S6 - Refractory Corrosion
	S7 - Convective Pass Heat Profiles
	S8 - Cell Heat and Material Balances
	S9 - Sootblower Evaluation and Sequencing

Coal Processing	C1 - Coal Sampling and Analysis
	C2 - Raymond System Component Performance
	C3 - Petrocarb System Component Performance
	C4 - Flue Gas Press. System Component Performance
HTAH Waste	H1 - Fan Systems Performance
Heat Recovery	H2 - HX Thermal Performance
Precipitator	P1 - Collection Efficiency

J. EMISSION LEVEL DETERMINATION

In order to evaluate the effect of combustion process modifications on boiler emission levels the following instrumentation is proposed.

1. NO_x : Chemiluminescence Analyzer
2. O_2 : Paramagnetic Analyzer
3. CO: Nondispersive Infrared Analyzer
4. HC: Flame Ionization Analyzer
5. SO_2 : Wet Chemistry
6. Carbon Loss: ASME Particulate Sampling Train

In addition to these methods of measurement, check methods for NO_x will be performed using the PDS chemical analysis (ASTM D1608).

The specifications for the above mentioned emission analyzers are as follows:

NO_x Analyzer

The $\text{NO} - \text{NO}_x$ Analyzer consists of one (1) control unit, one (1) analyzer unit, and one (1) NO_2 to NO converter.

Range: Three Ranges 0 - 100 ppm
0 - 1000 ppm
0 - 2000 ppm

Sensitivity: 1 ppm full scale

Reproducibility and Accuracy: $\pm 1\%$ full scale

Zero Drift: 1% full scale in 24 hours

Span Drive: 2% full scale in 24 hours

THC Analyzer

Range: 1 - 100,000 ppm

Accuracy: $\pm 1\%$ full scale

Sensitivity: 1 ppm carbon scale at 68 F

CO Analyzer

Range: 0 - 100, 0 - 1000 ppm

Accuracy: $\pm 1\%$ full scale

Zero and Span Drive: 1% full scale in 24 hours

Sensitivity: 1% full scale

O₂ Analyzer

Range: 0 - 10%, 0 - 25% O₂

Accuracy: $\pm 1.5\%$ full scale

Sensitivity: 0.05% O₂

SO₂ Wet Chemistry Method

The sodium hydroxide-bromphenol blue methods, which was developed at the C-E Kreisinger Development Laboratory, will be used to determine the SO₂ concentration in the flue gas.

ASME Particulate Sampling Train

The particulate sampling train will consist of necessary sampling probes as described in ASME Test Code PTC 21. Isokinetic samples will be obtained to determine the percent carbon loss in the flyash.

Probe Locations

A stationary grid of gas sampling probes will be installed at three locations. The sampling location for the determination of NO_x and related gaseous emission levels versus unit operation will be the economizer outlet. Isokinetic dust samples will also be obtained at the economizer outlet duct to be analyzed for carbon loss.

Emission Sampling and Analysis Train

A sampling and analysis train will provide the proper flue gas conditioning to each meter to maintain continuous and simultaneous analysis of emission levels.

Method for Converting Emission Levels from a Volume to a Weight Basis

The analyzer chosen to measure emission levels are directly read in terms of parts per million on a volumetric basis. However, it is also necessary to report emissions in terms of lbs/m BTU fired. The following discussion describes the equations involved in a representative conversion when analyzed on a dry basis.

NO_x Conversion ppm (Vol. - Dry Basis) to lb/NO₂ 10⁶ BTU Fired

The values which are needed to make the conversion are:

1. NO_x - ppm Dry Basis Value (NO_x - ppm - D)
2. Percent Oxygen Reading Where NO_x Sample is Taken (% O₂)
3. Complete Fuel Analysis as Fired
 - (a) Carbon % by wt (C)
 - (b) Hydrogen % by wt (H)
 - (c) Sulfur % by wt (S)
 - (d) Moisture % by wt (M)
 - (e) Oxygen % by wt (O)
 - (f) Nitrogen % by wt (N)
 - (g) Higher Heating Value of Fuel - BTU/lb (HHV)

For the purpose of simplicity in discussion, the abbreviations in the brackets above will be used in the conversion analysis.

K. WATERWALL ABSORPTION MEASUREMENT

In order to determine waterwall absorption rates, chordal drilled thermocouples will be installed in the furnace waterwall tubes. Depth of the thermocouple below the surface of the tube will depend on the tube diameter.

A method of calibrating the installed thermocouples has been devised to check on the uniformity of the TC's. The unit is "bottled up" with all vents closed (superheater, drum, etc.) and all air dampers shut and circulating pumps running. Each thermocouple reading should then approach an average temperature. Any TC which does not read within one or two degrees of the average should be adjusted.

Plotting Test Data

The absorption rates measured on the vertical column of thermocouples are plotted on a graph vs furnace elevation; using test average readings on oil and gas fired units, and peak rates for coal fired units. A smoothly faired curve is then drawn through these points giving a test vertical profile of the center tube.

The test average absorption rates in the horizontal rows are averaged and these averages are then plotted on the same graph as the vertical profile. Another vertical profile is now drawn through these horizontal average rates having a shape similar to the center tube vertical profile. This is now

now considered the average absorption profile for the furnace and assumes that the horizontal averages form the same general contour as the test vertical profile for the center tube.

Calculation of Heat Flux from Chordal Drilled Thermocouple for Subcritical Pressure

The following is a description for determining the crown heat flux with subcritical pressure.

- D_o = outside tube diameter, nominal
- L = average wall thickness at metal surface
- D_M = mean tube diameter = $D_i + L$
- D_i = inside tube diameter = $D_o - 2L$
- D_p = diameter of thermocouple location
- K = metal conductivity

1. Metal ΔT_M

$\Delta T_M = (Q/A) D_o L / D_M K$ = metal temperature drop from crown to inside diameter but, since the thermocouple is not at the crown the measured temperature is at some location, P . Therefore, P must be determined, either graphically or by measurement. Then: $T'_M = (Q/A)' D_p L / D_M K$ = metal temperature drop from thermocouple to inside diameter.

2. Film ΔT_f (By Jens and Lottes)

$\Delta T_f = 60 (Q/A)'' 10^{6 \cdot 0.25} / e^{(P/900)}$ but, since $(Q/A)''$ is the heat flux at the inside diameter and we are interested, at the moment, in the heat flux at location P , the film temperature drop becomes

$$\Delta T_f = \frac{60 (D_p / D_i) (Q/A)' / 10^{6 \cdot 0.25}}{e^{(P/900)}}$$

3. Overall ΔT_o

$$\Delta T_o' = T'_M + \Delta T_f$$

$$\Delta T_o' = (Q/A)' \frac{D_p L}{D_M K} + \frac{60 (D_p / D_i) (Q/A)' / 10^{6 \cdot 0.25}}{e^{(P/900)}}$$

$\Delta T'_o$ = thermocouple temperature - saturation temperature . This now tells us that for a given tube size, tube material and pressure, a $(Q/A)'$ will result in one $\Delta T'_o$. Or, conversely, a measured thermocouple temperature will yield one heat flux. In order to convert $(Q/A)'$, the flux at the TC, to (Q/A) the flux at the crown, we assume radial heat flow and decrease $(Q/A)'$ by a ratio of diameters. Thus, $Q/A = (D_p/D_o) (Q/A)'$.

L. EVALUATION OF CORROSION POTENTIAL

Substoichiometric combustor operation will result in reducing air atmospheres in the slag and seed recovery furnaces. In order to determine what effect these conditions will have on waterwall and finishing SH tube wastage the following instrumentation will be used. Basically, the test involves exposing a metal coupon held at WW or SH metal temperatures to furnace conditions for a finite time period. At the end of this time period the coupon will be evaluated for weight loss and visual evidence of attack. Ash/seed deposits will also be collected using the probe and will be subjected to evaluation in terms of corrosion potential as well as furnace slagging.

Description of Equipment and Instrumentation

The most reliable method of evaluating corrosive potential in a boiler is by exposing a sample of tube metal for a finite period of time and measuring the resulting weight loss. This can be accomplished by using a probe to insert the metal coupon into the furnace and using air to maintain the desired temperature.

Typical instrumentation to automatically maintain the desired temperature will consist of an electronic controller, and a pneumatic controller. The pneumatic controller operates as a switching device, using solenoid valves, to regulate the amount of cooling air going to the probe. The amount of air is based on a signal from the electronic controller which is tied into the sensing thermocouple at the probe coupon.

Probe Location in Furnace

The general location of the probes would be in the seed and air heater furnaces.

Evaluation of Data

It is extremely important the the rate of weight loss measured during the test period is no assumed to hold throughout much longer time periods.

Tube wastage is not usually linear with respect to time; a higher rate of wastage quite often occurring during periods of initial operation.

In order to interpret corrosion potential, a control case will be utilized. The control case will involve exposure of a similar type of metal coupon for the time period equal to the test period using the same coal under conventional firing conditions.

Coupon weight losses from the two modes of boiler operation will be compared in terms of weight loss as well as visual inspection. Deposits collected from each case will be carefully analyzed to determine differences in composition. Deposit compositions will be evaluated with respect to coupon weight loss in each case and mechanisms of corrosion postulated in applicable.

M. COAL AND ASH ANALYSES

Coal and ash sampling and analyses will be performed essentially in accordance with the following ASTM procedures.

<u>ASTM Specification</u>	<u>Title</u>
D-271-70	Sampling and Analysis, Laboratory of Coal and Coke
D-2013-68	Samples, Coal, Preparing for Analysis
D-410-38	Sieve Analysis of Coal
D-311-30	Sieve Analysis of Crushed Bituminous Coal
D-2015-66	Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter
D-409-71	Grindability of Coal by the Handgrove-Machine Method
D-1857-68	Fusibility of Coal Ash
D-2795-69	Analysis of Coal and Coke Ash

STEAM GENERATOR RESULTS EVALUATION

<u>Test</u>	<u>Parameters to be Established for Designing Utility Steam Generator Components</u>	<u>Steam Generator Components</u>
Thermal Performance	Heat Transfer Rates, Proper Gas Flow Baffling, Fouling, Sootblowing Performance	All Components
Waterwall Heat Absorption	Heat Transfer Rate, Absorption Profiles	Furnace Size, Circulation Ratio, Circulating Pump, Feedwater Pump, Circulation Systems, Sootblower Requirements
Emission Levels	a) NO _x b) CO/CO ₂ THC c) Dust Loading	•Slag Furnace Size •Location of oxidizing nozzles. •Excess air required. •Location of oxidizing nozzles. •Fan size. •Convective surface spacing. •Sootblower requirements. •Hopper sizes. •Storage tanks. •Electrostatic precipitator requirements. •Fan size.
Bottom Solids Analysis	Physical and Chemical Properties of Solids	•Hopper slope. •Sootblower requirements. •Method of transport.
Pressure Parts Corrosion	Coupon Material Study	•Type of material and wall thickness to be used throughout the steam generator (waterwalls, superheater, air preheater, economizer).
Refractory Corrosion	---	•Suitability of the selected refractory in the slag furnace.

STEAM GENERATOR RESULTS EVALUATION (Continued)

<u>Test</u>	<u>Parameters to be Established for Designing Utility Steam Generator Components</u>	<u>Steam Generator Components</u>
Convective Pass Heat Profiles	Heat Transfer Rates	<ul style="list-style-type: none"> • Spacing • Sootblower effectiveness. • Flow Baffle Distribution
Cell Heat and Material Balance	Flows and Temperatures	<ul style="list-style-type: none"> • Hopper sizes. • Storage tanks.
Sootblower Evaluation and Sequencing	Heat Transfer Rates	<ul style="list-style-type: none"> • Location and sequencing of sootbblowers.

APPENDIX C

CHANNEL CALCULATIONS FOR MHD GENERATORS

1.0 MHD CHANNEL PROGRAMS PDG 73, PDG 79 AND PDG 95

PDG 73 is a single precision program written in FORTRAN IV for the IBM 360/44. This program provides an analysis of the behavior of a segmented Faraday generator. It is a "design program," i.e., a calculation for which the velocity distribution is specified in the channel and the cross sectional area is computed as a function of distance.

Program PDG 73 can be conceptually divided into two parts. The first deals with the calculation of thermochemical equilibrium for the specified gases.

The second part of the calculation involves the use of the thermochemical equilibrium program for calculations in specific regions of the generator. A similar use of the thermochemical equilibrium program was made in order to calculate the isentropic expansion of arbitrary gases through a nozzle, which corresponds to the calculations that must be performed in order to compute the inlet conditions for the generator.

Since the thermochemical equilibrium program is extensively documented elsewhere, no detailed discussion of it is included in this note. This deals primarily with the generator calculation, which itself will be divided into two portions; the computation of inlet conditions and the description of the properties of the generator channel.

The first task in the generator program is to compute the inlet conditions for the channel. This proceeds by the calculation of the initial conditions ("stagnation") and the calculation of the throat conditions; (the supersonic or subsonic inlet).

After the calculation of the inlet conditions, one is prepared to describe the channel conditions by integrating the following system of five ordinary differential equations, where $U_c = f(x)$ is the supplied channel function.

$$\frac{dP_c}{dx} = -j_y B - \rho_c U_c \frac{dU_c}{dx} \quad (A-1)$$

$$\frac{dT_c}{dx} = \frac{\left\{ \frac{-E y_c j_y - p_c U_c^2 \frac{dU_c}{dx}}{\rho_c U_c} \right\} - \left(\frac{\partial h_c}{\partial P_c} \right)_{T_c} \frac{dP_c}{dx}}{\left(\frac{\partial h_c}{\partial T_c} \right) P_c} \quad (A-2)$$

$$\frac{dA_{ac}}{dx} = - A_{ac} \frac{1}{U_c} \frac{dU_c}{dx} + \frac{1}{\rho_c} \frac{d\rho_c}{dx} \quad (A-3)$$

$$\frac{d\theta}{dx} = - \frac{\theta}{U_c} \frac{dU_c}{dx} (2 + H) - \frac{\theta}{\rho_c} \frac{d\rho_c}{dx} + \frac{C_f}{2} \quad (A-4)$$

$$\frac{d\bar{H}}{dx} = \frac{1}{\theta} \text{Rey}_\theta^{-1} e^{5(\bar{H} - 14)} - \left[\text{Rey}_\theta \frac{\theta}{U_c} \frac{dU_c}{dx} - .0135(\bar{H} - 14) \right] \quad (A-5)$$

where

$$\frac{d\rho_c}{dx} = \left(\frac{\partial \rho_c}{\partial P_c} \right)_{T_c} \frac{dP_c}{dx} + \left(\frac{\partial \rho_c}{\partial T_c} \right) P_c \frac{dT_c}{dx}$$

The initial conditions of Eqs. (A-1), (A-2), (A-3), are obtained from the inlet calculation, and for Eqs. (A-4), (A-5) these initial conditions are simply inputs.

The channel calculations include simplified heat loss terms for both laminar and turbulent conditions. They involve the following items:

$$\dot{q}_l = \left[\frac{.332}{\text{Rey}^{.5} P_r^{.67}} \right] \rho_c U_c \Delta H_q, \text{ the laminar heat loss rate.}$$

$$\dot{q}_t = \left[\frac{.029}{\text{Rey}^{.2} P_r^{.67}} \right] \rho_c U_c \Delta H_q, \text{ the turbulent heat loss rate.}$$

$\gamma_e = 1.20211 \times 10^{-8} a_x^2 \overline{MW}_x / T_c$, where a_x is the local speed of sound (cm/sec), $\overline{MW}_x$ the local mean molecular weight of the mixture

(gm/mole) and γ_e is the "expansion gamma" which is thus not a simple ratio of specific heats but instead based on a_x and hence $\frac{\partial P}{\partial S} \Big|_S$.

$P_r = 4\gamma_e / (9\delta_e - 5)$ which is the local Prandtl number

ΔH_q is defined as the enthalpy difference $[h_o - h_{wall}]$.

The integrated laminar and turbulent losses are computed by integrating such that $Q_{L,t} = 4 \int^x \dot{q} L, T^{dx}$.

The PDG 79 program, is a modified version of PDG 73. The basic difference is that whereas the PDG 73 accepts as input a velocity $U_c/U_1 = F(X_c)$, PDG 79 accepts instead the actual area of the channel, D_{la} and D_{2a} .

Program PDG 95 is used for diagonal connected channels. The differential equations which describe the channel conditions are basically the same as in PDG 79. Areas, sizes, conductivity, etc., are computed as before. However, α is no longer an input but is computed. Inputs are also added to compute a local value of the wall angle, ϕ_{wX} , and the load current has to be specified.

2.0 MHD 2 CHANNEL PROGRAM

MHD 2 channel program is a recent program which was developed and is continuously updated to improve upon existing analytical models. These improvements have focused mainly up to now on the addition of a third boundary layer integral equation, the enthalpy conservation equation. Thus, a temperature profile can be calculated and electrical quantities like the voltage drops and axial shorting in the boundary layer can be computed and taken into account into the performance of the generator. Also, the model is flexible enough so as to be able to include additional models for arcing and slag development effects along the walls of the channel. An effort is made to minimize reliance on empirical factors of quantities like the friction coefficient, the heat transfer coefficient, and the dissipation integral, by means of better theoretical models.

2.1 Description of the Model

The MHD generator model consists of two parts: the channel calculation, and the burner to channel inlet calculation. The calculation of the thermodynamical properties of the working fluid from the burner to the inlet of the channel is done in two steps:

1. A burner subprogram calculates the total enthalpy flux out of the burner from the heating value of the fuel, the fuel and seed composition, the N/O ratio of the oxidizer, the air preheat temperature and the burner efficiency.
2. A core isentropic expansion is calculated from burner stagnation conditions to the inlet area, for either a subsonic or supersonic case; then boundary layer inlet boundary conditions are applied and a displacement area at the channel inlet is calculated. With this value of inlet displacement area, the expansion calculation is done a second time, and this process is repeated till convergence on the displacement area is achieved.

2.2 Channel Calculation

The channel calculation is a quasi one-dimensional calculation which separates the flow into a one-dimensional core, electrode boundary layer and sidewall boundary layer. The core is described by the standard 3 one-dimensional equations (continuity, momentum and total enthalpy), and both electrode boundary layer as well as sidewall boundary layer are described separately by 3 integral equations (momentum, kinetic energy, and total enthalpy), and both electrode boundary layer as well as sidewall boundary layer are described separately by 3 integral equations (momentum, kinetic energy, and total enthalpy). The system of 9 ordinary differential equations is:

$$\frac{1}{\rho_c} \frac{d\rho_c}{dx} + \frac{1}{U_c} \frac{dU_c}{dx} + \frac{1}{A^*} \frac{dA^*}{dx} = 0 \quad (A-6)$$

$$\rho_c U_c \frac{dU_c}{dx} = - \frac{dP_c}{dx} + J y_c B \quad (A-7)$$

$$\rho_c U_c \frac{dH}{dx} = E x_c J x_c + E y_c J y_c \quad (A-8)$$

where ρ_c is the core density, U_c is the core velocity, A^* is the displacement area, P_c is the core pressure (assumed constant throughout both boundary layers), B is the magnetic field intensity, $\bar{E}$ is the electric field, $\bar{J}$ is the current density, and H is the total enthalpy.

The electrode wall boundary layer equations are written

$$\frac{d\theta}{dx} + \frac{\theta}{\rho_c} \frac{d\rho_c}{dx} + \frac{(\delta^* + 2\theta)}{U_c} \frac{dU_c}{dx} = \frac{\tau_w}{\rho_c U_c^2} \quad (A-9)$$

$$\frac{d\delta_{KE}}{dx} + \frac{\delta_{KE}}{\rho_c} \frac{d\rho_c}{dx} + \frac{(3\delta_{KE} + 2\delta)}{U_c} \frac{dU_c}{dx} = \frac{2 \int_0^\delta \mu \left(\frac{\partial U}{\partial y} \right)^2 dy}{\rho_c U_c^3} \quad (A-10)$$

$$\begin{aligned} \frac{d\delta_H}{dx} + \delta_H \left(\frac{1}{\rho_c} \frac{d\rho_c}{dx} + \frac{1}{U_c} \frac{dU_c}{dx} \right) \\ = \frac{-q_w - (\delta^* + \delta_H) (\vec{E} \cdot \vec{J})_c + \delta ((\vec{E} \cdot \vec{J})_c - \langle \vec{E} \cdot \vec{J} \rangle_\delta)}{\rho_c U_c (H_c - H_w)} \end{aligned} \quad (A-11)$$

here δ is the boundary layer thickness, θ is the momentum thickness

$$\theta = \int_0^\delta \frac{\rho U}{\rho_c U_c} \left(1 - \frac{U}{U_0} \right) dy$$

δ^* is the displacement thickness

$$\delta^* = \int_0^\delta \left(1 - \frac{\rho U}{\rho_c U_c} \right) dy$$

τ_w is the wall sheer stress, δ_{KE} is the kinetic energy thickness

$$\delta_{KE} = \int_0^\delta \frac{\rho U}{\rho_c U_c} \left(1 - \frac{U^2}{U_c^2} \right) dy,$$

δ_ρ is the density thickness

$$\delta_\rho = \int_0^\delta \frac{\rho U}{\rho_c U_c} \left(\frac{\rho_c}{\rho} - 1 \right) dy,$$

μ is the viscosity, δ_H is the enthalpy thickness

$$\delta_H = \int_0^\delta \frac{\rho U}{\rho_c U_c} \left(1 - \frac{H}{H_c} - \frac{H_w}{H_w} \right) dy,$$

q_w is the wall heat flux, and $\langle \vec{E} \cdot \vec{J} \rangle_\delta$ is the average $\vec{E} \cdot \vec{J}$ over the electrode wall boundary layer.

The side wall boundary layer equations read

$$\begin{aligned} \frac{d\theta_{sw}}{dx} + \frac{\theta_{sw}}{\rho_c} \frac{d\rho_c}{dx} - \frac{(\delta_{sw} - \delta_{sw}^* - 2\theta_{sw})}{U_c} \frac{dU_c}{dx} \\ + \frac{\theta_{sw}}{\rho_c U_c^2} \left[\langle J_y \rangle_{sw} B - \frac{dP_c}{dx} \right] = \frac{\tau_w}{\rho_c U_c^2} \end{aligned} \quad (A-12)$$

$$\begin{aligned} \frac{d\delta_{KEsw}}{dx} + \frac{\delta_{KEsw}}{\rho_c} \frac{d\rho_c}{dx} - \frac{(2\delta_{sw} - 2\delta_{sw}^* - 3\delta_{KEsw})}{U_c} \frac{dU_c}{dx} \\ = - \frac{2(\delta_{sw} - \delta_{sw}^* + \delta_{KEsw})}{\rho_c U_c^2} \left[\langle J_y \rangle_{sw} B - \frac{dP_c}{dx} \right] \\ + \frac{2 \int_0^\delta \mu \left(\frac{\partial U}{\partial y} \right)^2 dy}{\rho_c U_c^3} \end{aligned} \quad (A-13)$$

$$\begin{aligned} \frac{d\delta_{Hsw}}{dx} + \delta_{Hsw} \left(\frac{1}{\rho_c} \frac{d\rho_c}{dx} + \frac{1}{U_c} \frac{dU_c}{dx} \right) \\ = \frac{-q_w - (\delta_{sw}^* + \delta_{Hsw}) (\vec{E} \cdot \vec{J})_c + \delta_{sw} \left[(\vec{E} \cdot \vec{J})_c - \langle \vec{E} \cdot \vec{J} \rangle_{sw} \right]}{\rho_c U_c (H_c - H_w)} \end{aligned} \quad (A-14)$$

where sw stands for sidewall boundary layer, and $\langle J_y \rangle_{sw}$ and $\langle \vec{E} \cdot \vec{J} \rangle_{sw}$ are the average current density and $\vec{E} \cdot \vec{J}$ on the sidewall.

Each one of the boundary layer equations (Eqs. (A-9 through A-14) has a "source" term which must be calculated in a semiempirical fashion. For the momentum Eqs. (A-9) through (A-12) this is the shear stress τ_w for the kinetic energy Eqs. (A-10) through (A-13) this is the dissipation integral $\int_0^\delta \mu \left(\frac{\partial U}{\partial y} \right)^2 dy$ and for the enthalpy equations this is the wall heat flux q_w . For the shear stress, we calculate the derivative of the velocity profile at the wall, and multiply it by a roughness R_f :

$$\tau_w = \mu \left(\frac{\partial U}{\partial y} \right)_w \cdot R_f$$

This roughness factor is calculated by taking the ratio of the rough wall friction coefficient (with a sand roughness height K_s) to the smooth wall friction coefficient, for a flat plate:

$$R_F(K_s, \rho_c, U_c, X) = \frac{c_{f \text{ rough}}}{c_{f \text{ smooth}}} = \frac{\left(2.87 + 1.58 \log \frac{X}{K_s} \right)^{-2.5}}{\left(2 \log \frac{\rho_c U_c X}{\mu_c} - 0.65 \right)^{-2.3}}$$

Since flows of MHD interest are far from being flat plate flows (due to finite $\frac{dp}{dx}$) the usual x dependence of R_f is changed to a dependence on local quantity (in this case the momentum thickness) by numerically integrating the rough flat plate momentum equation:

$$\frac{d\theta}{dx} = \frac{c_f}{2} = \frac{1}{2} \left[2.87 + 1.58 \log \frac{X}{K_s} \right]^{-2.5}$$

the solution of this numerical integration allows us to find the development of the momentum thickness with distance x and thus obtain a roughness correction factor as a function of θ : $R_f = R_f(K_s, \rho_c, U_c, \theta)$. For a typical flow of a generator like the Mark VI and a roughness height of .2 mm, this R_f is 1.6 at channel inlet and drops down to 1.2 at the outlet. For the dissipation integral we use a fit made by Truckembrodt from the results of Rotta, in terms of the Reynolds number based on the incompressible momentum thickness: $\int_0^\delta \mu \left(\frac{\partial U}{\partial y} \right)^2 dy = \frac{0.0056}{(\rho_c U_c \theta_I / \mu)^{1/6}}$

In order to account for compressibility effects, this integral is multiplied by a dissipation correction factor $\mathcal{D}$ in order to match flat plate conditions with no MHD effects. This factor ranges from 0.8 to 2 for supersonic flows near Mach 1. Figure A-1 shows the boundary layer velocity profile on a rough flat plate with no MHD effects at $x = 1/2$ meter for different dissipation factors $\mathcal{D}$, (1.6, 1.8, 2), as calculated from this model.

Finally, the wall heat flux q_w is calculated in a similar fashion as the shear stress. First, Reynold's analogy is used in order to calculate the smooth wall heat flux:

$$q_w = \frac{\tau_w}{P_t} \left(\frac{H_c - H_w}{U_c} \right)$$

Then this result is multiplied by a heat transport roughness factor R_H obtained from the friction roughness factor R_F by replacing the enthalpy thickness for the momentum thickness, so that we have $R_H = R_H(K_s, \rho_c, U_c, \delta_H)$.

The electrical calculation is done by assuming infinite segmentation and solving Ohm's law in the three regions: core, electrode wall boundary layer, and sidewall boundary layer, and coupling them to the proper connection equations (Faraday or diagonal connection).

A flow chart of the model is shown in Figure A-2. First the burner subprogram calculates the total enthalpy coming out of the burner: H . Then the mass flow rate $\dot{m}$, burner pressure P_o , area distribution $A(x)$, magnetic field distribution $B(x)$, and an initial displacement thickness equal to zero, are inputted into subprogram ISEN which does the isentropic expansion by means of integrating:

$$\frac{dT}{dp} = - \frac{T}{p^2} \left(\frac{\partial p}{\partial T} \right)_P \left(\frac{1}{\frac{\partial h}{\partial T}} \right)_P$$

from P_o (burner pressure), to the pressure which gives the desired mass flow rate, $\dot{m}$

$$\dot{m} = \rho U A^* = \frac{p}{RT} U A^* = \frac{p}{RT} \sqrt{2 [H - h(P, T)]} A^*$$

where $h(p, T)$ is a given static enthalpy function of pressure and temperature. For the first iteration step $A^* = A$ (since δ^* was assumed equal

to zero). With the set of thermodynamic variables known at inlet (p_i , U_i , T_i), control goes to subroutine CALC which calculates the boundary layer characteristics at a certain x position (in this case the channel inlet), given a set of boundary layer inlet conditions (δ_i , τ_{wi} , α_i). This is done by numerically integrating across the boundary layer to find quantities

$$\text{like } \delta^* = \int_0^{\delta} \left(1 - \frac{\rho U}{\rho_c U_c} \right) dy. \quad (\text{note that in order to do this integration.}$$

profiles must be provided for ρ (or T) and U as functions of the 3 input parameters δ , τ_w , and α . This will be explained below.

With the displacement thickness known, we go back and proceed to do the isentropic expansion again and find the first iterated values of p_i , U , and T_i . This procedure is iterated till the values of p_i , U_i , T_i and or δ_i^* converge within 1%.

At this point, the channel integration is initiated. RK2 is a subprogram that integrates the 9 simultaneous differential equations along the axial direction, and obtains the next x position variables given an integration step ΔX . In order for this integration to be done, the values of the derivatives are required, and these are obtained in subroutine DERIVS, from the boundary layer characteristics obtained in CALC, and the electrical calculation done in subroutine ELEC.

As was previously mentioned, we need a velocity and a temperature profile in the boundary layer as functions of δ , τ_w , and α in order to generate the integral quantities in the boundary layer (δ , O , δ_{KE} , δ_H , $\langle \sigma \rangle$, etc.). The velocity profile used is a two parameter profile (in δ , τ_w) with a logarithmic profile in the outer portion of the boundary layer and a laminar profile near the wall. If we define $\bar{\eta}$ and $\bar{U}$ as functions of δ and τ_w in the following way:

$$\bar{\eta} = \frac{\sqrt{\rho w}}{\mu_w} \sqrt{\tau_w} \delta$$

$$\bar{U} = \frac{U_c \sqrt{\rho w}}{\sqrt{\tau_w}}$$

Then the two parameter velocity profile (now in $\bar{\eta}$ and $\bar{U}$) is:

$$\frac{U}{U_c} = \frac{1}{\bar{U}} \left\{ \left[\left(1 - \frac{1}{C_1} - C_3 \right) \bar{\eta} \frac{Y}{\delta} - C_3 \right] e^{a \bar{\eta} \frac{Y}{\delta}} + \frac{1}{C_1} \ln \left(1 + \bar{\eta} \frac{Y}{\delta} \right) C_3 \right. \\ \left. + \frac{1}{2} \left[1 + \sin \left(\pi \left(-\frac{Y}{\delta} - \frac{1}{2} \right) \right) \right] \left[\bar{U} - \frac{1}{C_1} \ln \bar{\eta} - C_3 \right] \right\}$$

where c_1 , a , and c_3 are empirical constants.

For the temperature profile, a one parameter power law of the total enthalpy profile is used:

$$\frac{H - H_w}{H_c - H_w} = \left(\frac{Y}{\delta} \right)^a$$

This yields a temperature profile in terms of the parametric a and the velocity profile.

APPENDIX D
TYPICAL COMPUTER OUTPUT

PROGRAM PDG 73
ETF CHANNEL 06/14/77

H=1.1130E+00 C=1.0210E+00 N=7.8100E+00 O=2.4640E+00 K=4.2400E-02 CS=0.0000E-01

H=1.1130E+00	HE=0.0000E+00	LI=0.0000E-01	BE=0.0000E-01	B=0.0000E-01	C=1.0210E+00	N=7.8100E+00	O=2.4640E+00	F=0.0000E-01
NE=0.0000E-01	NA=0.0000E-01	MG=0.0000E-01	AL=0.0000E-01	SI=0.0000E-01	P=0.0000E-01	S=5.7600E-03	CL=0.0000E-01	A=0.0000E-01
K=4.2400E-02	CA=0.0000E-01	SC=0.0000E-01	TI=0.0000E-01	V=0.0000E-01	CR=0.0000E-01	MN=0.0000E-01	FE=0.0000E-01	CO=0.0000E-01
NI=0.0000E-01	CU=0.0000E-01	ZN=0.0000E-01	GA=0.0000E-01	GE=0.0000E-01	AS=0.0000E-01	SE=0.0000E-01	BR=0.0000E-01	KR=0.0000E-01
RB=0.0000E-01	SR=0.0000E-01	Y=0.0000E-01	ZR=0.0000E-01	NB=0.0000E-01	MO=0.0000E-01	TC=0.0000E-01	RU=0.0000E-01	RH=0.0000E-01
PD=0.0000E-01	AG=0.0000E-01	CD=0.0000E-01	TN=0.0000E-01	SN=0.0000E-01	SB=0.0000E-01	TE=0.0000E-01	I=0.0000E-01	XE=0.0000E-01
CS=0.0000E-01	BA=0.0000E-01	LA=0.0000E-01	CE=0.0000E-01	PR=0.0000E-01	ND=0.0000E-01	PM=0.0000E-01	SH=0.0000E-01	CU=0.0000E-01
GD=0.0000E-01	TB=0.0000E-01	DY=0.0000E-01	HO=0.0000E-01	ER=0.0000E-01	TM=0.0000E-01	YB=0.0000E-01	LU=0.0000E-01	HF=0.0000E-01
TA=0.0000E-01	M=0.0000E-01	RE=0.0000E-01	OS=0.0000E-01	IR=0.0000E-01	PT=0.0000E-01	AC=0.0000E-01	HG=0.0000E-01	TL=0.0000E-01
PB=0.0000E-01	BI=0.0000E-01	PO=0.0000E-01	AT=0.0000E-01	RN=0.0000E-01	FR=0.0000E-01	RA=0.0000E-01	AG=0.0000E-01	TH=0.0000E-01
PA=0.0000E-01	U=0.0000E-01	NP=0.0000E-01	PU=0.0000E-01	AM=0.0000E-01	CH=0.0000E-01	BK=0.0000E-01	CF=0.0000E-01	E=0.0000E-01

EMDOTT= 65.00000 Flow Rate (Kg/sec)
 EM1 = 0.85000 Mach #
 P0 = 5.40000 Inlet Stagnation Pressure
 SIGFAC = 1.00000 Factor for conductivity &
 WTFAC = 1.00000 Factor for wt
 ALPHA = 0.00000 Load factor
 BJ = 4.00000 Initial field

VEA = 150.0000 Local Electrode Voltage Drop Parameters
 VEB = 60.00000
 FTAU = 2.00000
 HO = 260.00000
 DELHC = 0.00000
 ASUBR = 0.00000
 ASUBT = 0.00000

Parameter for C_f Friction Calculation
 Stagnation Enthalpy (Cal/g)
 Reference Enthalpy
 Percent to 0 Inlet Supersonic Area Ratio
 Throat Area Percent to 0

HISPRS= 1.0000 TGUSS= 3000.000 PGUSS= 0.00 L = 1.00000000E-03 ASUB1S= 0.0000 SKIPIN= 0.00
 NSAME= 0 IGETH = 1 CHMOUT= 0.00 DELTAX = 1.00000000E-03 DELMIT= 1.00000000E-05
 TOL = 1.00000E-04 TLDN = 1.00000E-01 THETA1= 2.00000000E-03
 HBAR1 = 1.25000 ELO = 3.00000 MIT = 20 HSUBR = 0.50000000E-03 XSTOP = 11.000
 EPST = 1.00000000E-03 EPSP = 1.00000000E-03 EPSM = 5.00000000E-03 XMUR = 1.00000000E-03
 JKNUC = 0 TENMS = 1.00000000E-05 FACTOP = 0.30000000E-03 XSTART= 0.00 EPMDOT= 1.00000000E-03
 TOL = 1.00000E-04 ITSET = 1 IOUMP = 0 IPINPT= 1 IPLAST= 0 NGTH = 0
 FREQ = 1.000000 KOTDX= 0

NPTS8= 15 Mag. Field (Tesla)

BXTAB	BTAB	BXTAB	BTAB	BXTAB	BTAB
0.0000000	4.0000000	0.2500000	4.6666667	0.5000000	5.3333333
0.7500000	6.0000000	1.0000000	6.0000000	2.0000000	6.0000000
3.0000000	5.6700000	4.0000000	5.3400000	5.0000000	5.0000000
6.0000000	4.6800000	7.0000000	4.3500000	8.0000000	4.0000000
9.0000000	3.6900000	10.0000000	3.3600000	11.0000000	3.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

NPTS= 3 Constant Velocity Profile

XTAB	UTAB	XTAB	UTAB	XTAB	UTAB
0.0000000	1.0000000	5.0000000	1.0000000	10.0000000	1.0000000
0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

NPTSA= 3
AXTAB 0.0000000

ALTAB 0.6750000

AXTAB 5.0000000

ALTAB 0.6750000

AXTAB 11.0000000

ALTAB 0.6750000

Dominant Species Code

NUMBER=	10.0000000	10.1180000	10.1350000	10.1370000	10.2530000	10.2630000	10.2670000	10.2720000	10.2740000	10.3020000	10.3030000
	10.3040000	10.3160000	10.3110000	10.3250000	10.3320000	10.3340000	10.5130000	10.5230000	10.5240000	10.5330000	10.9920000
	10.9930000	11.9930000	21.2530000	21.2630000	21.3250000	21.5130000	21.6090000	0.0000000	0.0000000	0.0000000	0.0000000
	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

TWALL= 1.80000E+03

DELHC	MW	MOLE FRACTIONS	CO2	CO	H2O	H2	N2	O2	KOH	K
7.324E+02	2.978E+01		1.857E-01	0.000E-01	6.943E-02	2.832E-02	7.093E-01	0.000E-01	7.711E-03	0.000E-01

X B R DELX I	D1C D2C D1A D2A	AC AA AAC	PC TC HC RHOC REY	DATE 6.1477 SIGMA W*TAU MC-BAR POX-BAR POY-BAR	CASE UC GAMMA MC PCX PCY	2.000 MEMO DELTA* THETA DELTA VE PR	1 HBR H CF QOOT-L	PHI PHIC ALPHA QOOT-T	EYC EXC JY ALPHAC QINT-L	VX POWER POWER-VE POWER-NET QINT-T
0.00000E+01	4.1276E-01	1.7337E-01	3.6017E+01	1.0295E+01	7.9633E+02	1.4276E-03	1.2500E+00	3.3459E+00	2.5344E+03	0.0000E-01
4.00000E+00	4.1276E-01	1.7274E-01	2.6678E+03	9.8019E-01	1.1516E+01	2.0000E-03	7.1381E-01	3.9709E+00	6.3824E+02	0.0000E-01
0.00000E-01	4.1562E-01	1.7037E-01	1.8421E+02	8.4420E-01	8.5000E-01	2.0641E+02	6.8259E-03		6.7034E+03	0.0000E-01
1.00000E-03	4.1562E-01		4.7906E-01	5.3713E+00	5.4000E+00	1.5857E+02		6.7500E-01	7.9559E-01	0.0000E-01
3.8212E+03			1.7608E+07	5.4075E+00	5.4325E+00	8.5868E-01	6.5087E+04	8.4815E+05	0.0000E-01	0.0000E-01
1.00000E+00	4.4192E-01	1.9529E-01	3.8919E+00	9.5828E+00	7.9633E+02	4.4930E-03	1.2992E+00	1.6243E+00	3.6258E+03	1.3685E+03
6.00000E+00	4.4192E-01	2.0332E-01	2.6297E+03	1.6888E+00	1.1524E+00	5.9259E-03	7.9820E-01	1.8631E+00	1.9461E+03	5.7645E+06
0.00000E-01	4.5091E-01	1.9529E-01	1.6299E+02	8.3926E-01	8.5663E-01	5.3729E+02	6.6226E-03		1.1044E+04	6.9085E+02
5.6933E-02	4.5091E-01		4.1793E-01	4.9323E+01	4.6659E+00	1.7696E+02		6.7500E-01	7.5882E-01	5.0737E+06
3.5035E+03			2.0482E+07	4.6265E+00	4.6894E+00	8.5815E-01	5.2670E+04	7.1818E+05	1.0109E+05	1.3546E+06
2.00000E+00	4.8865E-01	2.3878E-01	2.4698E+00	8.5820E+00	7.9633E+02	8.6611E-03	1.3160E+00	1.3203E+00	3.6387E+03	3.5347E+03
6.00000E+00	4.8865E-01	2.5600E-01	2.5746E+03	2.0702E+00	1.1539E+00	1.1907E+02	7.9408E-01	1.5423E+00	2.3592E+03	1.4005E+07
0.00000E-01	5.0597E-01	2.3878E-01	1.3274E+02	8.3659E-01	8.6625E-01	9.5629E+02	6.5933E-03		9.7803E+03	1.6095E+06
1.4796E-01	5.0597E-01		3.4182E-01	3.6599E+00	3.7623E+00	2.0197E+02		6.7500E-01	7.6150E-01	1.2395E+07
3.0834E+03			2.0940E+07	3.6889E+00	3.7777E+00	8.5713E-01	4.2638E+04	5.8527E+05	1.9147E+05	2.5932E+06
3.00000E+00	5.4129E-01	2.9300E-01	1.9642E+00	7.5873E+00	7.9633E+02	1.4108E-02	1.3247E+00	1.1637E+00	3.4815E+03	5.9649E+03
5.6700E+00	5.4129E-01	3.2434E-01	2.5184E+03	2.4076E+00	1.1559E+00	1.7045E+02	8.2769E-01	1.3984E+00	2.4895E+03	2.2276E+07
0.00000E-01	5.6951E-01	2.9300E-01	1.0233E+02	8.3271E-01	8.7612E-01	1.4748E+01	6.6228E-03		7.8456E+03	2.5916E+06
1.5928E-01	5.6951E-01		2.7856E-01	2.9019E+00	3.0222E+00	2.3465E+02		6.7500E-01	7.7131E-01	1.9689E+07
2.6749E+03			2.0478E+07	2.9268E+00	3.0310E+00	8.5571E-01	3.5177E+04	4.7963E+05	2.7452E+05	3.7300E+06
4.00000E+00	5.9541E-01	3.5452E-01	1.5828E+00	6.6783E+00	7.9633E+02	2.0862E-02	1.3300E+00	1.0597E+00	3.3327E+03	8.4844E+03
5.3400E+00	5.9541E-01	4.0594E-01	2.4655E+03	2.9516E+00	1.1586E+00	2.4279E+02	8.5925E-01	1.3166E+00	2.5314E+03	2.9927E+07
0.00000E-01	6.3714E-01	3.5451E-01	7.4223E+01	8.2743E-01	8.8941E-01	2.0890E+01	6.6713E-03		6.1439E+03	3.5955E+06
2.6919E-01	6.3714E-01		2.3023E-01	2.3334E+00	2.4637E+00	2.7517E+02		6.7500E-01	7.8367E-01	2.6332E+07
2.3082E+03			1.9745E+07	2.3556E+00	2.4698E+00	8.5392E-01	2.9649E+04	3.9986E+05	3.5226E+05	4.7845E+06
5.00000E+00	6.4801E-01	4.1992E-01	1.3104E+00	5.8838E+00	7.9633E+02	2.8784E-02	1.3335E+00	1.0099E+00	3.1912E+03	1.0986E+04
5.0100E+00	6.4801E-01	4.9784E-01	2.4176E+03	3.0664E+00	1.1616E+00	3.2399E-02	8.8844E-01	1.3630E+00	2.4492E+03	3.6721E+07
0.00000E-01	7.0558E-01	4.1991E-01	4.9239E+01	8.2086E-01	8.9376E-01	2.7818E+01	6.7192E-03		4.6995E+03	4.5934E+06
4.5494E-01	7.0558E-01		1.9037E-01	1.9182E+00	2.0543E+00	3.2271E+02		6.7500E-01	7.9981E-01	3.2127E+07
1.9930E+03			1.9051E+07	1.9390E+00	2.0583E+00	8.5185E-01	2.5524E+04	3.4056E+05	4.2599E+05	5.7734E+06
6.00000E+00	6.9587E-01	4.8423E-01	1.1152E+00	5.2225E+00	7.9633E+02	3.7459E-02	1.3362E+00	1.0195E+00	3.0543E+03	1.3336E+04
6.6800E+00	6.9587E-01	5.9411E-01	2.3763E+03	3.3111E+00	1.1644E+00	4.0970E+02	9.1432E-01	1.3710E+00	2.2279E+03	2.2475E+07
0.00000E-01	7.7078E-01	4.8419E-01	2.8108E+01	8.1336E-01	9.0093E-01	3.5157E+01	6.7525E-03		3.5133E+03	5.5465E+06
4.5494E-01	7.7078E-01		1.6855E-01	1.6222E+00	1.7624E+00	3.7476E+02		6.7500E-01	8.1951E-01	3.6929E+07
1.7345E+03			1.8586E+07	1.6432E+00	1.7651E+00	8.4963E-01	2.2449E+04	2.9731E+05	4.9656E+05	6.7112E+06

X BR DELX I	D1C D2C D1A D2A	AC AA AAC	PC TC HC RHOC REY	DATE 6.1477 SIGMA W*TAU MC-BAR POX-BAR POY-BAR	CASE 2.000 UC GAMMA MC POX PCY	MEMO DELTA* THETA DELTA VE PR	1 HBAR H CF QDOT-L	PHI PHIC ALPHA QDOT-T	EYC EXC JY ALPHAC QINT-L	VX POWER POWER-VE POWER-NET QINT-T
7.0000E+00	7.3628E-01	5.4210E-01	9.8377E-01	4.7001E+00	7.9639E+02	4.6283E-02	1.3383E+00	1.1036E+00	2.9193E+03	1.5399E+04
4.3500E+00	7.3628E-01	6.8698E-01	2.3424E+03	3.4535E+00	1.1682E+00	4.9432E-02	9.3628E-01	1.5511E+00	1.8822E+03	4.7099E+07
0.0000E-01	8.2884E-01	5.4203E-01	1.1113E+01	8.0544E-01	9.0670E-01	4.2418E-01	6.7627E-03		2.5615E+03	6.4112E+06
4.5494E-01	8.2884E-01		1.5056E-01	1.4184E+00	1.5603E+00	4.2770E+00		6.7500E-01	8.4268E-01	4.0688E+07
1.5325E+03			1.8447E+07	1.4388E+00	1.5623E+00	8.4747E-01	2.0162E+04	2.6642E+05	5.6456E+05	7.6104E+06
8.0000E+00	7.6772E-01	5.8939E-01	8.9125E-01	4.3103E+00	7.9639E+02	5.4597E-02	1.3400E+00	1.3008E+00	2.7831E+03	1.7072E+04
4.0200E+00	7.6772E-01	7.6897E-01	2.3162E+03	3.4761E+00	1.1711E+00	5.7258E-02	9.5353E-01	1.9136E+00	1.4544E+03	5.0599E+07
0.0000E-01	8.7691E-01	5.8933E-01	-1.7482E+00	7.9761E-01	9.1155E-01	4.9125E-01	6.7469E-03		1.8034E+03	7.1476E+06
4.5494E-01	8.7691E-01		1.3848E-01	1.2810E+00	1.4254E+00	4.7758E+02		6.7500E-01	8.6931E-01	4.3451E+07
1.3827E+03			1.8663E+07	1.3021E+00	1.4269E+00	8.4555E-01	1.8465E+04	2.4485E+05	6.3035E+05	8.4868E+06
9.0000E+00	7.8989E-01	6.2393E-01	8.3467E-01	4.0397E+03	7.9639E+02	6.1900E-02	1.3414E+00	1.7189E+00	2.6437E+03	1.8298E+04
3.6900E+00	7.8989E-01	8.3483E-01	2.2977E+03	3.3821E+00	1.1735E+00	6.4068E-02	9.6616E-01	2.6499E+00	9.9764E+02	5.3052E+07
0.0000E-01	9.1369E-01	6.2385E-01	-1.0762E+01	7.9024E-01	9.1433E-01	5.4939E-01	6.7064E-03		1.1916E+03	7.7252E+06
5.9142E-01	9.1369E-01		1.3.81E-01	1.1926E+00	1.3399E+00	5.2147E+02		6.7500E-01	8.9962E-01	4.5326E+07
1.2779E+03			1.9233E+07	1.2149E+00	1.3412E+00	8.4404E-01	1.7203E+04	2.3018E+05	6.9415E+05	9.3303E+06
1.0000E+00	8.0347E-01	6.4557E-01	8.0232E-01	3.8721E+03	7.9639E+02	6.7902E-02	1.3427E+00	2.7542E+00	2.5000E+03	1.9074E+04
3.3600E+00	8.0347E-01	8.8224E-01	2.2866E+03	3.1892E+00	1.1755E+00	6.9097E-02	9.7441E-01	4.4564E+00	5.6099E+02	5.4574E+07
0.0000E-01	9.3928E-01	6.4554E-01	-1.6368E+01	7.8353E-01	9.1590E-01	5.9695E-01	6.6451E-03		6.8109E+02	8.0875E+06
5.9142E-01	9.3928E-01		1.2643E-01	1.1401E+00	1.2910E+00	5.5741E+02		6.7500E-01	9.3426E-01	4.6450E+07
1.2111E+03			2.0137E+07	1.1639E+00	1.2922E+00	8.4303E-01	1.6262E+04	2.2061E+05	7.5613E+05	1.0169E+07
NOT IN XTAB RANGE FOR X = 1.048E+01										
1.0475E+01	8.0347E-01	6.4557E-01	7.9355E-01	3.8721E+03	7.9639E+02	6.7902E-02	1.3425E+00	2.7542E+00	2.5000E+03	1.9006E+04
3.3600E+00	8.0347E-01	8.8224E-01	2.2827E+03	3.1892E+00	1.1755E+00	6.9097E-02	9.7441E-01	4.4564E+00	5.6099E+02	5.4441E+07
0.0000E-01	9.3928E-01	6.4366E-01	-1.7978E+01	7.8399E-01	9.1650E-01	5.9695E-01	6.6451E-03		6.8109E+02	8.0875E+06
5.9142E-01	9.3928E-01		1.2643E-01	1.1282E+00	1.2778E+00	5.5741E+02		6.7500E-01	9.3426E-01	4.6354E+07
1.2111E+03			2.0137E+07	1.1516E+00	1.2789E+00	8.4303E-01	1.6262E+04	2.2061E+05	7.4903E+05	1.0069E+07

LX = 7, SKIP CASE.

APPENDIX E

NOTES ON PARTICULATE RADIATION

Methods for estimating the emissivity of particulates in a furnace are given. We first consider how one estimates the emissivity for particles which are large compared to the wavelength of light in terms of the absorption coefficient of the particle material. We treat the optically thin limit where all of the particulate radiation reaches the walls. Then we give a correction to be used when the optically thin approximation is not valid. A consistent definition of gas emissivity follows and then at the end we give expressions for combining particulate and gas emissivities.

1. Estimate of Emissivity of Particles

For simplicity we estimate the emissivity of small particles assuming: 1) that the particles are spherical, 2) that their radius is large compared to the wavelengths of light, 3) the surface reflection is zero, and 4) the gas of particles is optically thin. We estimate the emissivity which is the fraction of the maximum Planck intensity by considering the case of particles contained in a large spherical container of radius R . We assume that the density of particles is sufficiently small so that radiation from all particles reaches the surface without attenuation. This is what is implied by the thin gas limit. A correction to be applied when this situation does not occur will be treated in the next section. We assume that the spherical shell absorbs all radiation incident on it from the particles. The maximum radiation which reaches the inner surface of the containing sphere is given by the product of the Planck intensity times the surface area of the sphere. The actual intensity is given by the product of this quantity and the emissivity according to

$$\epsilon_p B_\lambda(T) 4\pi R^2 = I_w \quad (E-1)$$

where ϵ_p is the emissivity attributed to the gas of small particles in the thin gas limit, $B_\lambda(T)$ is the Planck intensity corresponding to temperature T at wavelength λ , the sphere radius is R and the total intensity received by the sphere is I_w .

We can now calculate the radiation to the walls which is the total radiation emitted by all particles. The radiation per unit volume per steradian from the material whose absorption coefficient is k is given by

$$J = \frac{k B_{\lambda}(T)}{\pi} \quad (\text{E-2})$$

The total radiation per particle assuming $kr_R \sim 1$ is then given by

$$I_p = \frac{4}{3} \pi r_p^3 \cdot 4\pi \cdot \frac{k B_{\lambda}(T)}{\pi} \quad (\text{E-3})$$

where r_p is the particle radius. For a density of particles n_p the total radiation from all particles is given by

$$I_W = n_p \cdot \frac{4}{3} \pi R^3 \cdot I_p \quad (\text{E-4})$$

which, as we have indicated, is equal to the total radiation which reaches the wall in the thin gas limit. Equating the results in Eqs. (E-1) and (E-4) we can obtain the value of ϵ_p . The result is

$$\epsilon_p = n_p \cdot \frac{4}{3} \pi r_p^3 \cdot \frac{4 k R}{3} \quad (\text{E-5})$$

We note that the emissivity has the following reasonable properties: 1) it increases with the density of particles, 2) it increases with the volume per particle, 3) it increases with the absorption coefficient which by detailed balance means that it increases with the emission coefficient of the particle material and 4) it increases with the size of the radiating region (R). It is also interesting that the emissivity is independent of the temperature (in the approximation that k is constant) and the Planck intensity distribution.

As an example we evaluate the expression for the emissivity given by Eq. (E-5) taking $n_p = 6 \times 10^3 \text{ cm}^{-3}$, $r_p = 2 \times 10^{-4} \text{ cm}$, $k = 4 \times 10^3 \text{ cm}^{-1}$, $R = 6 \times 10^2 \text{ cm}$ we obtain $\epsilon_p = 0.64$.

2. Breakdown of Thin Gas Approximation

When the density of particles increases, light from some particles is absorbed in other particles before reaching the surface. This will reduce the particle radiation which reaches the wall to a value less than given

by Eq. (E-4). The individual particles do not absorb the light incident on them completely and transmit a fraction of the light given by

$$T_p \doteq e^{-kr_p} \quad (E-6)$$

where r_p is taken as the average distance the light ray travels in traversing the spherical particle. We next give the number of particles a light beam would intersect traversing from its emission location to the wall. Using the radius of the sphere as an effective traverse distance, we take

$$\tau = n_p \cdot \pi r_p^2 \cdot R \quad (E-7)$$

We can now estimate the fraction of light which actually reaches the wall compared to the estimate given by Eq. (E-4)

$$\frac{\epsilon}{\epsilon_P} = \begin{cases} \tau T_p + (1-\tau) & \tau < 1 \\ (T_p)\tau & \tau > 1 \end{cases} \quad (E-8a)$$

$$(E-8b)$$

The equation (E-8a), where the probability $\tau < 1$, is based on the idea that the fraction of particles which intersect the light rays reduce this fraction by T_p while the rays which are unaffected by particles give their complete radiation. When the probability τ exceeds 1, that is, there are more than one transmission through particles, then we take the expression given in Eq. (E-8b) as the appropriate reduction factor for estimating the actual wall radiation which comes from all particles.

As a specific example, we consider the values used in the preceding section. In this case, $T_p = 0.45$, $\tau = 0.45$, and since τ is less than 1, we use Eq. (E-8a). With these values we obtain the reduction in intensity reaching the walls from the particles and, hence, the reduction in the emissivity, to be 0.75. The emissivity in the case considered when corrected for the breakdown of the thin gas approximation, is reduced from the value given in the preceding section of 0.64 to the value 0.48.

3. Definition of Gas Emissivity

For consistency with the derivation of particle emissivity we calculate a thin gas emissivity. Using Eq. (E-2) for the radiation per unit volume

per steradian, we obtain the radiation to the wall from a spherical volume of radius R to be

$$I_W = \frac{4\pi}{3} R^3 \cdot 4\pi \cdot \frac{kB_\lambda(T)}{\pi} \quad (E-9)$$

Then the emissivity (consider Eq. (E-1)) is given by

$$\epsilon_S = \frac{4}{3} kR \quad (E-10)$$

where the subscript S is for spherical geometry. For cylindrical geometry

$$I_W = \pi R^2 h \cdot 4\pi \cdot \frac{kB_\lambda(\tau)}{\pi} \quad (E-11)$$

where h is the height of the cylinder. In the limit of $h \gg R$ we can neglect radiation to the ends and

$$\epsilon_C = 2kR \quad (E-12)$$

where the subscript C is for cylindrical geometry. One recognizes Eq. (E-12) as the emissivity from a thin gas of thickness $L = R$. To see this consider the radiation per unit area from one side of a thin slab of thickness L , which is

$$I_W = \frac{1}{2} \cdot 4\pi \cdot \frac{kB_\lambda(\tau)}{\pi} \cdot L \quad (E-13)$$

where the factor $\frac{1}{2}$ arises since $\frac{1}{2}$ of the light exits each side of the slab, the 4π is for the full solid angle, $kB_\lambda(\tau)/\pi$ is the radiation per unit volume per steradian, and L is the slab volume per unit area. In this case, the emissivity is defined by

$$I_W = \epsilon_{SL} B_\lambda(\tau) \quad (E-14)$$

where the subscript SL is for slab. Combining Eqs. (E-13) and (E-14) we obtain

$$\epsilon_{SL} = 2kL \quad (E-15)$$

4. Combining Emissivities

Expressions for combining emissivities and intensities are given here. The emissivity (ϵ_i) of species i can be expressed in terms of an effective optical depth (τ_i) using

$$\epsilon_i = 1 - e^{-\tau_i} \quad (E-16)$$

The total emissivity for N species is determined by the total optical depth according to

$$\epsilon_{\text{Tot}} = 1 - \exp(-\sum_{i=1}^N \tau_i) = 1 - \exp(\ell \ln \prod_{i=1}^N (1-\epsilon_i)) = 1 - \prod_{i=1}^N (1-\epsilon_i) \quad (\text{E-17})$$

For two species

$$\epsilon_{\text{Tot}} = 1 - (1-\epsilon_1)(1-\epsilon_2) = \epsilon_1 + \epsilon_2 - \epsilon_1\epsilon_2 \quad (\text{E-18})$$

In terms of intensities (I_i) and the Planck limit (B) we have using $\epsilon_i = I_i/B$ that the total intensity for two species is

$$I_{\text{Tot}} = I_1 + I_2 - (I_1 I_2 / B). \quad (\text{E-19})$$

A convenient form for the case in which one specie has an emissivity independent of wavelength is

$$I_{\text{Tot}} = \epsilon_1 B + (1 - \epsilon_1) I_2. \quad (\text{E-20})$$

From our example above $\epsilon_1 = 0.48$ and Eq. (E-20) becomes

$$I_{\text{Tot}} = 0.48B + 0.52 I_g \quad (\text{E-21})$$

where the subscript g stands for gas. This relation is used to obtain the total radiation curve in Section 2.0.

APPENDIX F

RESULTS FROM STUDIES OF DIFFERENT SEED REGENERATION PROCESSES

A. PERC (PITTSBURGH ENERGY RESEARCH CENTER PROCESS)

This process involves a two stage conversion of solid K_2SO_4 to solid K_2CO_3 ; the first being a reduction to solid K_2S using H_2 , CO or a mixture thereof, and the second involving reaction of a steam- CO_2 mixture with K_2S to form H_2S and the carbonate.

Reduction of K_2SO_4 with CO is exothermal, with an estimated heat evolution of 290 Btu/lb K_2SO_4 reduced. Reduction of K_2SO_4 with H_2 is endothermal, with estimated heat needs of 118 Btu/lb K_2SO_4 reduced. These heats are required or evolved at the system's temperature. If both reactions can be made to occur simultaneously in proper proportions, Stage I becomes thermally neutral. In Stage II, the heat evolved per pound of K_2SO_4 reacted in Stage I (to form 0.79 lbs K_2CO_3) is 413 Btu. In Stage I reduction of solid K_2SO_4 at $750^\circ C$, about 20% of the H_2 and about 20% of the CO can in thermodynamic theory be utilized in the reactor to make K_2S . In Stage II, most of the CO_2 and H_2O fed should in theory react at $500^\circ C$ to convert K_2S to K_2CO_3 .

The available literature indicates that, in experimental studies to date, only a small gas utilization has been attained. Thus, judging by his data, Joubert⁽¹⁾ attained 2% conversion of the H_2 or CO in Stage I, and 5% of the CO_2 in Stage II. These gas conversions should improve somewhat with longer contact times in countercurrent operations, unless the presence of increasing amounts of H_2O and CO_2 somehow inhibit rates. In any event, equilibrium limitations will prevent more than 20% utilization of the H_2 and CO in this reducing gas at $750^\circ C$.

1. Reactors, Stages I and II

It is clear that in Stage I, extensive reduction of K_2SO_4 by H_2 and/or CO requires longer contact time of the gas with the solid than was attained in Joubert's reactor. To attain higher conversions in large scale reactors, countercurrent operations are indicated. Unfortunately, such operations will involve temperatures above the $K_2S - K_2SO_4$ eutectic's melting point. Vertical shaft kilns as well as fluidized bed systems are therefore probably not suitable because of sticking problems. A rotary

kiln may be a possible reactor, provided that "ring" formation due to sticking can be controlled. The same comments also apply to the Stage II kiln, since low melting point eutectics may also form here. Before committing large funds to the ETF plant, a pilot operation is indicated, and the chances of success do not appear great.

2. Reactor Dimensions

Because of limited rate data, it is difficult to estimate residence times needed for either the gas or the solid streams in either stage. A two hour residence time per stage for the solid, depending on temperature, might be a first approximation.

3. Gas Utilization

Hopefully, in Stage I, a gas utilization of 50% of theoretical can be attained. This assumes the Stage I feed gas to be idealized "synthesis" gas from the partial combustion with air of a liquid hydrocarbon analyzing 26% CO, 26% H₂, the rest N₂. If 50% of theoretical conversion is attainable, then off-gas from the kiln would analyze 3.1% CO₂, 22.9% CO, 3.1% H₂O, 22.9% H₂ and the rest N₂. This gas, with a heating value of 125 to 150 Btu per cubic foot, could be utilized elsewhere in the plant and should receive heating value credit in evaluating the energy requirements for the PERC process. Highly idealized initial flow quantities, based upon the indicated gas utilization, are presented in Figures F-1 and F-2.

4. Gas Quality

In a Stage I reactor, CO₂ and H₂O concentrations would become large enough so that Stage II reactions would also occur to some extent. Thus, the off-gas from Stage I would be contaminated with some H₂S. The severity of this problem remains to be determined.

5. Sticking

In a rotary kiln reactor, serious melting would make grave difficulties because of ring formation. A possible solution would be to pass all the potassium sulfate recovered from the MHD process through the kiln, and reduce only that part of it needed for sulfur removal. Hopefully, the melting point diagrams will indicate that such partially reduced solid mixtures do not develop melting below 700°C. Several alternative modi-

Figure F-1 PERC Process-Stage I Theoretical Flow Diagram (Basis: Per 100 Pound Moles of Reducing Gas Fed) Assuming 50% of Equilibrium Could Be Attained

Figure F-2 PERC Process-Stage II Theoretical Flow Diagram (Basis: Per 100 Pound Moles of Reducing Gas Fed) (Assuming a Three-Fold Excess Needed of CO₂ and H₂O)

fications of this scheme, such as recycling a large quantity of K_2S , are imaginable.

6. Single Stage Operation

As indicated in point 4, it may be possible, as claimed by Bienstock,⁽²⁾ to combine Stages I and II in a single rotary reactor. However available information on rates is not encouraging.

Stage I

Idealized material flows shown in Figure F-1 assume an idealized feed gas from the partial combustion of a hydrocarbon oil with air. A gas conversion of 50% of theoretical in a rotary kiln shows relative quantities based on 100 pound moles of reducing gas fed to the rotary reactor.

Heats of Reaction

The reactions occurring are as follows:

Unfortunately, enthalpies and free energies of formation of the sulfide and the sulfate as reported in the literature (Refs. 3, 4, 5, and 6) are not always with reference to sulfur in the same standard state, are subject to considerable error, and are available only at 25°C. After making the necessary corrections to put these two reactions on the same standard state basis, the values of the enthalpy changes for them at 25°C (for the sulfate and sulfide in the solid state, see Thermodynamic Calculations section for details), are shown below. The ΔH° values may be taken as unchanged with temperature until the melting temperatures are reached, when some modification will be required.

The following gas phase reaction can also occur:

In theory, if Reactions (1) and (2) can be made to proceed simultaneously in the proper proportion by adjusting the ratio of H_2 to CO in the gas feed, then the overall reaction can be made thermally neutral.

In that case, only sensible heat need be supplied to the reactants.

Equilibrium

The available data on free energies are subject to some uncertainty, resulting in corresponding uncertainties in the calculated magnitude of the equilibrium constants for Reactions (1) and (2) at temperatures of interest. The most likely values of these equilibrium constants, namely $(P^4_{H_2O}/P^4_{H_2})$ for Reaction (1) and $(P^4_{CO_2}/P^4_{CO})$ for Reaction (2), are shown in Table F-1.

The equilibrium constants were calculated from the equations presented in the Thermodynamic Calculations section. At best, for either gas at 750°C, only about 20% of the reducing gas can be used in Stage I.

Kinetics

The most relevant data on kinetics appears to come from the work of Joubert. ⁽¹⁾ He passed reducing gas up through a vertical tube 2.86 cms, inside diameter, in which 10 grams (0.574 gm moles) of K_2SO_4 were reacted at around 750°C in a stream of reducing gas moving at 2400 cc STP per minute. This is equivalent to about 0.107 gram moles gas per minute, and the corresponding linear hot gas flow velocity is 0.74 ft/sec. This gas velocity was no doubt sufficient to fluidize the charge in the reaction tube, provided melting did not occur. Since an eutectic has been reported in the $K_2S - K_2SO_4$ system, which melts at 587°C (versus melting points of 1076°C for K_2SO_4 and 840°C for K_2S), the precise condition of the charge during reaction in the Joubert experiments (750°C) is difficult to assess.

Judging by Joubert's ⁽¹⁾ Figure 4, the 750°C line shows about 95% reaction of the K_2SO_4 charge in pure hydrogen in 20 minutes. This would mean a ratio of H_2O/H_2 in the off-gases of $0.0574 \times 0.95 / (0.107 \times 20 -$

TABLE F-1
PERC PROCESS - STAGE I
EQUILIBRIUM CONSTANTS

Temperature (°C)	<u>REACTION (1)</u>		<u>REACTION (2)</u>	
	Equilibrium Constant	$\frac{P_{H_2O}}{P_{H_2}}$	Equilibrium Constant	$\frac{P_{CO_2}}{P_{CO}}$
25	1×10^{-8}	0.01	1.8×10^{12}	1.16×10^3
500	5.5×10^{-4}	0.15	0.42	0.805
600	1.3×10^{-3}	0.19	0.052	0.478
750	3.5×10^{-3}	0.24	4.88×10^{-3}	0.264

0.0574 x 0.95), or about a 2.5% utilization of the hydrogen. In other words, hydrogen utilization falls far short of the equilibrium value for Reaction (1). Again by Figure 5,⁽⁵⁵⁾ 80% reduction is attained with CO in 20 minutes of operation at 750°C. This corresponds to a ratio of CO₂/CO in the off-gases of only 0.0574 x .8/ (0.107 x 20 - 0.0574 x 0.8), or only about a 2% utilization of the CO. This again falls far short of the equilibrium value for Reaction (2). It should be noted that H₂ and CO utilizations are even poorer when these gases are diluted with steam or nitrogen. Joubert also found that changes in gas flow velocities had no effect on the fraction of the solid reduced during any given period of operation. He found that rate was more or less proportional to the partial pressure of reducing gas used, as is evident from his Figures 6 and 7.⁽¹⁾ This data indicates that chemical reaction kinetics rather than diffusion is the rate controlling step. The data available with H₂ feed gas containing larger amounts of H₂O or CO containing larger amounts of CO₂, indicate that such dilution affects rates disadvantageously. The assumption in Figure 2-147, namely that 50% of equilibrium can be attained in the off-gases (10% utilization per pass of the H₂ and CO), is therefore very optimistic. Such a performance would require very long contact times between the solids and the gas.

Stage II

Idealized material flows shown in Figure F-2 assume an idealized feed gas as the off-gas from coke combustion with air, and 25% reaction of the entering CO₂ and H₂O. The same basis is used here as in Stage I.

Heats Of Reaction

The reactions in Stage II are presumably:

The limitations that were mentioned earlier apply to these thermodynamic data, and an estimate of absolute entropy for KOH was used. With these reservations, and taking K₂S, K₂CO₃, and KOH all as solids, the enthalpies of Reaction (4), (5) and (6) (see "Thermodynamic

Calculations section (Tables F-3 and F-4) for details) are:

Reaction (4) $\Delta H_{298}^{\circ} = -32.87$ kcals

Reaction (5) $\Delta H_{298}^{\circ} = -4.8$ kcals

Reaction (6) $\Delta H_{298}^{\circ} = -7.05$ kcals

Equilibrium

The estimated values for the equilibria of Reactions (4), (5) and (6) are shown in Table F-2. It will, of course, be recognized that the equilibrium constant for Reaction (4) is $(\text{COS}) / (\text{CO}_2)^2$, and for Reaction (5) is $(\text{H}_2\text{S}) / (\text{H}_2\text{O})^2$, where the quantities in brackets are partial pressures. It should be recognized that these values are subject to error, since the entropies of formations for KOH and K_2CO_3 were determined by estimations using approximation equations in the literature. Nevertheless, the probable errors are such that the conclusions below are substantially correct.

It is obvious that Reactions (4) plus (5) represent a favorable pathway, and that these two reactions should go to completion. In theory, 100% utilization is attainable of the CO_2 and H_2O charged.

Table F-2 indicates that equilibrium conversions for Reaction (4) rapidly diminish as the temperature rises above 600°C . Poor conversions at temperatures above 600°C are in fact observed by Joubert, which he explains by a melting mechanism. An alternative explanation is that equilibrium itself rapidly becomes unfavorable at temperatures above 600°C .

The unfavorable equilibrium constant for Reaction (5) explains why Joubert found no H_2S in the off-gases when passing pure steam through K_2S . Desulfurization occurred with CO_2 - H_2O mixtures because both Reactions (4) and (6) now presumably take place. The overall reaction in the mix is the sum of Reactions (4) and (6), or Reaction (7), $\text{K}_2\text{S} + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{K}_2\text{CO}_3 + \text{H}_2\text{S}$. For this reaction, ΔH° is -39.94 kcal, or 413 Btu evolved per pound of K_2SO_4 reduced in Stage I. Reaction (6) has a favorable equilibrium constant at all temperatures, hence little COS is to be expected in the off-gases if rates are reasonable.

Theoretically, therefore, in the presence of water vapor a large fraction of any CO_2 present should react with K_2S in Stage II operations.

TABLE F-2
PERC PROCESS - STAGE II
EQUILIBRIUM CONSTANTS

<u>Temperature (°C)</u>	<u>Reaction (4)</u>	<u>Reaction (5)</u>	<u>Reaction (6)</u>
300	67,000	Unfavorable	Favorable at
500	34	at all	all
650	1.0	temperatures	temperatures
800	0.08		

Kinetics

From Joubert's (1) Figure 9, it appears that rates and conversion are most favorable at 500°C, and that 80% conversion of K_2S to K_2CO_3 was attained in about 20 minutes, or 100% in about 50 minutes. The fraction of CO_2 reacted in the Joubert apparatus during these runs, however, is only about 3.9% ($100 \times (0.0570) (0.8) / 0.580 \times 20 = 3.9$) during the first 20 minutes (2600 cc STP per minute of a gas, 50% CO_2 & 50% steam, equivalent to 0.580 gram moles of CO_2 content per minute). The effectiveness of CO_2 in more highly dilute gas systems remains to be demonstrated.

TABLE F-3
PERC PROCESS
ENTHALPIES AND FREE ENERGIES OF FORMATION

	<u>Standard State, Sulfur</u>	<u>ΔH_f</u>	<u>ΔF_f</u>	<u>References</u>
K_2SO_4	solid	-342.66	-314.62	(1), (3), (4)
K_2S	solid	-100.00	-85.50*	(1)
K_2S	S_2 gas	-103.4	-95	(2)
KOH		-101.78	-91.35*	(1)
K_2CO_3		-274.93	-255.5*	(1), (3), (4)
H_2S	S_2 gas	-20.24	-17.47	(2)
COS	S_2 gas	-49.44	-50.12	(2)
CO		-26.4	-32.8	(1)
CO_2		-94.05	-94.26	(1)
H_2O (g)		-57.8	-54.6	(1)

* Estimated as follows:

K_2S : Elliott and Gleiser report -95 kcal for ΔF° at 298° , when the standard state for sulfur is S_2 . Recognizing that ΔF° at 298° K when the standard state is solid sulfur is about 9.5 kcal bigger than when the standard state is S_2 then ΔF° becomes -95. + 9.5 = -85.5 when forming K_2S from solid sulfur.

KOH: $1/2 H_2 + 1/2 O_2 + K = KOH$: $\Delta H^\circ = -101.78$ Estimating ΔS° by the method of Meissner⁽⁶²⁾ $\Delta S^\circ = -35$ EU. Therefore, for this formation reaction at 298° K: $\Delta F^\circ = (\Delta H^\circ - T\Delta S^\circ) = 101.78 + 35 \times 0.298 = 91.35$.

K_2CO_3 : $2K + C + 3/2 O_2 \rightleftharpoons K_2CO_3$; $\Delta H^\circ = -274.9$ kcal Estimating ΔS° for this reaction by the method of Meissner,⁽⁶²⁾ $\Delta S = 65$ EU. Hence ΔF° is $(\Delta H^\circ - T \Delta S^\circ)$ or -255.53 at 298° K.

TABLE F-4

PERC PROCESS

CALCULATED THERMODYNAMIC VALUES FOR REACTIONS INVOLVED

REACTIONS	Calculated at 298°K		ΔS°	Log K Equations
	ΔH°	ΔF°		
(1) $K_2SO_4 + 4H \rightleftharpoons K_2S + 4H_2O$	+11.5 kcal	+10.6 kcal	3.01 E. U.	$\frac{-2516}{T^\circ K} + 0.66$
(2) $K_2SO_4 + 4CO \rightleftharpoons K_2S + 4CO_2$	-28	-16.7	-37.9	$\frac{6126}{T^\circ K} - 8.3$
(3) $CO_2 + H_2 \rightleftharpoons CO + H_2O$	See Standard References			
(4) $K_2S + 2CO_2 \rightleftharpoons K_2CO_3 + COS$	-32.87	-22.1	-36.14	$\frac{7300}{T^\circ K} - 7.91$
(5) $K_2S + 2H_2O \rightleftharpoons 2KOH + H_2S$	-4.8	+4.06	-29.7	$\frac{1049}{T^\circ K} - 6.5$
(6) $COS + H_2O \rightleftharpoons CO_2 + H_2S$	-7.05	-7.01	- 0.13	$\frac{1542}{T^\circ K} - 0.03$

NOTE: In REACTIONS (1) and (2) the standard state for sulfur was assumed solid (rhombic) when taking values of F, H and S from the preceding table. In REACTIONS (4), (5) and (6), S_2 was taken as the standard state.

On June 14, 1977, the above analysis was discussed in a conference at the laboratories of the Pittsburgh Energy Research Center with the principal investigators involved in the experimental study of the PERC process. They generally agreed with the above conclusions. Although they believed that any seed regeneration process from which elemental sulfur could be produced as a byproduct would be economically advantageous, their process was not sufficiently developed to use in a conceptual design for the ETF. They could not offer reliable data on which to base such a design, at least not until further experiments on a pilot plant scale could be conducted. The latter, they asserted, might reduce uncertainties related to equilibria, reactant melting, reaction kinetics, and the maximum achievable concentration of H_2S in the off-gas from the carbonation stage to meet feed requirements of the Claus or Holmes-Stretford elemental sulfur conversion processes. The PERC investigators believed that about one year would be required for the pilot scale investigations, but that the prospects were poor for that program being undertaken in their laboratory. The PERC investigators also agreed that the Carbon Reduction Process - i. e., using carbon as the reductant instead of H_2 and/or CO - is an attractive process option which should be explored.

In general then, it was concluded that theoretically the PERC process does not appear to be technically viable and as yet has not been demonstrated to be technically viable. Consequently, it was dropped in this study from further consideration as a candidate seed regeneration process for the ETF.

B. HYDRATED LIME (CAUSTICIZING) PROCESS

This process involves the following two steps:

Reaction (1) $\text{K}_2\text{SO}_4 + \text{Ca}(\text{OH})_2 \rightleftharpoons 2\text{KOH} + \text{CaSO}_4$
Reaction of potassium sulfate in aqueous solution with solid slaked lime to form the relatively insoluble calcium sulfate.

Reaction (2) $2\text{KOH} + \text{CO}_2 \rightleftharpoons \text{K}_2\text{CO}_3 + \text{H}_2\text{O}$
After removal of the CaSO_4 by filtration, the solution is reacted with CO_2 to form potassium carbonate.

Since Reaction (1) will go only partially to completion when operating at reasonable concentrations, the salts recovered by evaporation following Reaction (2) will be a mixture of potassium sulfate and potassium carbonate. To meet EPA regulations on SO_2 emission, approximately 10% of the K_2SO_4 recycled from the MHD system needs to be converted to potassium carbonate for Montana coal, while roughly 71% must be converted for Illinois coal.

A flowsheet utilizing Montana coal is shown in Figure F-3 with quantities as follows, per 2000 lbs K_2SO_4 recycled from the MHD channel off-gases:

Lime Hydrate, $\text{Ca}(\text{OH})_2$	85 lb
Steam	14000 lb
Gypsum produced, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	156 lb
K_2CO_3	159 lb

These values are assumed to be the best attainable, with actual lime consumption probably 10% greater, actual steam consumption about 15% greater, and an inevitable potassium loss of 1 to 2%.

The chief uncertainties in the flow sheet are:

1. The size of the reactors needed to attain the necessary residence times
2. The concentration of the liquors from Reaction (1), and consequently the steam needed for evaporation
3. The conditions in Reaction (1) which involve potassium losses due to double salt formation

It is imaginable that Reaction (2), involving potassium carbonate formation with CO_2 , can be eliminated if a slurry of K_2SO_4 and KOH can be recycled directly back into the MHD channel.

*Note: Gypsum is reported here as CaSO_4 , rather than $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Figure F-3 Theoretical Flow Sheet Causticizing Process Montana Coal
(Basis: 2000 lb K_2SO_4)

With Illinois coal, steam consumption increases about 30 fold and lime consumption about 7 fold.

Causticizing

Reaction (1) (causticizing reaction) was originally proposed and studied many years ago. Inspection shows that the equilibrium constant K for this reaction is the ratio:

$$K_{\text{equil. const.}} = \frac{(\text{OH}^-)^2}{(\text{SO}_4^{=})} \quad (\text{F-1})$$

The quantities in brackets are the thermodynamic activities of the indicated ions. Lacking activity coefficient data, these thermodynamic activities are often approximated as being equal to the corresponding ion molalities.

The total potassium concentration in this solution in gram equivalents per 1000 grams water is as follows:

$$(\text{K})^+ = 2(\text{SO}_4^{=}) + (\text{OH}^-) \quad (\text{F-2})$$

This equation ignores the small amount of calcium in solution.

The composition of the equilibrium solution for Reaction (1) can be calculated theoretically from Eq. (F-1) as a function of the potassium concentration (K^+) . This calculation, however, is subject to several uncertainties resulting from the lack of data on ion activity coefficients for these solutions. Fortunately, some direct experimental data are available. Although these data are old, they appear to be reliable. These data are plotted in Figure F-4 and are in agreement with theory, showing that the ratio $(\text{OH}^-)/(\text{SO}_4^{=})$ decreases as the total potassium ion concentration increases.

The values in Table F-5 were derived by rough extrapolation of these data as they apply to the conversions required for Montana and Illinois coal. It was assumed that performances at 150° and at 190°C were similar.

From a plot of the equilibrium data, note that at 400 mM of $\text{SO}_4^{=}$ per liter (assumed roughly equal to molarity), (OH^-) is 100 mM per liter. Since 100 mM of OH^- are equivalent to 50 mM of $\text{SO}_4^{=}$, then the initial sulfate concentration was $(100/2 + 400)$, and the percent sulfate conversion to OH^- was:

Figure F-4 Causticizing Process SO_4^{2-} Concentration vs OH^- Concentration

TABLE F-5
CAUSTICIZING PROCESS ION CONCENTRATIONS AT 150°C

	<u>Montana Coal</u>	<u>Illinois Coal</u>
Final OH ⁻ concentration	0.1 molal	0.021 molal
Final SO ₄ ⁼ concentration	0.4 molal	0.0035 molal
Total initial SO ₄ ⁼ concentration	0.45 molal	0.014 molal
% conversion of initial SO ₄ ⁼ to OH ⁻	10%	75%

$$100 \times \frac{100/2}{100/2 + 400} \cong 10\%$$

Similarly, when $(\text{SO}_4^{=})$ is 3.5 mM/liter, then (OH^-) is 21 mM/liter and the initial $(\text{SO}_4^{=})$ concentration is $(3.5 + 21/2) = 14$ mM/liter. The efficiency of conversion is then $100 \times (21/2)/14 \cong 75\%$. Note that this point on Figure F-4 is extrapolated far beyond Herold's experimental points. Laboratory confirmation of this extrapolation is desirable.

Table 2-58 indicates that for Montana coal, which requires 10% re-generation of the recycled K_2SO_4 , an initial K_2SO_4 concentration of 0.45 molal is necessary. With Illinois coal, a solution of only 0.014 molal is permissible for the required 70% regeneration.

Note that no results are presented for temperatures below 120°C because the following double salts tend to form at these lower temperatures (the temperature stability limits have not been clearly established):

Syngenite

"Pentasalt"

Both these double salts are highly insoluble and would cause serious potassium losses in the filter cake, so they cannot be permitted to form. Apparently no trouble from double salt formation would be encountered at temperatures over about 150°C .

Possible Plant Operations

As just discussed, a key question is the fractional conversion of K_2SO_4 to KOH which can be attained in Reaction (1). The quantities of water which must be evaporated from the solutions formed with Montana and Illinois coals are shown in Table F-6..

The flowsheet shown in Figure F-3 is for Montana coal and shows theoretical quantities which could be modified as follows:

1. Potassium losses due to spillage, misting in the evaporators, etc. will probably be at least 1%.
2. Steam requirements should be increased by 10% - 15% to allow for heat losses.
3. Lime use efficiency will probably be about 95%.
4. Reactor size is based on an assumed 30 minute reaction time. Longer residence times will require larger reactors.

TABLE F-6
CAUSTICIZING PROCESS WATER EVAPORATION REQUIREMENTS

	<u>Initial Solution</u>		<u>Evaporation (Triple Effect)</u>
	<u>Molality</u>	<u>lb H₂O/lb K₂SO₄</u>	<u>lb Steam/lb K₂SO₄</u>
Montana Coal	0.45	12.77	5
Illinois Coal	0.014	410	164

Carbonation

The solution of mixed KOH and K_2SO_4 from Reaction (1) would then be reacted with CO_2 to convert the hydroxide to carbonate. The resultant solution would be dried in an evaporator and the dry salt (a mixture of K_2SO_4 and K_2CO_3) would be injected into the MHD channel.

As an alternative, this carbonate step could probably be eliminated entirely. That is, the mixed solution from Reaction (1) could be concentrated and then injected into the MHD channel. Unless most of the water present is evaporated, such a procedure would introduce considerable amounts of water into the channel.

The flowsheet shown in Figure F-3 for Montana coal is self-explanatory. Operations are continuous, with three reactors in series favored over a single reactor to avoid lime by-passing, thus more closely approximating piston flow.

The solids are fed to the reactors via lock-hoppers operating alternately. It may be preferable to prepare a slurry of these solids in the recycled condensate, followed by injection into the reactors with a slurry pump.

If this flowsheet is used without modification, then steam needs will be thirty times greater with Illinois coal (per 2000 lbs of K_2SO_4 from the MHD channel) and the size of the reactors will change. Lime needs will increase about seven fold.

The assumed residence time needed of 1/2 hour in these reactors should be experimentally checked. If slurry density in the reactors is assumed to be 65 lbs per cu. ft, the total volume of the three reactors is $27,625/2 \times 65$ or 212.5 cu. ft for K_2SO_4 flow of 2000 lb/hr.

4. Laboratory Program

Although the data plotted in Figure F-4 appear to be reliable, they should be checked experimentally with special attention paid to the conditions of temperature and pressure needed to avoid double salt formation. Rate studies of Reaction (1), exploring temperature and lime hydrate consumption vs time as a function of the excess K_2SO_4 used, are particularly important.

Although the so-called Lime Process appears to be the simplest of all the regeneration processes explored, it has certain disadvantages. It

produces gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) as the sulfur containing byproduct which must be disposed of as solid waste.

Moreover, as indicated in the foregoing analysis, theoretical considerations related to the equilibrium constant for the primary reaction in water solution between potassium sulfate (K_2SO_4) and lime ($\text{Ca}(\text{OH})_2$) require that the reactors be operated at 190°C (374°F) and at very low solution concentrations. The technical implications of the latter are severe for Montana coal and devastating for Illinois coal. Because approximately seven times more K_2SO_4 must be regenerated for the high sulfur Illinois coal case than for the low sulfur Montana coal case, impractically low solution concentrations must be used in the Reaction (1) stage. The huge amounts of water involved must eventually be removed by evaporation in order to regenerate the dry potassium carbonate needed for recycle to the MHD system. The practical implications of this fact are illustrated in Figures F-5 and F-6 which present early conceptual engineering flow diagrams for the ETF plant size chosen for this overall study. For the Montana case, about 150,000 lb/hr of water would have to be evaporated; for the Illinois case, about 30 x or 4,600,000 lb/hr of water would have to be evaporated. Even with a multiple effect evaporator system, the energy demands of this step would make it impossible to achieve a reasonable overall power generating efficiency for the MHD facility when high sulfur Illinois coal is fed. Since the Design Criteria for this study requires that the Illinois coal be one of the fuels used, the process appears to be technically impractical.

Consequently, the Hydrated Lime (Causticizing) Process was dropped from further consideration as a candidate seed regeneration process for the ETF.

MASS FLOW (lb/hr)

PLANT SIZE BASIS: MONTANA COAL - 57,143 lb/hr AS FED

Input:	K_2SO_4	-	11,486
	$Ca(OH)_2$	-	499
	$H_2O(l)$	-	132,061
	$H_2O(g)$	-	17,584

<u>Stream</u>	<u>K₂SO₄</u>	<u>CaSO₄-2H₂O</u>	<u>KOH</u>	<u>K₂CO₃</u>	<u>H₂O</u>
A	10,308	1159	756	---	149,401
B	10,308	---	756	---	149,401
C	10,308	---	---	931	149,401
D	10,308	---	---	931	---
E	---	---	---	---	149,401
F	---	---	---	---	131,817
G	---	---	---	---	17,584
H	---	---	---	---	244

Figure F-5 Causticizing Process Conceptual Flow Diagram - Material Basis: ETF Plant Size Montana Coal Feed

PLANT SIZE BASIS: ILLINOIS COAL - 51,919 lb/hr AS FED

Input:	K_2SO_4	11,222
	$Ca(OH)_2$	3,386
	$H_2O(l)$	4,056,679
	$H_2O(g)$	540,135

Stream	K_2SO_4	$CaSO_4 \cdot 2H_2O$	KOH	K_2CO_3	H_2O
A	3259	7860	5128	---	4,595,169
B	3259	---	5128	---	4,595,169
C	3259	---	---	6316	4,595,169
D	3259	---	---	6316	---
E	---	---	---	---	4,595,169
F	---	---	---	---	4,055,034
G	---	---	---	---	540,135
H	---	---	---	---	1645

Figure F-6 Causticizing Process Conceptual Flow Diagram - Material Basis: ETF Plant Size Illinois Coal Feed

C. FORMATE PROCESS

This process has been identified in the literature as having been developed and patented in Germany and the United States during the 1930's. It is described as a process industrially practiced in Germany for producing potassium carbonate (K_2CO_3) from potassium sulfate (K_2SO_4), first by treatment with hydrated lime and carbon monoxide at $200^\circ C$ ($392^\circ F$) and 15 atmospheres (220 psia) or 32 atmospheres (470 psia) to produce soluble potassium formate ($KCOOH$) and partially hydrated calcium sulphate ($CaSO_4 \cdot 2H_2O$), which can be separated by filtration. The formate solution is then dried and finally incinerated with air to form potassium carbonate. Yields, purities, and reaction rates are described as good under the operating conditions selected so as to preclude formation of inseparable double salts of $K_2SO_4 - CaSO_4$ (syngenite and a pentasulphate). A number of German and United States patents are identified in the references.

Investigations made in the course of this ETF study have confirmed that the process was in industrial use in Germany at least until the beginning of World War II and that at least one of the producing companies involved still exists (partly in East Germany, partly in West Germany), but that the process has now been superseded by the carbonation of caustic potash (KOH) produced by electrolysis of potassium chloride obtainable from local salt brines.

The technical evaluation of the so-called Formate Process conducted in this study has proceeded to the point of theoretically confirming all claims made in the patents and the literature references, but not of ascertaining precise operating conditions required for the critical steps. Information sources contacted in Germany have indicated, however, that such operational data can probably be obtained.

As a result, it has been concluded that the Formate Process is technically viable and can be seriously considered as the recommended seed regeneration process for the ETF, and for full scale MHD power plant operations as well.

Because of the specific requirements of chemical combination with sulfur dioxide (SO_2) in the MHD system, $KCOOH$ can be used directly in the second stage of the MHD combustor. Conversion to K_2CO_3 , therefore, is unnecessary. The details of how the above conclusions evolved in this study follow.

Although the Formate Process appears to be technically viable for both Montana and Illinois coal grades, it produces gypsum as the sulfur containing byproduct which must be disposed of as solid waste; and although the process was used industrially in Germany for many years, its adaptation to MHD generally and to the ETF specifically needs to be tested on a pilot scale, and/or more information on the German technology must be obtained. It should be understood that the design concepts presented herein are first approximations based on theoretical analysis. Application of these concepts directly to engineering design is presented in a preliminary way in Section 2.16.2 and must at this time be based on untested assumptions concerning rates of conversion of K_2SO_4 to $KCOOH$, behavior of the reactions at different pressures, temperatures, gas compositions, and many others. The technical uncertainties inherent in this kind of analysis can easily be resolved by pilot plant scale experiments or by reference to established industrial experience, but preferably both will be used.

The theoretical flowsheet presented in Figure F-7 is not optimized and several assumptions were made in its formulation.

To produce 2000 lb potassium carbonate, the material needs of this flowsheet are:

Potassium sulfate	3026 lb
Lime	1072 lb
Coke (10% ash)	445 lb
Steam	See Flowsheet

Losses of potassium in this process can probably be kept low relative to the potassium sulfate feed, assuming no formation of insoluble potassium compounds with the fly ash. Losses will be due largely to dusting, spillage, incompletely washed filter cakes, etc.

The potassium carbonate produced (2000 lb) is impure, being mixed with about 504 lb of potassium sulfate. By the presence of this excess potassium sulfate the reaction is caused to go more readily to completion in the proposed tower reactor. The process also produces 2493 lb of gypsum.

Two elements in this process introduce design uncertainties which can be resolved by bench and/or pilot scale experiments:

BASIS: Pounds per 2000 lbs K_2CO_3 produced

967/968

1. The residence time, i. e., size of the tower reactor needed for completion of Stage I reaction, and

2. The arrangement and details of the spray burner in Stage II.

However, if design information on the German plants which used the Formate Process becomes available, bench or pilot scale work may not be required.

A major flowsheet simplification will result if the Stage II reactor (the spray burner, etc.) can be eliminated by introducing a strong potassium formate solution directly into the MHD combustor. Oxidation of potassium formate to potassium carbonate is strongly exothermal, and depending on the concentrations of the formate solution handled, evolves heat well in excess of that needed to evaporate the water present in this solution. Moreover, materials handling will be simplified in that the formate solution taken directly from the evaporator can be readily pumped through the plant in heated lines.

The Formate Process for converting K_2SO_4 to K_2CO_3 is disclosed in the German patents of E. Wiedbrauck, assigned to Chemische Fabrik Buckau and other German companies. It is basically a two-stage process:

Stage I

Potassium sulfate is dissolved in water and $Ca(OH)_2$ is added. "Purified" producer gas is bubbled through this slurry at $200^\circ C$ and pressures of 30 to 35 atmospheres. On a dry basis, this gas typically analyzes 30-35% CO and H_2 , the rest N_2 . This gas quickly becomes saturated with water vapor upon coming in contact with the reacting solutions, whereupon its composition is approximately 19% CO, 44% N_2 , the rest H_2O . The reaction occurring is:

The $CaSO_4$ formed is filtered off and the potassium formate solution is sent to the second stage.

Stage II

The filtered solution from Stage I is concentrated to precipitate potassium formate crystals, which are in turn recovered by filtration, and the mother liquor is recycled to Step I. The potassium formate crystals are incinerated in an oxidizing atmosphere, yielding potassium carbonate.

By operating with an excess of potassium sulfate in Stage I to improve reaction rates in the tower, the carbonate from Stage II carries a considerable amount of sulfate.

The gases containing carbon monoxide required in the tower reactor are generated in an orthodox coke-burning gas producer. By using coke as the fuel, it is hoped that the formation of tars and other undesirable hydrocarbons will be minimized, but their removal from the crude producer gas must be planned for in the usual manner. The CO_2 in these gases must next be removed prior to entering the tower reactor to prevent the loss of lime hydrate as CaCO_3 . Such CO_2 removal can be by the usual scrubbing with amine or bicarbonate solutions. Inevitably, such treatment will also remove SO_2 from these gases.

Heat Effects

$$\text{REACTION (1)} \quad \Delta H^\circ_{298} = - 27.13 \text{ kcal}$$

$$\text{REACTION (2)} \quad \Delta H^\circ_{298} = - 109.9 \text{ kcal}$$

The above value of ΔH° for REACTION (1) is for the reagents as solids. When reacting in solution, this ΔH° value for REACTION (1) will be smaller numerically, but the exact magnitude cannot be estimated at this time because of a lack of data. The Germans have estimated ΔH° for this reaction to be -7 Kcals, which is probably correct.

Although the enthalpies cited are at 25°C , they change little with temperature and may be taken as applying at all temperatures of interest. They indicate that heat evolutions for REACTION (1) is small, but very significant for REACTION (2).

Equilibrium

REACTION (1) will go substantially to completion under the proposed operating conditions of 35 atm and 200°C . A small amount of calcium ion will remain in solution as the sulfate. The appearance of this calcium in the potassium formate product is assumed to be allowable.

Flowsheet

The separate operating steps as illustrated in the flowsheet are:

Dissolver

Potassium sulfate, water, and hot recycled mother liquor are mixed with lime hydrate ($\text{Ca}(\text{OH})_2$). The solubility curve for potassium sulfate vs temperature, indicates that a saturated solution of K_2SO_4 in pure water contains 20.7% by weight of this salt at 110°C . This concentration will be reduced to about 20% by any recycled calcium formate present.

It is assumed in this flowsheet that the dissolver operates continuously, at atmospheric pressure and at the solution' boiling temperature (110°C). Hot water feed comes from evaporator condensate, with fresh water makeup, as shown.

Tower Reactor

The slurry from the dissolver is pumped through heat exchanger X-1, where its temperature rises to 200°C . The operating pressure is 35 atmospheres. The hot slurry then descends through the tower which will be designed for a reasonable liquid slurry residence time. One possible tower design could be like the "carbonating" towers in ammonia-soda plants, with a single large bubble cap per plate and considerable liquor depth per plate.

The literature suggest that there is substantially no sticking of precipitating solids (CaSO_4) on the walls of this vessel. Consequently, plugging problems should not be severe. A series of autoclaves through which the liquor flows counter-current to the gases could be substituted for this tower. The number of autoclaves required, like the number of plates in the tower, can be estimated only after equilibrium data becomes available. A reasonable estimate of the number of stages is 3-5.

As REACTION (1) proceeds in the tower, the concentration of K_2SO_4 falls while the concentration of potassium formate increases, and finely divided calcium sulfate precipitates. At temperatures below about 200°C , the potassium sulfate remaining in solution reacts at least in part with the newly formed calcium sulfate to form the double salts syngenite ($\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot \text{H}_2\text{O}$) and pentasalt ($5\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot \text{H}_2\text{O}$). These double salts are quite insoluble and stable below about 200°C . At operating temperatures below 200°C , this double salt formation would represent a loss of potassium

values for the process since they would be removed in a mixture with the gypsum (calcium sulfate) residue. For these reasons, REACTION (1) in the tower must be conducted at a temperature of 200°C where double salts apparently do not form. The high pressure is needed to maintain the liquid phase.

The double salt problem is illustrated by the solubility diagrams shown in Figures F-8, F-9 and F-10 for the system $\text{CaSO}_4\cdot\text{K}_2\text{SO}_4\cdot\text{H}_2\text{O}$. Addition of potassium formate to this system alters the relationships somewhat, but insoluble double salts still form.

Calcium sulfate precipitates as the dihydrate, i. e., gypsum ($\text{CaSO}_4\cdot 2\text{H}_2\text{O}$), which tends to appear as a gel and will be difficult to separate from the potassium formate solution. This difficulty can be overcome by recycling enough formate solution so that the potassium sulfate solution entering the tower contains at least 10% formate (German Patent 457,112 which describes a sodium salt system, but which according to Gmelin⁽⁷⁾ is equally applicable to potassium systems).

Calcium Sulfate Filter

This can probably be a pressurized continuous rotary filter with cake washing elements as required.

Multi-Effect Evaporator

The filtrate from the above, which comprises a potassium formate solution with traces of calcium salts, is concentrated in a multi-effect evaporator. The crystals of potassium formate are removed as they form and the mother liquor is recycled to the dissolver. Potassium formate is quite soluble (See Table F-7) and quite concentrated solutions are possible. For this flowsheet, the concentration of about 40% was chosen arbitrarily.

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Figure F-8 Formate Process Mutual Solubilities in Water $CaSO_4 \cdot 2H_2O$
 K_2SO_4

Point A: Saturated with I, III

Point B: Saturated with III, IV

Salt I: $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Salt II: $5\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot \text{H}_2\text{O}$

Salt III: $\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$

Salt IV: K_2SO_4

SOURCE: ICT, IV, pg. 229, 239, 353 in weight %

25°C:

III $\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot \text{H}_2\text{O}$
41.5% - 53% - 5.5%

II $5\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot \text{H}_2\text{O}$
78% - 20% - 2%

I $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
79.1 - 20.9

I $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Figure F-9 Formate Process Mutual Solubilities in Water (25%)

Point C: Saturated with I, II
 Point D: Saturated with II, III
 Point B: Saturated with III, IV

Salt I: $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
 Salt II: $5\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot \text{H}_2\text{O}$
 Salt III: $\text{CaSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot 2\text{H}_2\text{O}$
 Salt IV: K_2SO_4

100°C

SOURCE: Seidell, 4th Ed., Vol 1., Pg. 673

Figure F-10 Formate Process Mutual Solubilities in Water (100°C)

TABLE F-7
 FORMATE PROCESS
 POTASSIUM FORMATE SOLUBILITY IN WATER
 Source: ICT, Vol. IV, Page 240 (3)

<u>T °C</u>	<u>Mole Fraction</u>
-20	0.365
0	0.390
20	0.420
40	0.456
60	0.500
80	0.550
100	0.621
120	0.711
140	0.836
157	1.0

D. CARBON REDUCTION PROCESS

Early in the ETF study it was recognized that the pulp and paper industry uses a well established process analagous to the proposed reduction of K_2SO_4 , which could be considered for seed regeneration. The pulp industry process, known as "black liquor recovery," involves the recovery of chemicals and energy of combustibles (lignin) from an exhausted wood digestion solution. The method employed is essentially to burn concentrated black liquor in a reduction furnace to provide most of the steam and power required for the pulp mill and simultaneously to reduce sodium sulfate (Na_2SO_4) to sodium sulfide for reuse in wood digestion. This approach appeared to be conceptually applicable to the seed regeneration problem, i. e., reduction of K_2SO_4 to K_2S followed by carbonation to K_2CO_3 . Therefore, a decision was made to examine Carbon Reduction as an additional process option.

At the outset a literature search was made using bibliographies obtained from the Institute of Paper Chemistry and other resources. A substantial number of technical references was assembled for the reduction of Na_2SO_4 to Na_2S and a few references, mostly Russian, were identified for the reduction by carbon of K_2SO_4 to K_2S (see Bibliograph section). In the course of the literature search, a series of papers was identified which describe the related work of Atomics International Division of Rockwell International Corporation (see Bibliograph section). Their application is as a step in their proposed flue gas desulfurization process. The approach is patterned after black liquor recovery furnaces but uses petroleum instead of a lignin-petroleum mixture as the carbon source to regenerate Na_2S from Na_2SO_4 , followed by carbonation to Na_2CO_3 .

Because of the technical similarity between the Atomics International work and the seed regeneration objective, the theoretical analysis of the Carbon Reduction Process was based on their generalized concept. The latter, except for the carbon source, is almost identical to that used in black liquor recovery systems. Of course the reduction equipment proposed by Atomics International is substantially different. Because of their experience in black liquor recovery furnace designs generally, consultations were held with engineers from the Combustion Engineering Company to assess prospects for successfully designing a reduction furnace for the conversion

of K_2SO_4 to K_2S , conceptually similar to those used by the pulp and paper industry. Combustion Engineering Company believes that a Tomlinson-type, molten salt reduction furnace for this purpose could be successfully designed, built, and operated. Admittedly, however, these assurances are only conjecture. Although the theoretical analysis of the Carbon Reduction Process presented here confirms technical viability, it is considered only literature reports by Atomics International. The successful application of their equipment to seed regeneration is at this time only a hypothetical possibility. Any carbon reduction approach to seed regeneration, albeit an attractive possibility, will have to be tested on laboratory and pilot plant scales before a meaningful assessment can be made.

Equilibrium

The reduction of K_2SO_4 to K_2S by direct contact with carbon is thermodynamically favorable at about $800^{\circ}C$, which is well below the melting temperatures of K_2SO_4 ($1076^{\circ}C$) and K_2S ($840^{\circ}C$), but above the eutectic mixture melting temperature of $570^{\circ}C$. In any furnace operation, temperatures in excess of $800^{\circ}C$ are likely. With solid carbon present, the off-gas will have a high ratio of CO/CO_2 .

Heats of Reaction

The reduction of K_2SO_4 to K_2S by solid carbon is highly endothermal:

When CO_2 forms rather than CO , the heat needs are smaller:

Depending on furnace design and operation, probably 95% of the reduction is by Reaction (1), forming CO rather than CO_2 . In the Atomics International furnace as described, a high ratio of CO/CO_2 is probable. Operations favoring Reaction (2) rather than Reaction (1) are possible but probably require an impractical degree of control of feed rates.

In addition to the carbon needed to carry out the reduction of K_2SO_4 by Reaction (1), a substantial amount of carbon is also required to supply the heat needed for these endothermal reactions. The amount of carbon that is consumed in heating depends upon furnace design, i. e., on the off-gas composition which can be attained. The higher the CO_2 content in the off-gas, the smaller the carbon needs become, but the greater the sulfur contamination.

Kinetics

The reaction between solid carbon and molten K_2SO_4 is reasonably rapid at elevated temperatures and depends upon the existence of a large contact area between these two phases. In the Atomics International furnace, the carbon (petroleum coke) presumably floats on the surface of the melt in the reduction side of the furnace. In the references cited, no information is presented on particle sizes needed, or on the melt area and surface volume needed for a given rate of operation (Oldenkamp and Stegmann).⁽⁸⁾

Carbon Used

Coals and metallurgical coke are probably unsuitable for this operation because of their high ash content. A typical metallurgical coke contains 10% ash. If carbon requirements for the reduction are as previously indicated, then the ash introduced by this coke will probably tie up more potassium as silicates than can be tolerated. The only low-ash material which shows promise is petroleum coke which may contain up to about 1/2% ash. The extent to which ash from petroleum coke will combine with potassium requires laboratory study.

Furnace Design

At least three different furnace design concepts are possible:

1. Blast Furnace Concept

Here the carbon (presumably low-ash petroleum coke) and molten K_2SO_4 are fed to the top of a shaft furnace, much like a blast furnace, with molten K_2S and molten slag withdrawn below. An air blast is introduced into the bottom of the shaft through suitable tuyeres. Reaction (1) occurs within the shaft together with combustion of carbon to CO. Product gases escape at the top of the shaft.

2. Spray Burner Concept

Here finely ground coke is mixed with the molten K_2SO_4 (or with a saturated aqueous solution of K_2SO_4) and the slurry is blown into the furnace through a suitable spray nozzle. Alternatively, the powdered carbon and the K_2SO_4 might be blown in through separate nozzles, with the two streams impinging on each other. The reactions occurring in this furnace are the same as in the blast furnace.

3. The Atomics International Furnace Concept

This is a two compartment vessel with exothermal (air) oxidation of K_2S on one side and endothermal reduction of K_2SO_4 with carbon on the other. Heat is transferred between the two chambers by melt circulation. Oxygen (as sulfate) for the combustion of the carbon is also transferred by this recirculation.

To reduce sulfur volatilization as H_2S or COS , dry CO_2 - free air is probably required in the oxidation. The temperature of the reduction zone ($1400^\circ F$ claimed) is presumably high enough so that little CO_2 forms, thus theoretically minimizing the appearance of sulfur compounds in the off-gas.

In all cases, the furnace design is not simple. The proposed Atomics International design is clever, but it involves serious problems of scaleup including fluid flow complications and materials of construction.

Sulfur Contamination of Furnace Gases

In the Carbon Reduction Process, carbonyl sulfide forms when CO_2 comes into contact with K_2S . As in the PERC process, the following reactions occur:

If any moisture is present, COS will react further to form H_2S .

Some gaseous sulfur compounds will inevitably be present in the furnace off-gas because of these reactions, although the high furnace temperatures in the Atomics International system will tend to suppress them.

Flow Sheet

A possible Atomics International concept flow sheet is presented in Figure F-11. The set of conditions chosen for this case were 62 lb atoms of carbon (744 lb) to reduce 4 moles K_2SO_4 (696 lb). An 80% reduction of the K_2SO_4 fed is assumed in order to keep the melting point low.

In this Atomics International flowsheet concept, a high rate of melt recycle must be maintained to transfer the needed heat between the two furnace compartments. The total flow of melt must be about:

$$(174)(297,441 + 859,644) / (21.88)(1700 - 1400)$$

or 30,672 lb per four moles of K_2SO_4 reduced. Because of the magnitude of this flow, problems of design and size of the reactor required for this task are serious. The size and locations of the openings in the partition separating the two compartments in the reaction vessel are of particular concern, as well as the construction of the separating wall.

In this flow sheet concept, it is proposed that the product melt be withdrawn and quenched in a pool of saturated solution of the product salts, and that CO_2 (flue gas) be bubbled simultaneously through the mixture. Conversion of K_2S and K_2CO_3 will probably occur in solution via:

and

Equilibrium theory shows that these reactions are favored at low temperatures and will probably proceed in a slurry of the product salts. The steam generated in cooling the melt can be refluxed by a partial condenser as shown. If it proves impractical to operate the quenching system with a saturated slurry as proposed, quenching with water will be required. In this case, the evaporators needed to recover the dissolved salts will require 9 lbs of steam per pound of salt precipitated. The quenching system needs to be explored on a pilot plant scale.

(In the reduction process described by Atomics International, reaction of the melt with steam and CO_2 is proposed. This approach is uncertain since the reactions involved are strongly exothermic, and removal of the heat of reaction plus the sensible heat of melt cooling will be difficult.)

Notes: MC_p values: 35 for K_2SO_4 , 18.6 for K_2S
for melt, average $MC_p = \frac{(4 \cdot 18.6 + 35)}{5} = 21.88$

REACTOR ENERGY BALANCE

Sensible Enthalpy, entering Streams (70°F base)

let X = 1b atoms carbon used in combustion	
K_2SO_4 feed	$\frac{Btu}{0.0}$
Air (7.15) (600-70) ($\frac{1}{.21}$) ($\frac{X}{2}$)	9022X
Coke (feed @ 70°F)	
for reaction 16 lb atoms	0.0
for combustion X lb atoms	$\frac{0.0}{9022X}$

Sensible Enthalpy, leaving Streams (70°F base)

CO	(16+X) (1400-70) (7.14)	151,939 + 9496X
Melt at 1400°F	(5) (1400-70) (21.88)	145,502
Nitrogen	($\frac{78}{.21}$) ($\frac{X}{2}$) (1700-70) (7.09)	21,737X
		297,441 + 31,233X

Chemical Enthalpy

$$(123,260 \times .95 + 45,960 \times .05) \times 1.8 \times 4$$

$$-X (1.8 \times 26,400) = 859,644 - 47,520X$$

This overall Enthalpy Balance: (=0)

$$859,644 - 47,520X + 297,441 + 31,233X - 9022X = 0$$

$$X = 46 \text{ lb atoms}$$

NOTE: C_p for:

Air	= 7.15 Btu/lb mole °R
H_2	= 7.09 Btu/lb mole °R
CO	= 7.14 Btu/lb mole °R
Melt	= 21.88 Btu/lb mole °R

Figure F-11 Theoretical Flow Diagram-Carbon Reduction Process
Basis: Moles (lb)/4 Mules K_2SO_4 Reduced

(In the furnace itself, as shown in the proceeding figure, K_2SO_4 is reduced with carbon on the left side. The large heat requirements are supplied by the recirculating melt from the right side of the furnace. The mixture of K_2SO_4 and K_2S from the left side of the furnace is in part withdrawn as product and in part recycled to the right side of the furnace for reoxidation and heating.)

The application to the ETF plant size of the foregoing theoretical analysis appears in Figures F-12, F-13 and F-14. These conceptual flow diagrams summarize the theoretical material and heat balance computations made for both the Montana and Illinois coal feed cases. It should be noted that a quenching/carbonation system to provide about a 70% solids concentration solution is assumed. If a more dilute solution is required for melt cooling (10% solids is usual for the smelt quenching system in black liquor recovery processes), the heat required for subsequent evaporation will be much larger. Whether or not a spray drier would still be applicable was not determined. A multiple effect evaporator might have to be used. Its capital cost and the chargeable energy consumption requirements (as steam instead of "free" flue gas) would be made greater. A summary of the chargeable energy requirements appears in Table 2-62. The net energy requirements are significantly larger than for the proposed Formate Process.

There are also other uncertainties or potential disadvantages of the Carbon Reduction Process. The walls of the Atomics International furnace are constructed of fused alumina. Although this material withstands attack from molten sodium salts, its resistance to molten potassium salts is uncertain. (A water cooled wall of the Tomlinson type furnace might be a solution.)

The relatively large quantity of carbon which must be fed to the reductor raises serious questions of potassium-ash complexing. Low ash petroleum coke could perhaps be fed but there would be an operating cost penalty over metallurgical coke or anthracite coal. The potential losses of potassium values vs. type of carbon source fed would have to be explored.

The proportion of CO vs CO_2 obtained in the reduction of K_2SO_4 is uncertain. This theoretical analysis assumed a 99% molar output of CO.

Streams:	A	B	C	D	E	F	G	H
Temp (F°)	1400°	40°	300°	100°	212°	150°	300°	150°
Press (atm)	1	1	1	1	1	1	1	1

MASS FLOW (lb/hr)

PLANT SIZE BASIS: MONTANA COAL - 57,143 lb/hr AS FED

Streams entering furnace:

K_2SO_4 - 1,469
 Carbon - 1,084
 Air - 4,407

Gas Streams leaving furnace:

CO - 2,492
 N_2 - 3,372
 CO_2 - 57

Streams:	A	B	C	D	E	F	G	H
K_2SO_4	295	---	---	295	---	295	---	---
K_2S	743	---	---	---	---	---	---	---
$H_2O(l)$	---	1472	---	849	---	---	---	---
K_2CO_3	---	---	---	931	---	931	---	---
Flue Gas	---	---	2824	---	2527	---	22,215	22,215
H_2S	---	---	---	---	229	---	---	---
$H_2O(g)$	---	---	---	---	502	---	---	849

Figure F-12 Carbon Reduction Process Conceptual Flow Diagram -
Materials Basis: ETF Plant Size Montana Coal Feed

Streams:	A	B	C	D	E	F	G	H
Temp (F°)	1400°	40°	300°	100°	212°	150°	300°	150°
Press (atm)	1	1	1	1	1	1	1	1

MASS FLOW (lb/hr)

PLANT SIZE BASIS: ILLINOIS COAL 51,919 lb/hr AS FED

Streams entering furnace:

K_2SO_4 - 9,932

Carbon - 7,409

Air - 30,200

Gas Streams leaving furnace:

CO - 17,039

N_2 - 23,134

CO_2 - 392

Streams:	A	B	C	D	E	F	G	H
K_2SO_4	1769	---	---	1769	---	1769	---	---
K_2S	5039	---	---	---	---	---	---	---
$H_2O(l)$	---	9972	---	5758	---	---	---	---
K_2CO_3	---	---	---	6316	---	6316	---	---
Flue Gas	---	---	19,152	---	17,141	---	150,550	150,550
H_2S	---	---	---	---	1,557	---	---	---
$H_2O(g)$	---	---	---	---	3,391	---	---	5,758

Figure F-13 Carbon Reduction Process Conceptual Flow Diagram -
Material Basis: ETF Plant Size Illinois Coal Feed

		ENTHALPY* (Btu/Hr)	
STREAM		MONTANA COAL	ILLINOIS COAL
1.	Air, heated from 70°F - 600°F	.58 x 10 ⁶	3.96 x 10 ⁶
2.	CO, CO ₂	.86 x 10 ⁶	5.9 x 10 ⁶
3.	N ₂	1.39 x 10 ⁶	9.55 x 10 ⁶
4.	A	.25 x 10 ⁶	1.66 x 10 ⁶
5.	B	-.044 x 10 ⁶	-.30 x 10 ⁶
6.	C	.16 x 10 ⁶	1.09 x 10 ⁶
7.	D	.03 x 10 ⁶	.23 x 10 ⁶
8.	E	.65 x 10 ⁶	4.43 x 10 ⁶
9.	G	1.27 x 10 ⁶	8.6 x 10 ⁶
10.	F	.02 x 10 ⁶	.14 x 10 ⁶
11.	H	1.28 x 10 ⁶	8.69 x 10 ⁶
12.	K ₂ SO ₄ leaving MHD System	.11 x 10 ⁶	.73 x 10 ⁶
HEATS OF REACTION			
I	C + ½ O ₂ → CO ΔH = -29 kcal/gmol	- 3.34 x 10 ⁶	-22.93 x 10 ⁶
II	K ₂ SO ₄ + 4C → K ₂ S + 4CO ΔH = 123.3 kcal/gmol	1.42 x 10 ⁶	9.63 x 10 ⁶
III	K ₂ SO ₄ + 2C → K ₂ S + 2CO ₂ ΔH = 45.9 kcal/gmol	.03 x 10 ⁶	.19 x 10 ⁶
IV	CO + ½ O ₂ → CO ₂ ΔH = -67.636 kcal/gmol	-10.84 x 10 ⁶	-74.1 x 10 ⁶
V	K ₂ S + 2CO ₂ → K ₂ CO ₃ + COS ΔH = -35.27 kcal/gmol	- .43 x 10 ⁶	- 2.9 x 10 ⁶
VI	COS + H ₂ O → H ₂ S + CO ₂ ΔH = 8.37 kcal/gmol	.10 x 10 ⁶	.69 x 10 ⁶
VII	K ₂ CO ₃ + SO ₂ → K ₂ SO ₄ + CO ΔH = -23.17 kcal/gmol	- .28 x 10 ⁶	- 1.9 x 10 ⁶
VIII	CO + ½ O ₂ → CO ₂ ΔH = 67.636 kcal/gmol	- .82 x 10 ⁶	- 5.56 x 10 ⁶

* NOTE: Enthalpy of all streams relative to 70°F

Figure F-14 Carbon Reduction Process Conceptual Flow Diagram - Heat Balances Basis: ETF Plant Size Montana and Illinois Coal Feeds

TABLE F-8

CARBON REDUCTION PROCESS ENERGY REQUIREMENTS

BASIS: ETF Plant Size -Montana and Illinois Coal Feeds

	Btu/Hr*	
	Montana Coal	Illinois Coal
1. Furnance	15.72 x 10 ^{6**}	107.43 x 10 ^{6**}
2. Quench Tank (off-gas steam from 212°F to 100°F)	- 0.40 x 10 ⁶	- 2.68 x 10 ⁶
3. Spray Drier	1.27 x 10 ⁶	8.61 x 10 ⁶
4. MHD Channel (Seed feed system only)	- 1.01 x 10 ⁶	- 6.88 x 10 ⁶
SUBTOTAL	15.58 x 10 ⁶	106.48 x 10 ⁶
5. Less Flue Gas Heat	- 1.43 x 10 ⁶	- 9.7 x 10 ⁶
6. Plus CO Combustion	-10.84 x 10 ⁶	-74.1 x 10 ⁶
7. Plus Air Preheat to 600°F	0.58 x 10 ⁶	3.96 x 10 ⁶
NET TOTAL	3.89 x 10 ⁶	26.6 x 10 ⁶
	(1.167 MW)	(7.99 MW)

* + Heat demand on the system
 - Heat evolved from the system.

** Basis 14,500 Btu/lb carbon.

Lastly, the sulfur byproduct from the process is hydrogen sulfide (H_2S) which is an environmental hazard and difficult to contain. Although the subsequent conversion of H_2S to saleable elemental sulphur via the Claus or Holmes-Stretford process might offer economic advantages, the magnitude is uncertain and the wisdom of operating such a chemical manufacturing plant as part of a power generating facility is subject to question. Capital cost estimates for the Carbon Reduction Process and its adjunct sulfur producing facility were not made.

E. FLUE GAS DESULFURIZATION

A possible alternative to seed regeneration for control of SO_2 emission is the application of flue gas scrubbing processes, now in current use of a commercial scale. This study assumes that seed regeneration is a requirement for the ETF and that flue gas scrubbing for SO_2 removal will not be used. However, for purposes of economic comparison with the recommended Format Process, conceptual ETF capital cost estimates were prepared for both cases, assuming Montana coal feed. The results indicate that the estimated capital costs of a limestone slurry flue gas desulfurization system for the ETF operating on Montana coal will be double the estimated capital costs for the proposed Formate Process.

APPENDIX F

REFERENCES

1. Joubert, J. I. et al, "Kinetic of Regeneration of Spent Seed from MHD Power Generation Systems," 15th MHD Symposium, 1976
2. Bienstock, D. et al, "Air Pollution Aspects of MHD Power Generation," 13th MHD Symposium, 1973
3. US Bu. Standards, Bulletin 500
4. Elliott and Gleiser, Thermochemistry of Steel Making, Addison Wesley, 1960
5. US Dept. Commerce, Natl Bu. Standards, N SRDS - NBS #7
6. US Dept. Commerce, Natl Bu. Standards, N SRDS - NBS #30
7.

<u>German Patents</u>	<u>Effective Patent Date</u>	<u>Publication Date</u>
457,112	Jan. 17, 1925	Feb. 23, 1928
590,158	May 4, 1930	Dec. 7, 1933
592,496	April 21, 1931	Jan. 25, 1934
595,709	April 21, 1931	Mar. 29, 1934
596,522	Jan. 26, 1932	April 19, 1934
8. Oldenkamp, R. D.; Stegmann, G. C.; "Control of Gaseous Sulfur Compound Emissions"; International Conf. Proc. Paper, Univ. of Salford, England; April 1973, Vol. 2 (From Inst. of Chem. Engineering, London, England 1973)

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