

A PRELIMINARY ANALYSIS OF MHD RETROFIT FOR THE COLSTRIP POWER PLANT

MASTER

Prepared For
The United States Department of Energy
Division of Magnetohydrodynamics
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Gilbert/Commonwealth

ENGINEERS/CONSULTANTS Reading, PA / Jackson, MI
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GILBERT/Commonwealth
READING, PENNSYLVANIA

JUNE 1980

FOREWORD

The Department of Energy, Office of Magnetohydrodynamics (DOE/MHD) requested Gilbert/Commonwealth to perform a preliminary assessment of a direct fired oxygen enriched MHD power train and a separately fired MHD power train each integrated with a unit of the Montana Power Company Colstrip Power Plant. This work was performed under Contract No. ET-78-C-01-2688.

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TABLE OF CONTENTS

<u>SECTION</u>	<u>PAGE</u>
FOREWORD	i
LIST OF FIGURES	iv
LIST OF TABLES	vi
EXECUTIVE SUMMARY	1
1.0 INTRODUCTION	6
1.1 Objectives	8
1.2 Assumptions	8
2.0 THE MHD CYCLE	10
2.1 Design Considerations	10
2.1.1 MHD Power Cycle	10
2.1.2 Oxidizer Temperature	10
2.1.3 Topping Cycle Components	11
2.2 Oxidizer Delivery System	14
2.2.1 Oxygen Enriched Cycle	14
2.2.2 Separately Fired Cycle	17
2.3 Preheater	19
2.3.1 Oxygen Enriched Cycle	19
2.3.2 Separately Fired Cycle	19
2.4 Combustor	20
2.5 MHD Generator	23
2.6 Heat and Seed Recovery System	27
2.6.1 Oxygen Enriched Cycle	30
2.6.2 Separately Fired Cycle	30
2.7 Coal Preparation	31
3.0 THE COLSTRIP STEAM CYCLE	32
3.1 The Existing Plant	32
3.2 Cycle Arrangement Under Retrofit	34

TABLE OF CONTENTS(Cont'd)

<u>SECTION</u>	<u>PAGE</u>
4.0 THE INTEGRATED SYSTEM	39
4.1 Performance	39
4.1.1 MHD Out of Service	39
4.1.2 Oxygen Enriched System	39
4.1.3 Separately Fired System	42
4.1.4 Retrofit Benefits	42
4.2 Operating Conditions	43
4.2.1 Oxygen Enriched System	43
4.2.2 Separately Fired System	48
4.2.3 MHD Out of Service	50
4.3 Plant Layout	50
4.4 Operating Concerns	50
4.4.1 MHD Shutdown	50
4.4.2 Control Of Steam Blend	53
4.4.3 Oxygen Plant Considerations	53
5.0 CONSTRUCTION TIME AND COST	54
5.1 Construction Time	54
5.2 Construction Cost	54
5.2.1 System Cost	54
5.2.2 Cost Basis	57
6.0 CONCLUSIONS	58
7.0 REFERENCES	60

LIST OF FIGURES

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
1	System Summary	3
2	Oxygen Enriched MHD Topping Cycle	13
3	Separately Fired MHD Topping Cycle	13
4	Oxidizer Delivery System With 95 Mole Percent Oxygen Plant For Oxygen Enriched MHD Cycle	18
5	Mollier Chart For Channel Plasma, Oxidizer Enriched to 35 Mole Percent Oxygen	21
6	Mollier Chart for Channel Plasma, Air Oxidizer	22
7	MHD Generator Description, Direct Fired Oxygen Enriched Topping Cycle, 35 Mole Percent Oxygen Preheated to 1,100°F	24
8	MHD Generator Description, Separately Fired Topping Cycle, Air Preheated to 2,500°F	25
9	MHD Heat And Seed Recovery System, Oxygen Enriched Topping Cycle	28
10	MHD Heat And Seed Recovery System, Separately Fired Topping Cycle	29
11	Colstrip Power Plant	33
12	Range of Application for MHD Integration Methods	35

LIST OF FIGURES (Cont'd)

<u>Figure Number</u>	<u>Title</u>	<u>Page</u>
13	Retrofit Steam Cycle Flow Schematic	37
14	Heat and Mass Balance for Oxygen Enriched Colstrip Retrofit System	44
15	Heat and Mass Balance For Separately Fired Colstrip Retrofit System	45
16	Heat and Mass Balance for Stand-Alone Operation of Colstrip Steam Cycle	46
17	Plot Plan Of Oxygen Enriched Colstrip Retrofit Plant	51
18	Plot Plan of Separately Fired Colstrip Retrofit Plant	52

LIST OF TABLES

<u>Table Number</u>	<u>Title</u>	<u>Page</u>
1	Topping Cycle Components	12
2	Comparison of the Composition of 35 Mole Percent Oxygen Enriched Air with Standard Air	15
3	Comparison of the Oxygen Enriched and Separately Fired MHD Generators	26
4	System Performance Summary	40
5	Auxiliary Loss Breakdown	41
6	Steam Flows	48
7	Estimated Construction Cost for Retrofitting an Oxygen Enriched MHD Cycle to the Colstrip Power Plant	55
8	Estimated Construction Cost for Retrofitting a Separately Fired MHD Cycle to the Colstrip Power Plant	56

EXECUTIVE SUMMARY

The U.S. Department of Energy, Office of Magnetohydrodynamics (DOE/MHD) has established a development program to demonstrate the commercial feasibility of magnetohydrodynamic power generation through the operation of an Engineering Test Facility (ETF). This study presents two MHD power system designs as candidates for the Engineering Test Facility.

The two system designs involve open-cycle MHD power trains retrofitted to the coal fired Colstrip power plant owned by the Montana Power Company. Under retrofit operation, the MHD topping cycle generates electric power from hot (4,500°F) coal combustion gas flowing through the MHD generator, and produces steam for the Colstrip plant from heat recovered from combustion gas leaving the MHD generator. The Colstrip plant acts as a steam bottoming cycle, receiving a portion of its steam supply from the MHD heat recovery system. A portion of the plant steam supply is also obtained from the original Colstrip boiler operated under partial loading. A retrofit facility reduces construction time and cost from what would be required for an entirely new MHD test facility by using not only the available steam cycle equipment, but most of the supplemental facilities as well. Retrofitting also induces the participation of a utility, which is a major step towards gaining commercial acceptance of the MHD concept.

One retrofit system employs an oxygen enriched, direct fired MHD power train in which the combustion oxidizer is a mixture of air and oxygen preheated to a moderate temperature (1,100°F). The preheat is obtained in a recuperative type heat exchanger by extracting heat directly from the MHD exhaust gas. The other retrofit system uses an MHD power train with nonenriched air preheated to a high temperature (2,500°F) as the oxidizer. For this system, preheat is obtained in a regenerative type heat exchanger subsystem that is fired separately with oil.

This report presents a preliminary design and cost estimate for each retrofit system. Previous studies by Gilbert/Commonwealth, AVCO, and General Electric were drawn upon for design criteria. The MHD cycle for the oxygen enriched

retrofit system was developed for this study by employing, whenever possible, the MHD parameters used by AVCO in their separately fired ETF system design. The MHD cycle for the separately fired retrofit system was based directly on the AVCO ETF design. Both MHD channels are sized for the gas flow rate used by AVCO. The MHD cycle is integrated to the Colstrip plant with minimal effect on the existing Colstrip equipment, allowing the plant to readily resume normal operation should the MHD cycle be taken out of service.

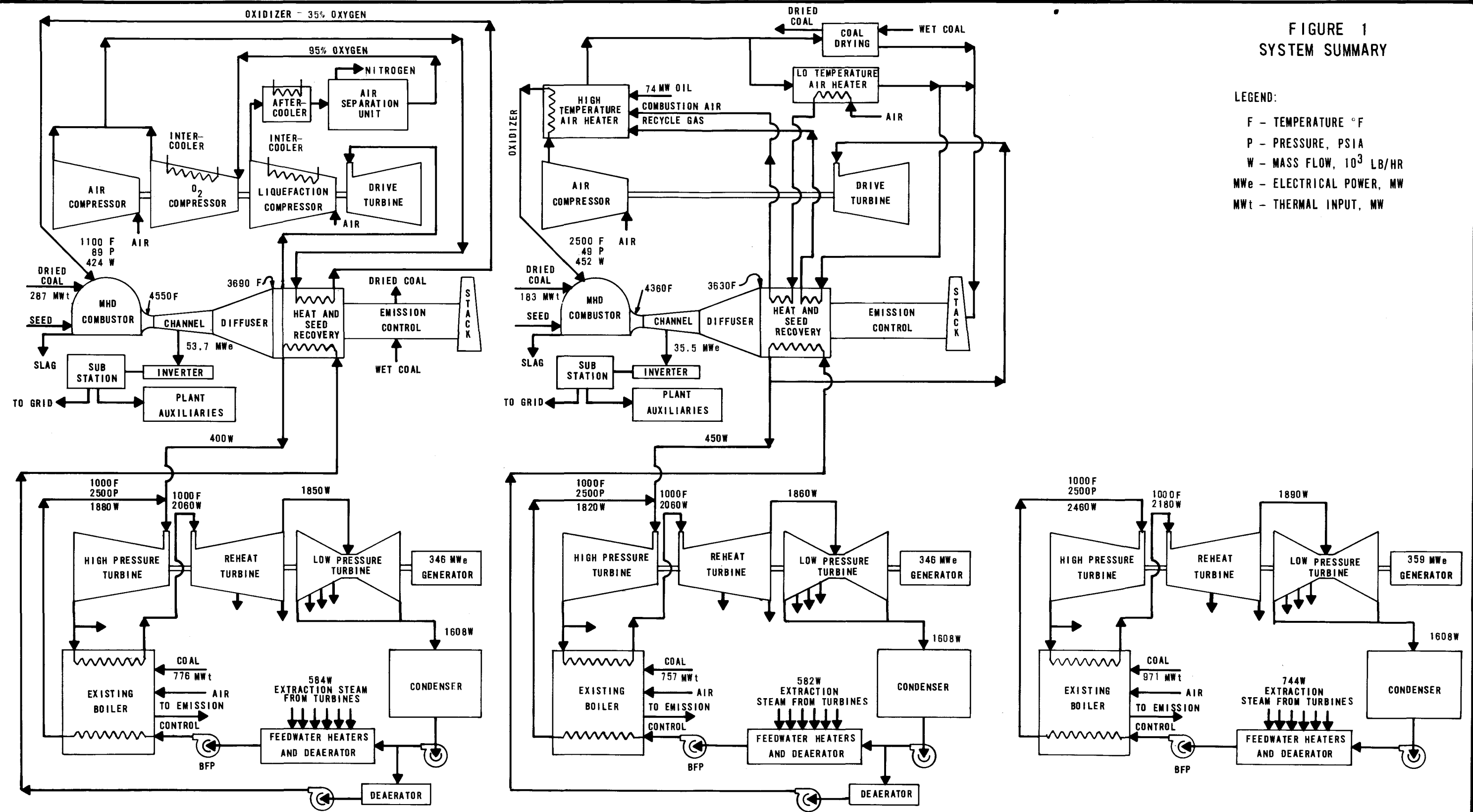
The Colstrip plant entered commercial service in 1976 and consists of two identical power generating units each producing nominally 350 megawatts of electric power (MWe). Only Unit 2 of the plant is involved in the MHD retrofit; Unit 1 is independently operated. The plant operates on a subcritical, single reheat cycle with turbine design conditions of 2,535 psia and 1,000°F at the high pressure turbine throttle, and 1,000°F at the reheat turbine inlet.

Integration of the MHD topping cycles to the Colstrip bottoming cycle is by steam connection in which the MHD power train has its own system of heat and seed recovery heat exchangers to produce steam independently of the existing Colstrip equipment. Superheat steam from the MHD heat recovery system is blended with superheat steam from the turned down Colstrip boiler and fed to the high pressure turbine at approximately the design flow rate. Inlet flow to the high pressure turbine is reduced from the design flow rate by about 7.5 percent with either MHD cycle, because less extraction steam is drawn from within the turbines and overloading of the low pressure turbine sections would otherwise occur. Extraction steam flow is less than design conditions because feedwater to the MHD topping cycle is heated by cooling MHD components and not by extraction feedwater heaters.

Figure 1 summarizes the flow schematics for the oxygen enriched retrofit system, the separately fired retrofit system, and the steam cycle with either MHD cycle shut down and operation returned to original plant design conditions. Significant performance and operating parameters are also shown in this figure.

FIGURE 1
SYSTEM SUMMARY

LEGEND:
 F - TEMPERATURE °F
 P - PRESSURE, PSIA
 W - MASS FLOW, 10³ LB/HR
 MWe - ELECTRICAL POWER, MW
 MWt - THERMAL INPUT, MW



DIRECT FIRED, OXYGEN ENRICHED

NET POWER OUTPUT	374 MWe
NET HEAT INPUT	1066 MWt
EFFICIENCY	35.1%
HEAT RATE	9740 BTU/KWH

SEPARATELY FIRED, NON-ENRICHED

NET POWER OUTPUT	355 MWe
NET HEAT INPUT	1016 MWt
EFFICIENCY	34.9%
HEAT RATE	9780 BTU/KWH

MHD OUT OF SERVICE

NET POWER OUTPUT	336 MWe
NET HEAT INPUT	971 MWt
EFFICIENCY	34.6%
HEAT RATE	9860 BTU/KWH



The oxygen enriched direct fired retrofit system supplies the main combustor with air enriched to 35 mole percent oxygen and preheated to 1,100°F. Air is enriched by mixing with a stream of 95 mole percent pure oxygen produced by a highly efficient oxygen plant consuming 215 kWh of compression power per ton of oxygen produced. Input to the MHD combustor is 287 megawatts thermal (Mwt) of coal and output from the MHD generator is 53.7 MWe. About 17 percent of the total steam flow to the high pressure turbine in the oxygen enriched system is contributed by the MHD topping cycle heat recovery system.

The separately fired system preheats the main combustor air to 2,500°F in an air heater subsystem fired with 74 Mwt of fuel oil. The separately fired high temperature air heater subsystem follows the AVCO ETF design which recycles its preheater combustion gas. Recycled preheater gas plus air for combustion within the high temperature air heater are heated to 1,100°F by metallic recuperative heat exchangers in the MHD heat recovery system. Main combustor thermal input is 183 Mwt and MHD electric power output is 35.5 MWe. Steam from the separately fired MHD heat recovery system constitutes about 20 percent of the high pressure turbine flow in the separately fired retrofit system.

In conventional operation without MHD in service, the Colstrip steam cycle operates with 971 Mwt of coal input to produce 336 MWe of net plant output at 34.6 percent net plant efficiency (9,860 Btu/kWh heat rate). In operation with the oxygen enriched MHD cycle, the Colstrip boiler is fired at 80 percent of its design capacity, total plant fuel input is 1,066 Mwt, net plant output is 374 MWe, and net plant efficiency is 35.1 percent (heat rate of 9,740 Btu/kWh). The oxygen enriched retrofit system thus produces about 40 MWe additional electric power at an efficiency approximately 0.5 percentage points higher than the original plant. In operation with the separately fired MHD cycle, the Colstrip boiler is fired at 78 percent of capacity, total plant fuel input is 1,016 Mwt, net output is 355 MWe, and efficiency is 34.9 percent (heat rate of 9,780 Btu/kWh). The separately fired retrofit system produces about 20 MWe more power at an efficiency about 0.3 percentage points higher than the conventional plant.

Construction time for either the oxygen enriched or the separately fired MHD retrofit plant is estimated to be about 5.5 years. Total estimated cost is \$171 million for the oxygen enriched facility and \$198 million for the separately fired facility, both on a basis of overnight construction and mid-1978 dollars. On the same basis, previous retrofit studies would show that an all new MHD power plant using the same separately fired power train to fully fire a smaller steam cycle would cost approximately \$233 million and require 6½ years to construct.

Evaluations in this study are preliminary. Should either MHD retrofit system be given further consideration as an ETF candidate, more detailed design and economic evaluations would be required.

SECTION 1.0
INTRODUCTION

Energy Conversion Alternative Studies (ECAS)¹ have shown magnetohydrodynamic (MHD) power systems to be one of the most attractive, high potential alternatives for advanced, coal fired electric power generation for utility baseload applications. Projected MHD systems will operate with overall coal pile to busbar efficiencies approaching 50 percent and will generate electricity in compliance with Federal environmental standards at costs competitive with other power plant systems. A development program was established by the U. S. Department of Energy, Office of Magnetohydrodynamics (DOE/MHD), aimed at the commercialization of MHD power generation. This program includes a demonstration of the commercial feasibility of a fully integrated MHD topping/steam bottoming power system through the construction and operation of an Engineering Test Facility (ETF).

Two MHD retrofit systems are presented in this report as candidates for the Engineering Test Facility. Under retrofit, the MHD power cycle is added onto an existing steam power cycle that has been operating as a commercial power plant. The MHD cycle serves as a topping cycle, and the steam cycle serves as a bottoming cycle. This offers several advantages for a test facility. Time and money are saved by not having to construct conventional plant equipment. In addition to the major power generation equipment, supporting facilities such as coal handling and preparation, power distribution, buildings and grounds, etc., can be utilized. Checkout time and licensing procedures can also be reduced. Also, the utility owning the facility becomes closely involved, which can help significantly to gain acceptance of the MHD concept within the power generating community as a whole.

The Colstrip power plant, owned by the Montana Power Company and located in Colstrip, Montana, is the facility considered for retrofit in this study. The Montana Power Company has shown interest in the development of MHD by offering the Colstrip and other power plants for study as potential sites for MHD retrofit. The Colstrip plant is fired with coal (obtained from a nearby mine site) making it attractive for MHD application because coal handling

facilities are present, and is in the size range that would be of most interest to utilities for a demonstration plant. Colstrip consists of two independent power generating units, each with 350 MWe of power output. Space is available alongside Unit 2 of the plant for locating the MHD equipment, contributing to the feasibility of retrofitting to this unit. The plant is in relatively new condition with equipment that should offer minimal interference with testing of the MHD equipment. Since the Colstrip plant contributes significantly to the Montana power grid, it is desirable that the plant be able to continue operation as much as possible throughout the duration of the MHD testing. Modifications to the plant must be kept to a minimum in order to reduce construction time. Also, independent or stand-alone operation of the conventional steam cycle must be possible during shutdowns of the MHD cycle.

The first retrofit system uses an MHD cycle employing oxygen enrichment as the method for attaining the high flame temperatures required for MHD power generation with coal combustion gas. Air enriched with oxygen as the oxidizer for the MHD combustor eliminates the need for a high temperature air heater. Enriched air can be used with preheat temperatures in the 1,000 to 1,400°F range, as opposed to the 2,400 to 3,000°F range required to obtain required combustion temperature when nonenriched air is used as the oxidizer. Oxygen enrichment is seen as a near term approach because it eliminates the development problems expected with the high temperature air heater but entails the complexity of an oxygen production plant. Oxygen enrichment can aid an early demonstration of the functionality of MHD, but may detract from its appeal as a commercial prospect. The current ETF program favors the oxygen enrichment approach.

The second retrofit system uses a separately fired MHD cycle without oxygen enrichment. A separately fired high temperature air heater is considered an earlier commercial prospect for preheating than a direct fired high temperature air heater, the most efficient preheat method, because the separately fired heater does not have severe corrosion and fouling problems. A clean fuel may be combusted to supply heat in the separately fired heater,

whereas the direct fired heater extracts heat from high temperature MHD gas containing seed and slag that corrode and foul the preheater. Since separate firing does not have the complexity of an oxygen plant, it is of interest for a test (and demonstration) facility.

Oil was chosen for firing the separately fired high temperature air heater in this study, rather than coal or gasified coal. Although an all coal fired station is appealing in light of the national energy concern, direct coal firing of a separately fired air heater may produce corrosion and fouling, and coal gasification introduces an additional complexity that is not desirable in an MHD test facility.

1.1 OBJECTIVES

The objectives of this study were to identify a preliminary design for each of the two types of MHD retrofit systems, and evaluate the performance and construction cost of each design. Previous studies²⁻¹¹ formed the base for MHD cycle design, particularly the AVCO separately fired ETF system designs^{2,3}. A detailed computer simulation was made to evaluate the design and performance of each system, while costs were estimated through simple scaling and extrapolation of results from the more detailed studies of References 2, 3, 4, and 5. Should either of these two retrofit systems prompt further interest, a more detailed conceptual design effort would be required to optimize plant design and to improve on the simple scaling assumptions used for cost evaluation.

1.2 ASSUMPTIONS

Key assumptions made for this study are listed below. Material relating to these assumptions will appear in the sections following.

- o Montana Rosebud coal is used for both MHD combustor and conventional boiler firing.

- o Both MHD topping cycles are sized to have 143.3 lb/sec (65 kg/s) of channel gas flow which is the same flow used in the AVCO separately fired ETF design.²
- o Preheat temperature is 1,100°F and oxygen enrichment level is 35 mole percent oxygen in the oxygen enriched system.
- o Preheat temperature is 2,500°F and the high temperature air heater is oil fired in the separately fired system.
- o Both retrofit systems have the ability for stand-alone operation with the MHD cycle out of service.
- o Each MHD topping cycle includes a separate heat and seed recovery system, and cycle integration is by steam blending.
- o Steam flow at the turbine throttle for each retrofit system is as high as possible without exceeding design flow at any point.
- o Air and oxygen compressors are driven by steam turbines.
- o Local ambient conditions are 80°F, 12.2 psia, and 50 percent relative humidity (1.3 percent moisture by weight).

SECTION 2.0
THE MHD CYCLE

2.1 DESIGN CONSIDERATIONS

2.1.1 MHD Power Cycle

Both MHD power cycles were selected to make use of previous studies.^{2,3,4,5,6} Prior ETF design studies for the DOE consider MHD systems with thermal inputs sized from 250 to 500 MWt. An important system design produced by the AVCO ETF study² was a separately fired nonenriched MHD system sized for a total fuel input of 274 MWt. The Gilbert/Commonwealth (G/C) retrofit study³ used a reference MHD power cycle simulation based closely on the 274 MWt MHD cycle from AVCO. Thermal input for the G/C reference cycle was 184 MWt of coal to the combustor and 74 MWt of fuel oil to the separately fired air heater subsystem for a total thermal input of 258 MWt. Because the size of this G/C reference cycle is within the prevailing range of interest, and because a number of studies are related to it, the combustor, MHD generator, and separately fired air heater subsystem of the G/C reference MHD cycle were used without change for the separately fired retrofit to the Colstrip plant.

The power train for the oxygen enriched retrofit to the Colstrip power plant was made as similar as possible to the separately fired retrofit power train. The same MHD parameters are used, when appropriate, and the MHD channel is designed for the same gas flow rate (143 lb/s). This gives a common base for comparing both retrofit systems. Other design features for the oxygen enriched system were drawn from Reference 7 which developed a 500 MWt oxygen enriched MHD topping cycle design for an ETF power plant with all-new construction. Coal input to the oxygen enriched MHD cycle for the Colstrip retrofit system is 287 MWt.

2.1.2 Oxidizer Temperature

Efficient MHD power generation requires that the gases passing through the MHD channel have high electrical conductivity. For coal fired systems, high conductivity is achieved by seeding the combustion gases with potassium

compounds and by having combustor flame temperature range upwards from 4,300°F. This range of flame temperature can be obtained either by burning with oxygen enriched air preheated to a range of 1,000-1,400°F, depending on oxygen concentration, or by burning with nonenriched air preheated to the 2,400-3,000°F range.

The oxygen concentration after enrichment for the oxygen enriched retrofit system was selected to be 35 mole percent (versus 20.5 mole percent for air). This level was shown to be slightly below the thermodynamic performance optimum, both by Gilbert/Commonwealth studies⁷ and by AVCO and GE in their ETF and PSPEC studies^{2,4,5}. A concentration on the low side of the thermodynamic optimum was chosen because an economic optimum would be in this direction when accounting for the costs of an oxygen plant.

The choice of preheat temperature for either MHD cycle involves a trade-off between system performance, cost, and purpose. For the purpose of these test facilities, it was considered important to minimize potential problems and cost. Preheat temperature for the enriched case was held to 1,100°F to increase the possibility that the tube bank, recuperative air heater can use low cost metal alloys rather than expensive exotic ones. This preheat temperature is lower than values used in other studies^{2,4,5,7} for 35 percent oxygen, and system efficiency is slightly lower. However, the direct fired preheater for the oxygen enriched system should involve less development risk and less cost.

Two values for the preheat temperature of the separately fired ETF system, 2,500°F and 3,000°F, were presented by AVCO². The lower of these values, 2500°F, was chosen for the preheat temperature of the separately fired retrofit system with the intention of reducing development risks regarding durability of the ceramic material in the separately fired air heater.

2.1.3 Topping Cycle Components

The major MHD topping cycle subsystems and their components are listed in Table 1 and partially shown in the flow schematics of Figures 2 and 3. These major components and their more significant operating conditions are discussed

in the following sections. Detailed operating conditions are presented Section 4 where the integrated system is discussed.

TABLE 1
TOPPING CYCLE COMPONENTS

<u>Subsystem</u>	<u>Required Equipment</u>	
	<u>Oxygen Enriched Cycle</u>	<u>Separately Fired Cycle</u>
Oxidizer Delivery System	Oxygen Plant, with Liquefaction Air Compressor and Air Separation Unit Oxygen Compressor, Blend Air Compressor	Air Compressor
Preheater	Low Temperature Air Heater	High Temp Air Heater, Gas to Air Heat Exchangers, Gas and Air Blowers
Combustor	Combustor	Combustor
MHD Generator	Nozzle, Channel, Diffuser, Magnet, Inverter	Nozzle, Channel, Diffuser, Magnet, Inverter
Heat and Seed Recovery System	Radiant Furnace Superheater Low Temperature Air Heater High Temperature Economizer Precipitator Secondary Air Preheater, Low Temperature Economizer	Primary Radiant Furnace Secondary Radiant Furnace with Finishing Superheater and Evaporator, Convective Section with Gas to Air Heat Exchanger, Gas to Gas Heat Exchanger, Initial Superheater, and Evaporator Economizer Precipitator
Coal Preparation	Pulverizer, Mechanical Collector, Bag House	Pulverizer, Mechanical Collector, Bag House

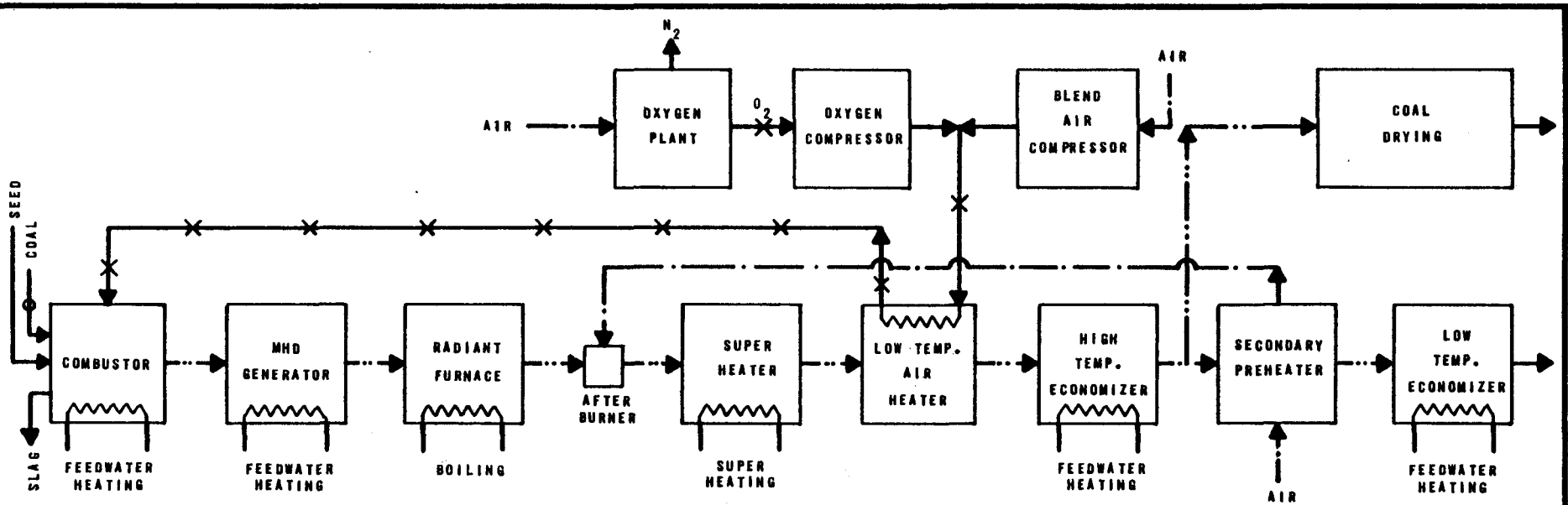


FIGURE 2 OXYGEN ENRICHED MHD TOPPING CYCLE

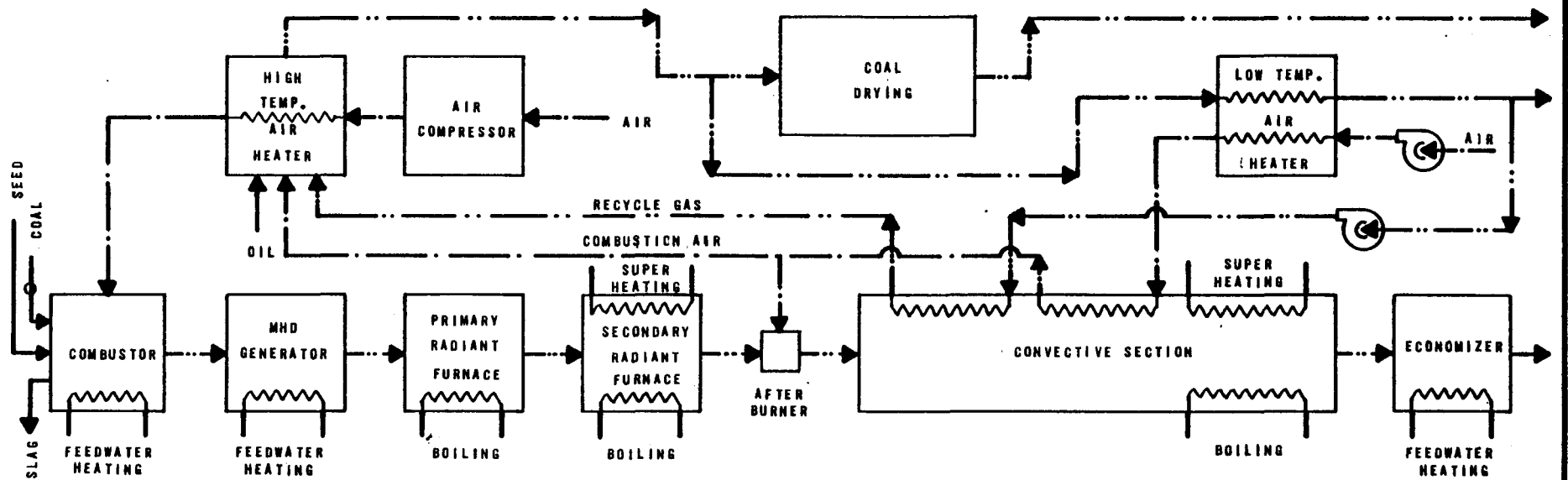


FIGURE 3 SEPARATELY FIRED MHD TOPPING CYCLE



2.2 OXIDIZER DELIVERY SYSTEM

2.2.1 Oxygen Enriched Cycle

Oxygen Plant

Methods for producing oxygen for MHD systems are discussed in Reference 10. A simple and reliable system with low power requirements is desired to provide oxygen for an MHD cycle. Conventional oxygen production processes are not designed for low power consumption because other factors in their application are more important. Conventional processes used in an MHD power generation facility would cause net plant efficiency to suffer greatly. Reference 10 identified two oxygen production processes most suitable for MHD application. One process produces oxygen with 61 mole percent purity and the other with 95 mole percent purity.

The 61 percent purity plant has a lower power consumption than the 95 percent purity plant, but the former requires expansion turbines to obtain power from a nitrogen stream discharged at high pressure. These expansion turbines constitute an expense and complexity not present in the 95 percent process. Also, some development effort would be required for the 61 percent plant. For a large commercial MHD cycle with large oxygen requirements the 61 percent plant would be chosen. But for a small test facility, the 95 percent plant is more appropriate and was therefore selected for this study. The 95 percent plant requires 215 kWh of power for each ton of oxygen discharged, and does not involve excessive complexity or developmental uncertainty.

Commercial oxygen plants produce oxygen by a cryogenic process involving the fractional distillation of liquid air. Air is liquified by an expansion from about five atmospheres pressure, and a succession of fractional distillations are carried out which boil off nitrogen gas to leave successively purer oxygen liquid. The distillation steps occur on trays within distillation columns. Liquid on the upper trays distills off a relatively pure nitrogen gas leaving a relatively impure oxygen liquid. This liquid is purified as it falls from tray to tray. Liquid at the lowermost trays distills off relatively impure nitrogen gas leaving a relatively pure oxygen liquid. Ordinarily two

distillation columns are used. One is a high pressure column which receives the discharge from the liquefaction compressor, and the other is a low pressure column receiving discharge from the high pressure column.

In the oxygen production process selected, a third, medium pressure distillation column is employed. This column receives a portion of the air from the liquefaction compressor drawn off before the final stage of compression (at about three atmospheres). Virtually all of the power consumed by the oxygen plant goes to the liquefaction compressor, and bypassing a portion of this compression significantly reduces plant power consumption.

The composition of oxygen product from this air separation process is 95 mole percent oxygen, 4.5 mole percent argon, and 0.5 mole percent nitrogen. Oxygen product temperature and pressure are 5-10°F below and 0.5-1.0 psi above atmospheric conditions. A stream of waste nitrogen is also produced in the process. No use is made of the nitrogen in this study.

Table 2 gives the composition of the blend of air and oxygen that constitutes the oxidizer for the oxygen enriched MHD cycle. The blend air contains 35 percent oxygen by volume and 38 percent oxygen by weight.

TABLE 2
COMPARISON OF THE COMPOSITION OF
35 MOLE PERCENT OXYGEN ENRICHED AIR
WITH STANDARD AIR

Constituent	Molecular Weight	Mole Fraction		Weight Fraction	
		Enriched Air	Standard Air	Enriched Air	Standard Air
Oxygen (O ₂)	31.999	0.3500	0.2052	0.3806	0.2285
Nitrogen (N ₂)	28.013	0.6178	0.7650	0.5881	0.7458
Argon (Ar)	39.948	0.0155	0.0091	0.0211	0.0127
Water (H ₂ O)	18.016	<u>0.0167</u>	<u>0.0207</u>	<u>0.0102</u>	<u>0.0130</u>
		1.0000	1.0000	1.0000	1.0000
Molecular weight of mixture		29.427	28.732		

Compression System

Reference 10 also identifies several design options for compressing air for the oxygen plant, air for the MHD combustor, and oxygen for the MHD combustor. The options are concerned with compressing the three flow streams individually as separate flows or jointly as mixed flows. Major factors to be considered are: 1) cost, since multiple small compressors to compress separate streams cost more than large compressors to compress combined streams; 2) safety, since the compression of an oxygen rich gas carries the danger of metal fires within the compressor and requires intercooling and specialized compressor design; 3) compressor efficiency, which is influenced by both compressor design and size; and 4) total system efficiency, since compressor power and oxidizer preheat are affected by compressor efficiency and the amount of intercooling employed.

A compression system using separate compressors for each of the three flow streams was chosen. The three compressors involved are: 1) a liquefaction air compressor within the oxygen plant, 2) an oxygen compressor to compress the 95 mole percent oxygen plant product gas to the required MHD combustor pressure, and 3) a blend air compressor to supply air at MHD combustor pressure to mix with compressed oxygen to produce 35 mole percent oxygen oxidizer gas.

The liquefaction air compressor for the oxygen plant is intercooled to minimize compression power while providing the lowest possible temperature to the air separation unit. Aftercooling of the compressed air as it leaves the compressor is also employed. This highly intercooled compressor has a three-section axial-radial design, operates with a compression ratio of 6.2, and receives an inlet flow of 113 lb/s.

The oxygen compressor is intercooled to keep temperatures below the point at which metal will burn in the presence of high purity oxygen. This compressor is specially constructed for safe compression of gas with high oxygen content by using special seals and large clearances. It is expected to be of three-stage centrifugal design, operating with a compression ratio of 7.1 and a flow of 25.5 lb/s.

The blend air compressor is not intercooled and has an axial design with a compression ratio of 7.6 and flow of 92.2 lb/s. Intercooling is not employed, and the resulting higher compressor power is accepted, in order to retain all the heat of compression within the blend air. Retaining the heat of compression reduces the heat load required in the preheater.

This separate compressor system was selected to allow the intercooling in the liquefaction and oxygen compressors without intercooling the blend air compressor. Capital cost is higher than for systems which combine the compressions but the highest system efficiency is attained. Intercooling is employed only where it is required or where it reduces compression power without increasing the oxidizer preheat requirement. Reducing the amount of oxidizer preheat by retaining heat of compression is more beneficial to overall system efficiency than reducing compression power by intercooling.

Figure 4 is a preliminary plot plan of the oxidizer delivery system for the enriched cycle. Steam turbine drives are shown for each of the compressors. The left side of the figure illustrates the air separation unit for separating air into oxygen and nitrogen. The column box houses the three distillation columns. The revex and valve boxes represent a reversing heat exchanger unit for cooling the feed air stream by warming the discharge oxygen and nitrogen streams. Nitrogen and air streams are reversed in a cyclic fashion so that moisture and carbon dioxide condensed from the feed air onto the exchanger passages will sublime into the nitrogen and be carried away. Expansion turbines are used in a portion of the expansion process to recover some compression power.

2.2.2 Separately Fired Cycle

The separately fired MHD power train uses a single, multistage, axial flow compressor to supply primary air at the MHD combustor pressure. The compression ratio is 4.5, and flow is 125.6 lb/s. The compressor is not intercooled in order to retain the heat of compression. A steam turbine drive is used.

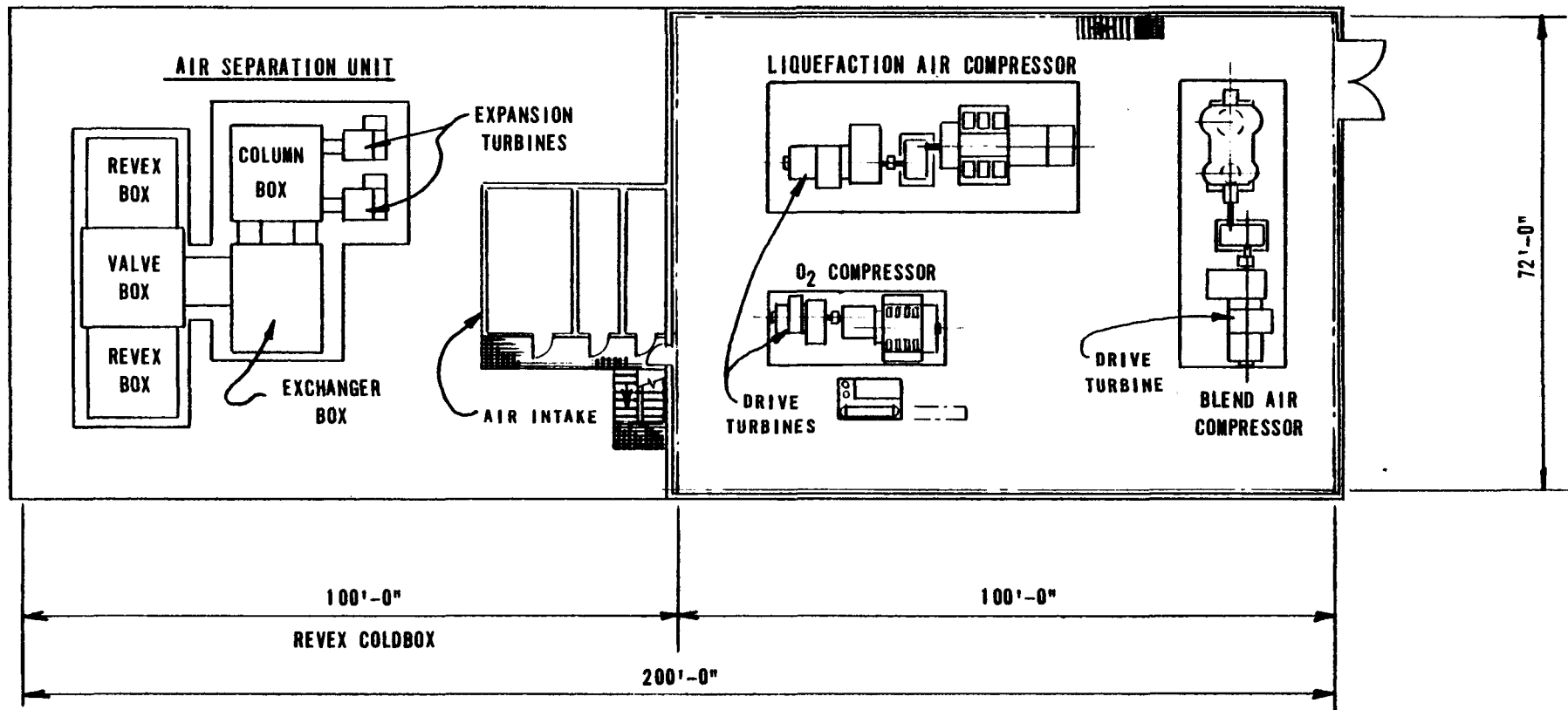


FIGURE 4
OXIDIZER DELIVERY SYSTEM
WITH 95 MOLE PERCENT OXYGEN PLANT
FOR OXYGEN ENRICHED MHD CYCLE



2.3 PREHEATER

2.3.1 Oxygen Enriched Cycle

The direct fired preheater for the oxygen enriched MHD cycle heats the oxidizer from compressor discharge conditions up to the 1,100°F preheat temperature. Heat is obtained directly from the hot MHD combustor gas. This gas contains a potentially corrosive mixture of slag and seed compounds. Being of low temperature duty, the heat exchanger has a recuperative design in which heat transfer takes place across banks of metallic tubes. The 1,100°F preheat temperature is expected to be low enough such that highly exotic and expensive tube materials are not required, but tube material must be able to resist corrosion from the seed and slag laden gas.

2.3.2 Separately Fired Cycle

The separately fired MHD cycle uses a separate high temperature air heater subsystem to preheat the pressurized combustion air to 2,500°F. The heater itself is a regenerative type, comprised of four matrices of refractory brick. Oil fired combustion occurs within the heater. The four individual matrices operate in a cycle, alternately absorbing heat when combustion gas is passed through and releasing heat when air is passed through. An arrangement of valves directs the gas and air flows. These valves must operate under high temperatures and with a large pressure differential between the pressurized air and the essentially atmospheric combustion gas. Cycle sequencing provides a continuous supply of air at near constant temperature to the MHD combustor. The technology for constructing such an exchanger system to function without erosion or fouling problems is considered attainable, though not yet developed.

As illustrated in Figure 3, the separately fired preheater subsystem recycles a portion of the preheater combustion gas back to the preheater combustion region. Both the recycle gas and the preheater combustion air enter the preheater combustion region at 1,100°F. This keeps the flame temperature from being destructively high, while avoiding the thermal stress that could result

from allowing cold air to enter the combustion region. Part of the heat required to heat the recycle gas and the preheater combustion air to 1,100°F is obtained from the MHD exhaust gas in recuperative heat exchangers similar to the direct fired low temperature air heater used in the oxygen enriched cycle.

A portion of the preheater combustion gas that is not recycled is fed to the coal mills to be used for coal drying. An additional heat exchange between the hot preheater combustion gas and the preheater combustion air captures most of the thermal energy contained in the portion of the preheater combustion gas that is discharged to the stack. An air fan and a recycle gas fan are employed to drive the flows involved.

Approximately 74 Mwt of fuel oil is fired in the separately fired high temperature air heater. Heat loss in the air heater is assumed to be eight percent (9 Mwt) of the total thermal energy of the inlet flow streams. Although fuel oil is initially used for firing, the high temperature air heater design can accept firing with coal-derived fuel gas should this be desired in the future.

2.4 COMBUSTOR

Pressurized combustors fired with pulverized coal are used for both MHD power cycles used in this study. Both combustors were assumed to operate at 95 percent stoichiometry, reject 70 percent of the coal ash as slag, and be seeded with potassium carbonate and potassium sulfate to achieve 1 percent potassium by weight in the discharge gas. (Combustion is completed downstream at 105 percent stoichiometry by injecting secondary air in the heat and seed recovery system.) A Mollier chart for the plasma from each combustor is shown in Figures 5 and 6.

Flame temperature and combustor pressure are 4,547°F and 89.3 psia in the oxygen enriched cycle and 4,361°F and 48.8 psia in the separately fired cycle.

FIGURE 5
MOLLIER CHART FOR CHANNEL PLASMA
OXIDIZER ENRICHED TO 35 MOLE PERCENT OXYGEN



PROPERTIES OF MHD PLASMA

5% MOIST MONTANA ROSEBUD COAL 1% POTASSIUM BY WEIGHT
 95% OF STOICHIOMETRIC OXIDIZER
 1.3% MOIST AIR

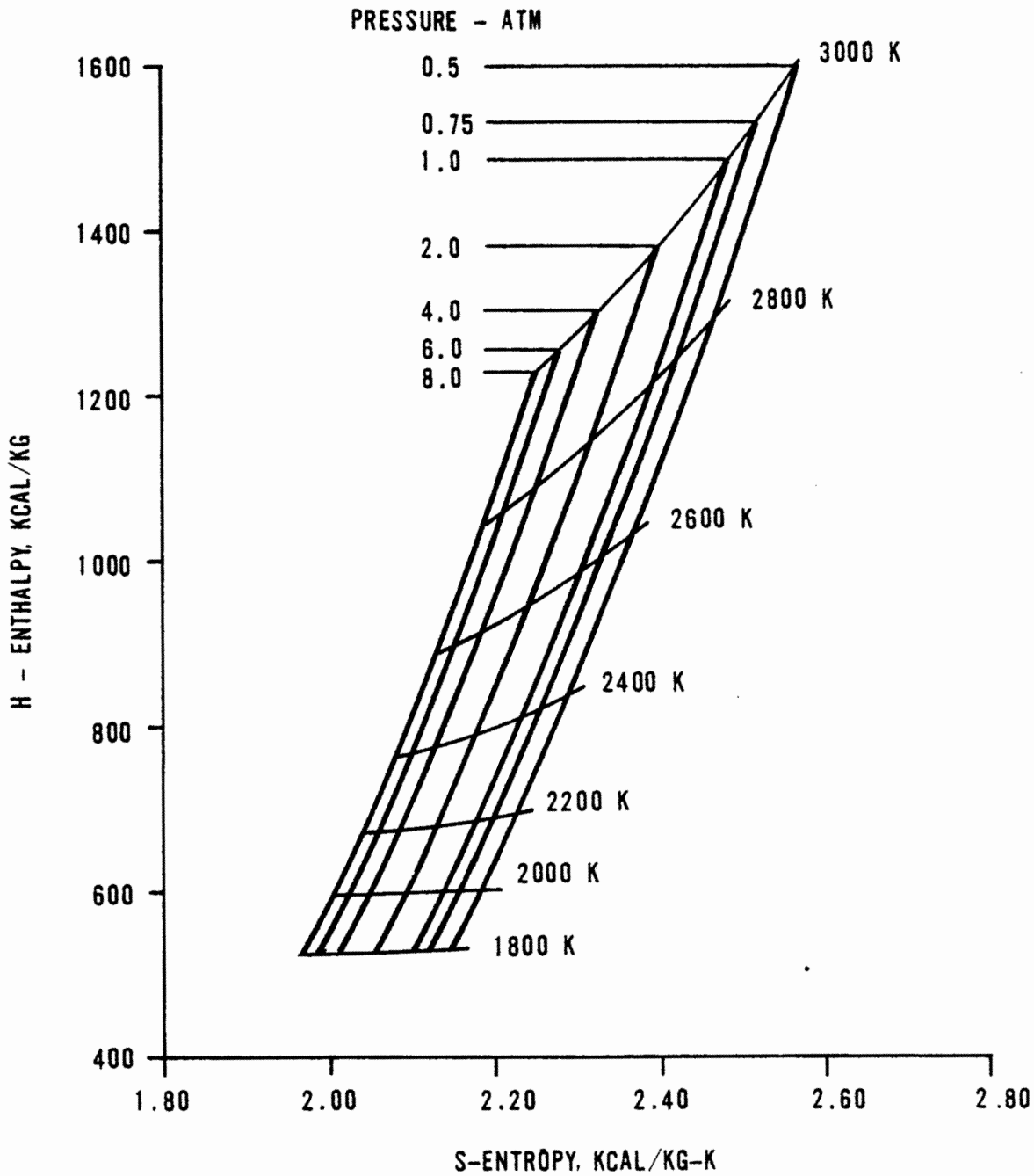
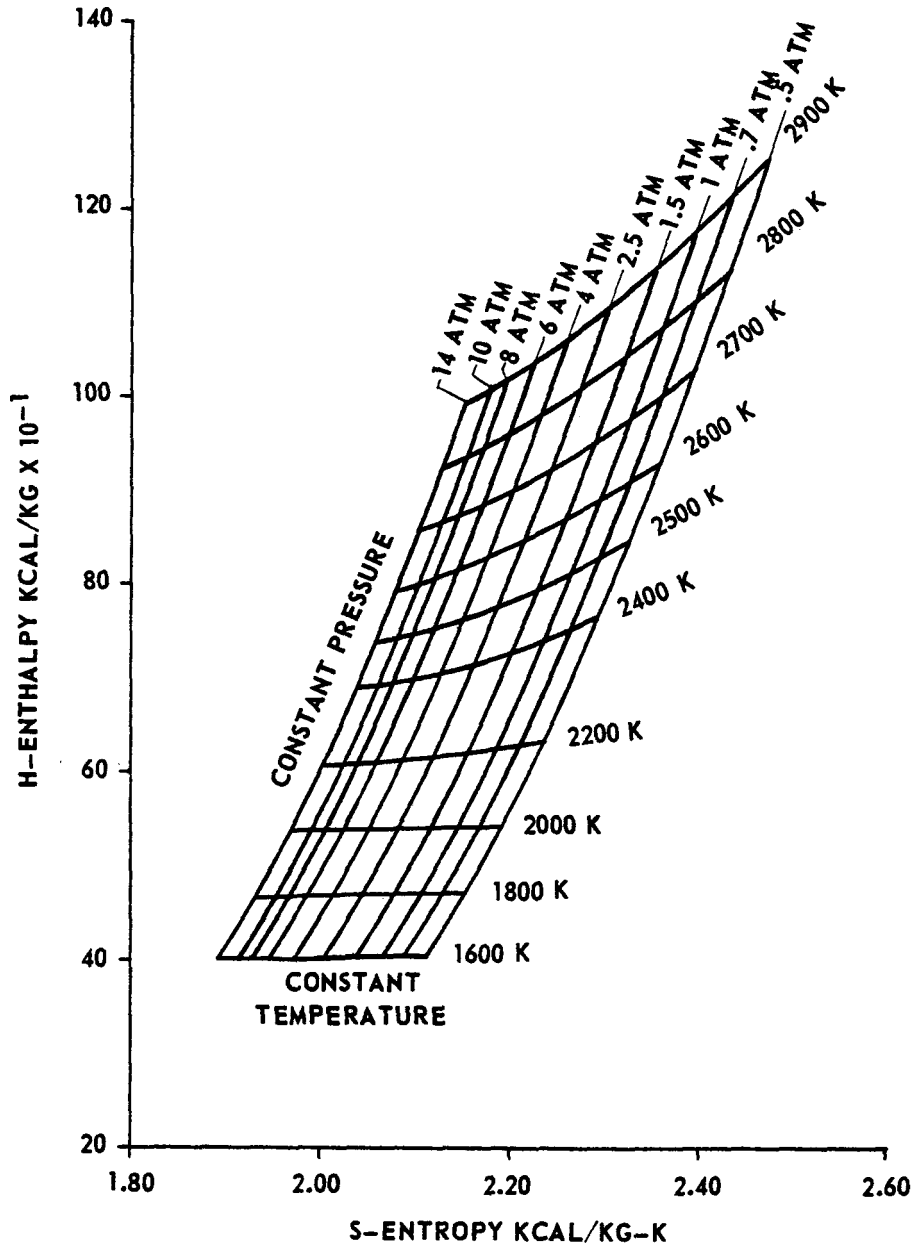




FIGURE 6
MOLLIER CHART FOR CHANNEL PLASMA
AIR OXIDIZER

PROPERTIES OF MHD PLASMA
5% MOIST MONTANA ROSEBUD COAL 1% POTASSIUM BY WEIGHT
1.3% MOIST AIR 95% OF STOICHIOMETRIC AIR



A detailed assessment of combustor design was not performed. Combustor heat loss to the feedwater cooled waterwalls was established by a simplified analysis calibrated to agree with the AVCO PSPEC and ETF studies. For the oxygen enriched and the separately fired combustors, the heat loss was taken to be 6.7 and 6.9 percent of the coal thermal input, respectively. Percent heat loss increases as combustor size decreases because a smaller combustor has a larger ratio of wall surface (heat loss area) to combustion volume.

2.5 MHD GENERATOR

The MHD generator subsystem is comprised of several components. They are the nozzle, channel, superconducting magnet, dc-to-ac inverter, and diffuser. For the oxygen enriched cycle, the performance for each component is consistent with assumptions used by AVCO and GE in their PSPEC and ETF studies. For the separately fired cycle, the performance for the components is based upon the AVCO ETF assumptions established in Reference 2. These assumptions were used in the Gilbert/Commonwealth separately fired retrofit evaluations of Reference 3. The separately fired MHD generator from Reference 3 is used without change for the separately fired retrofit cycle in this study.

The inlet pressure of the oxygen enriched channel was set at 89 psia to produce a channel length-to-inlet diameter ratio of 20:1. Inlet pressure of the separately fired channel was set at 48.8 psia, the same as the AVCO ETF channel. Both channels were assumed to have a subsonic, constant velocity (800 m/s), constant loading parameter (0.75 oxygen enriched, 0.69 separately fired), Faraday connection design. The Hall field for both channels was limited to 2,500 V/m by tapering the magnetic field from a maximum of 6 Tesla at the channel entrance to the required level necessary to maintain the 2,500 V/m maximum further along the channel. Figures 7 and 8 illustrate the geometry, flow rates, and performance characteristics for the two MHD generators. Detailed performance characteristics of the two generators are compared in Table 3.

The diffuser, consisting of a divergent section followed by a transition section, is designed to decelerate the high velocity gases leaving the channel

GENERATOR POWER OUTPUT: 53.7 MWe

CHANNEL HEAT LOSS: 17.6 MWth
DIFFUSER HEAT LOSS: 7.7 MWth
TOTAL HEAT LOSS: 25.3 MWth

LEGEND

W = FLOW - KG/S
T = TEMPERATURE - K
P = PRESSURE - ATM
Cpr = DIFFUSER PRESSURE RECOVERY COEFFICIENT
V = VELOCITY - M/S
M = MACH NUMBER
A = DUCT AREA - M²

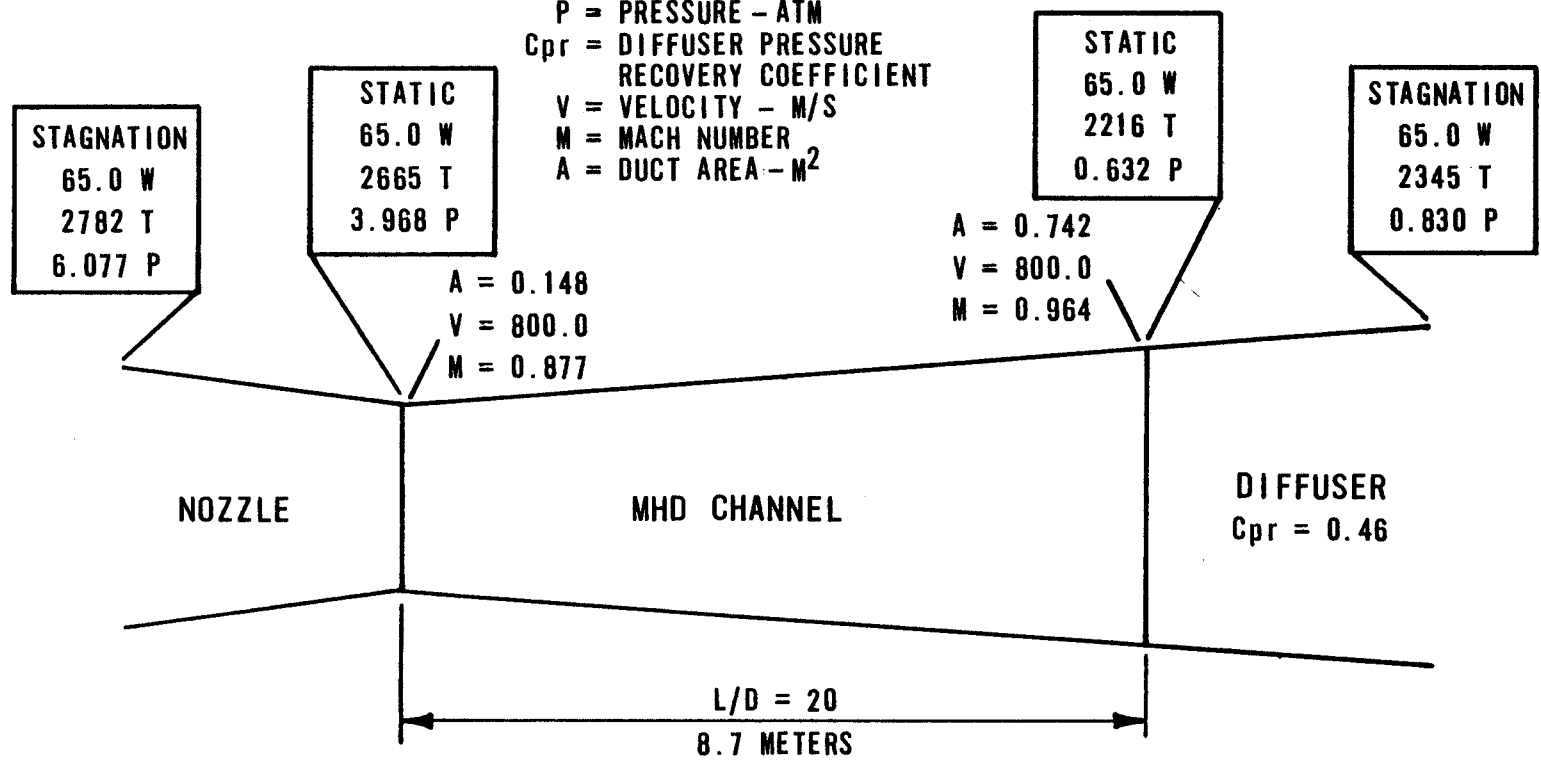


FIGURE 7
MHD GENERATOR DESCRIPTION
DIRECT FIRED OXYGEN ENRICHED TOPPING CYCLE
35 MOLE PERCENT OXYGEN PREHEATED TO 1100°F



GENERATOR POWER OUTPUT: 35.5 MWe

CHANNEL HEAT LOSS: 11.5 MWth

DIFFUSER HEAT LOSS: 13.7 MWth

TOTAL HEAT LOSS: 25.2 MWth

LEGEND

- W = FLOW - KG/S
- T = TEMPERATURE - K
- P = PRESSURE - ATM
- C_{pr} = DIFFUSER PRESSURE RECOVERY COEFFICIENT
- V = VELOCITY - M/S
- M = MACH NUMBER
- A = DUCT AREA - M²

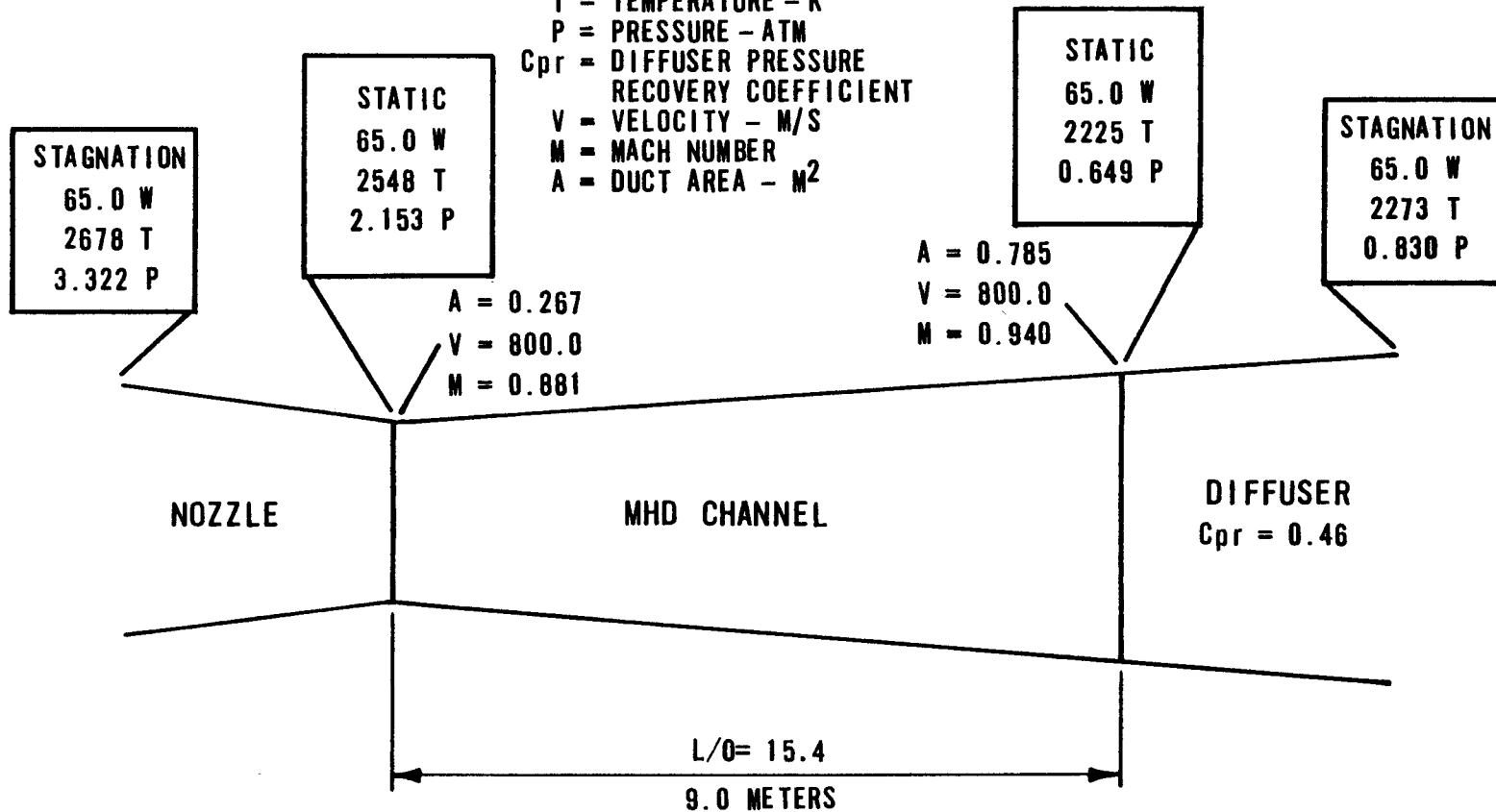


FIGURE 8
MHD GENERATOR DESCRIPTION
SEPARATELY FIRED TOPPING CYCLE
AIR PREHEATED TO 2500°F



TABLE 3

COMPARISON OF THE OXYGEN ENRICHED AND
SEPARATELY FIRED MHD GENERATORS

<u>Oxidizer</u>	<u>Units</u>	<u>Oxygen Enriched</u>	<u>Separately Fired</u>
type	-	O ₂ enriched air	air
O ₂ content	% by mole	35.0	20.5
preheat	K (°F)	866 (1,100)	1,644 (2,500)
preheater fuel input	MWt	0	74.3
<u>Combustor</u>			
coal type	-	Rosebud	Rosebud
coal moisture	%	5	5
coal input	MWt	287.1	183.5
combustor & nozzle	MWt	19.1	12.6
heat loss	% coal input	6.7	6.9
discharge gas flow	kg/s	65.0	65.0
discharge pressure	atm abs.	6.08	3.32
discharge temperature	K (°F)	2,782 (4,547)	2,678 (4,361)
seed in gas	% potassium	1	1
<u>Channel</u>			
connection	-	Faraday	Faraday
loading parameter ky	-	0.75 (constant)	0.69 (constant)
velocity	m/s	800 (constant)	800 (constant)
inlet Mach number	-	0.88	0.88
exit Mach number	-	0.96	0.94
maximum Hall field	V/m	2,500	2,500
maximum magnetic field	Tesla		
<u>Diffuser</u>			
heat loss	MWt	7.7	13.7
pressure recovery	-	0.46	0.46
discharge pressure	atm abs.	0.83	0.83
discharge temperature	K (°F)	2,303 (3,686)	2,273 (3,632)
combustor-to-diffuser pressure ratio	-	7.32	4.00

to approximately 30 meters/second before entering the heat and seed recovery section. A 2-1/2 degree half angle and an exit-to-inlet area ratio of 3.5:1 was selected for the divergent section based on design data presented in Reference 11. The transition section, which connects the divergent section to the radiant boiler, is a constant area duct with a cross-sectional area sized to complete the deceleration. For this application, the divergent/transition combination is expected to have a pressure recovery coefficient of 0.46 for both oxygen enriched and separately fired systems. The diffusers discharge into the radiant boiler at ambient pressure, 12.2 psia.

2.6 HEAT AND SEED RECOVERY SYSTEM

Integration of the MHD topping cycle to the Colstrip steam bottoming cycle is accomplished by steam blending rather than by gas blending to minimize the impact on both the equipment and stand-alone operation of the Colstrip plant. With steam blending, both an MHD heat and seed recovery system and the Colstrip boiler raise steam to be blended together to feed the main turbine. The MHD heat and seed recovery system is physically separated from the existing boiler as an independent set of heat exchangers, rather than running MHD exhaust gases through the Colstrip boiler. This separation allows the high temperatures of the MHD gas, and the corrosion and deposition problems associated with its slag and seed, to be dealt with by designing a new system of heat exchangers. Extensive modification³ to the existing boiler system is thereby avoided, and return to original operation when the MHD out of service is facilitated.

The hot gas from the diffuser of either power train enters the heat and seed recovery system (steam generator) with sufficient temperature and energy to generate steam and to provide all or some of the preheat to the oxidizer. An illustration of the physical arrangement of the major components for the two heat and seed recovery systems is given in Figures 9 and 10. The components are radiant furnaces, superheaters, air and gas heaters, evaporators, economizers, and electrostatic precipitators.

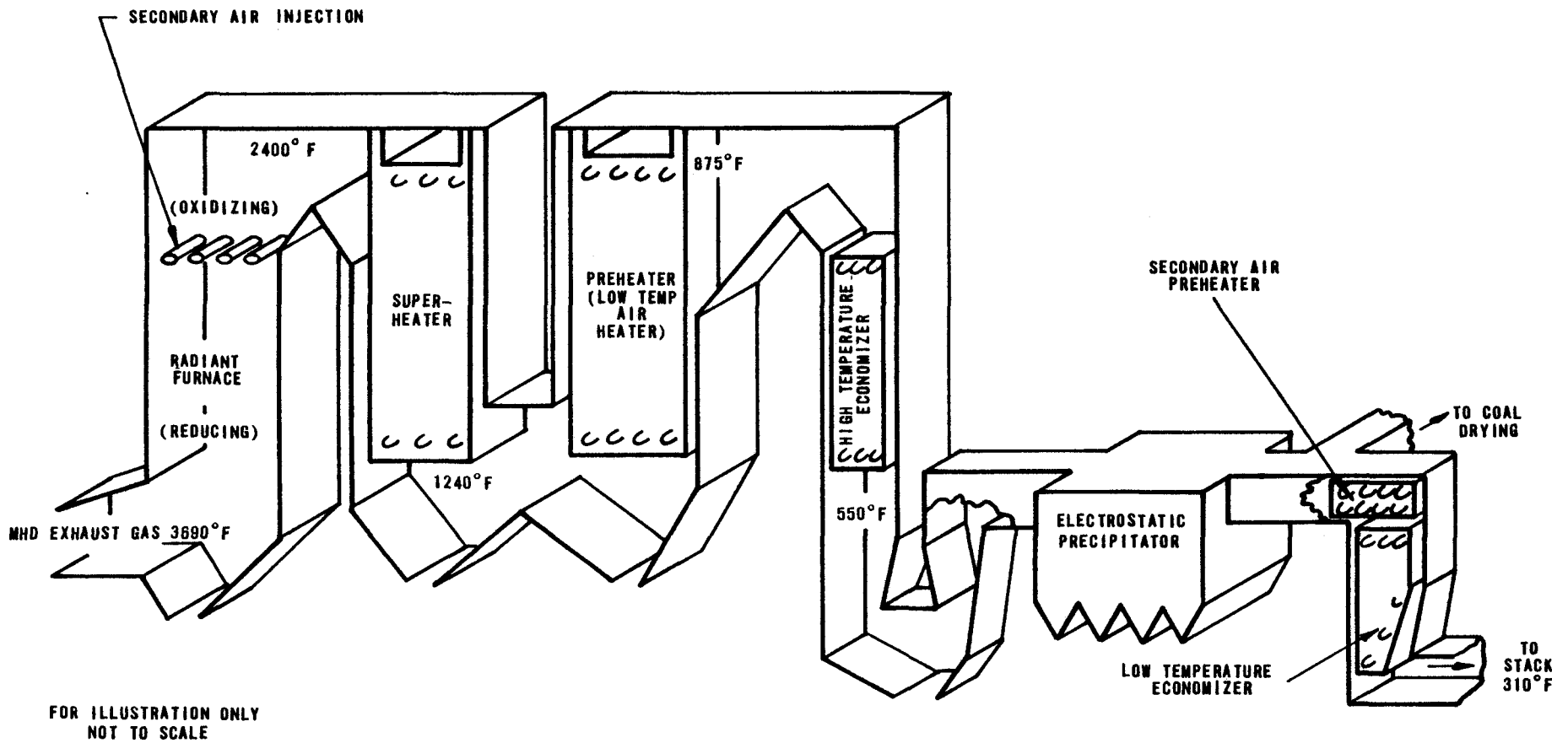
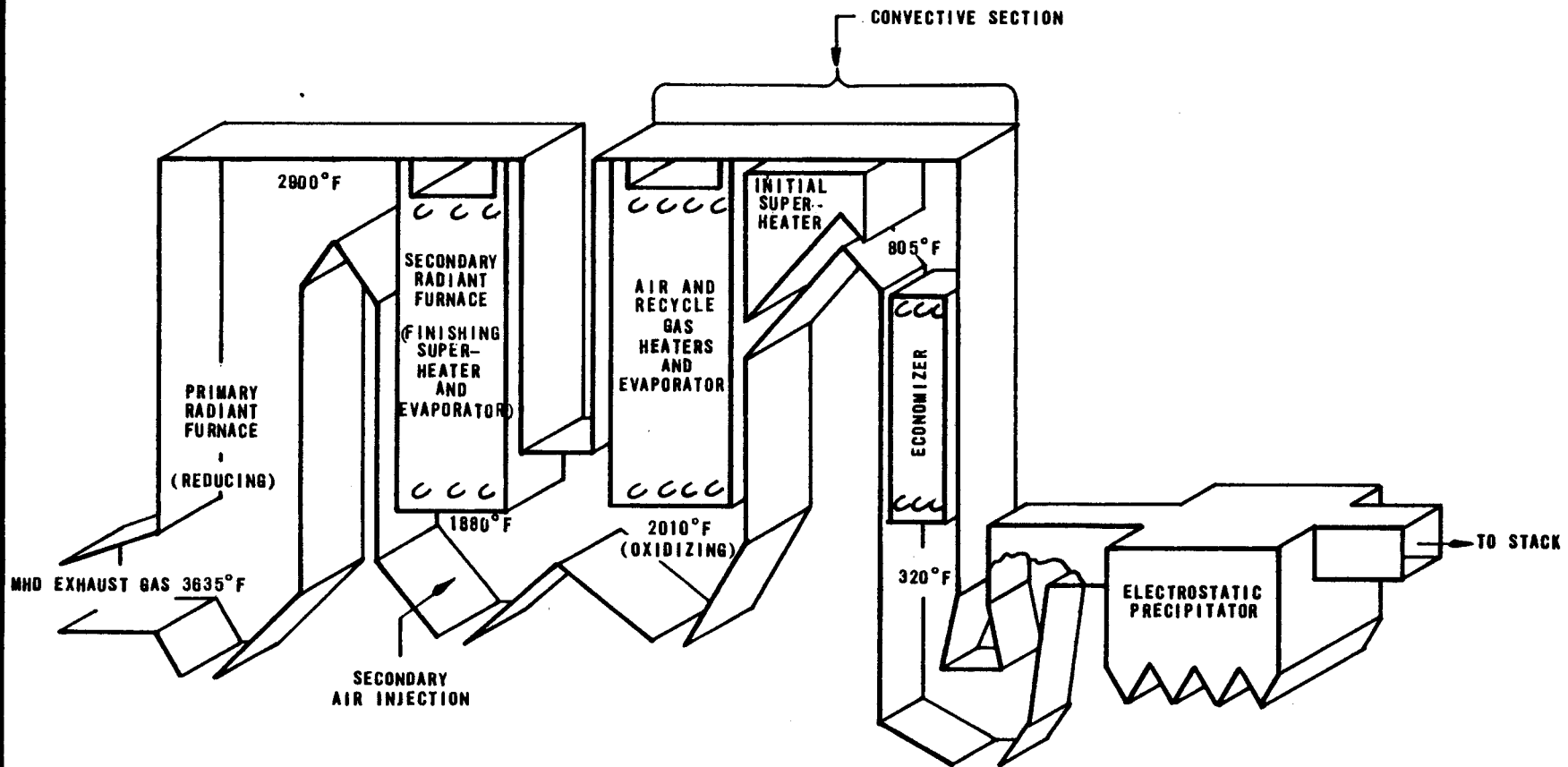


FIGURE 9
MHD HEAT AND SEED RECOVERY SYSTEM
OXYGEN ENRICHED TOPPING CYCLE





FOR ILLUSTRATION ONLY
NOT TO SCALE

FIGURE 10
MHD HEAT AND SEED RECOVERY SYSTEM
SEPARATELY FIRED TOPPING CYCLE



Flue gas exits the diffuser, at about 3,690°F in the oxygen enriched cycle and 3,630°F in the separately fired cycle, and enters the water-cooled radiant furnace. A portion of the slag remaining in the gas is condensed in this furnace. The gas, in a reducing state, transfers heat to the water-cooled walls, cooling at a rate of about 340°F/s which is slow enough to prevent unacceptably high levels of NO_x from "freezing." After the first radiant furnace, the component arrangement in the two heat and seed recovery systems differs as described below.

2.6.1 Oxygen Enriched Cycle

Figure 9 illustrates the arrangement of the heat and seed recovery system for the enriched cycle. To complete the combustion of the coal from the MHD combustor, secondary air heated to 300°F is injected into the hot gas at the exit of the primary radiant furnace to give a stoichiometry of 105 percent. Heat is released by the combustion of carbon monoxide and other species not fully oxidized in the main MHD combustor. The flue gas, now in an oxidizing state at 2,400°F, enters the superheater which is also housed in water-cooled walls. Seed material condenses on these walls and is removed. The gas then preheats the combustion oxidizer in the preheater, and heats feedwater in the high temperature economizer section. Flue gas then enters the gas cleanup system at 550°F for particulate removal and final seed recovery. Cleaned gas splits into a stream used for coal drying and a stream used for preheating secondary air and for low temperature economizing. The gas leaving the low temperature economizer exhausts to the stack at about 310°F.

The heat exchanger system recovers nearly all the seed material injected into the combustor. A portion of the potassium sulfate recovered will be regenerated to sulfur-free potassium carbonate for reinjection into the combustor. The sulfur in the coal readily combines with the potassium carbonate to form potassium sulfate. In this manner, sulfur removal from the exhaust gases is achieved, and, by properly adjusting the ratio of regenerated seed to potassium sulfate, the EPA sulfur emission limits are met.

2.6.2 Separately Fired Cycle

The separately fired MHD heat and seed recovery system is the same as the arrangement proposed by AVCO in their ETF system design. This arrangement is illustrated in Figure 10.

Downstream of the primary radiant furnace is the secondary radiant furnace which houses the finishing superheater and also supports evaporation within its water cooled walls. The finishing superheater supplies the additional superheat required to raise steam from the initial superheater up to turbine throttle conditions. Gas enters this secondary radiant furnace in a reducing state at 2,900°F and discharges at 1,880°F. Much of the slag is condensed and removed. Secondary air at 518°F is injected at the outlet of this furnace, bringing the gas to oxidizing conditions at 2,010°F.

In the convective section following the secondary radiant furnace, combustion air and recycle gas for the separately fired high temperature air heater are heated, and initial superheat plus additional evaporation in wall tubes occurs. The gas exhausts this section at about 800°F, passes through an economizer, and enters the cleanup system at 320°F.

2.7 COAL PREPARATION

In both MHD retrofit cycles, Montana Rosebud coal with 22.7 percent moisture is crushed and fed to the pulverizers where it is dried to five percent moisture. In the oxygen enriched cycle the coal is dried using 550°F MHD exhaust gas. In the separately fired cycle, 576°F exhaust gas from fuel oil combustion in the high temperature air heater is used to dry the coal. In both cycles, the coal is separated from the drying gas in cyclone collectors and baghouses at 150°F and is carried by transport gas to the MHD combustor. The ratio of drying gas to coal flow is approximately 2.5-to-1 which is within the normal operating range of conventional pulverizers.

SECTION 3.0
THE COLSTRIP STEAM CYCLE

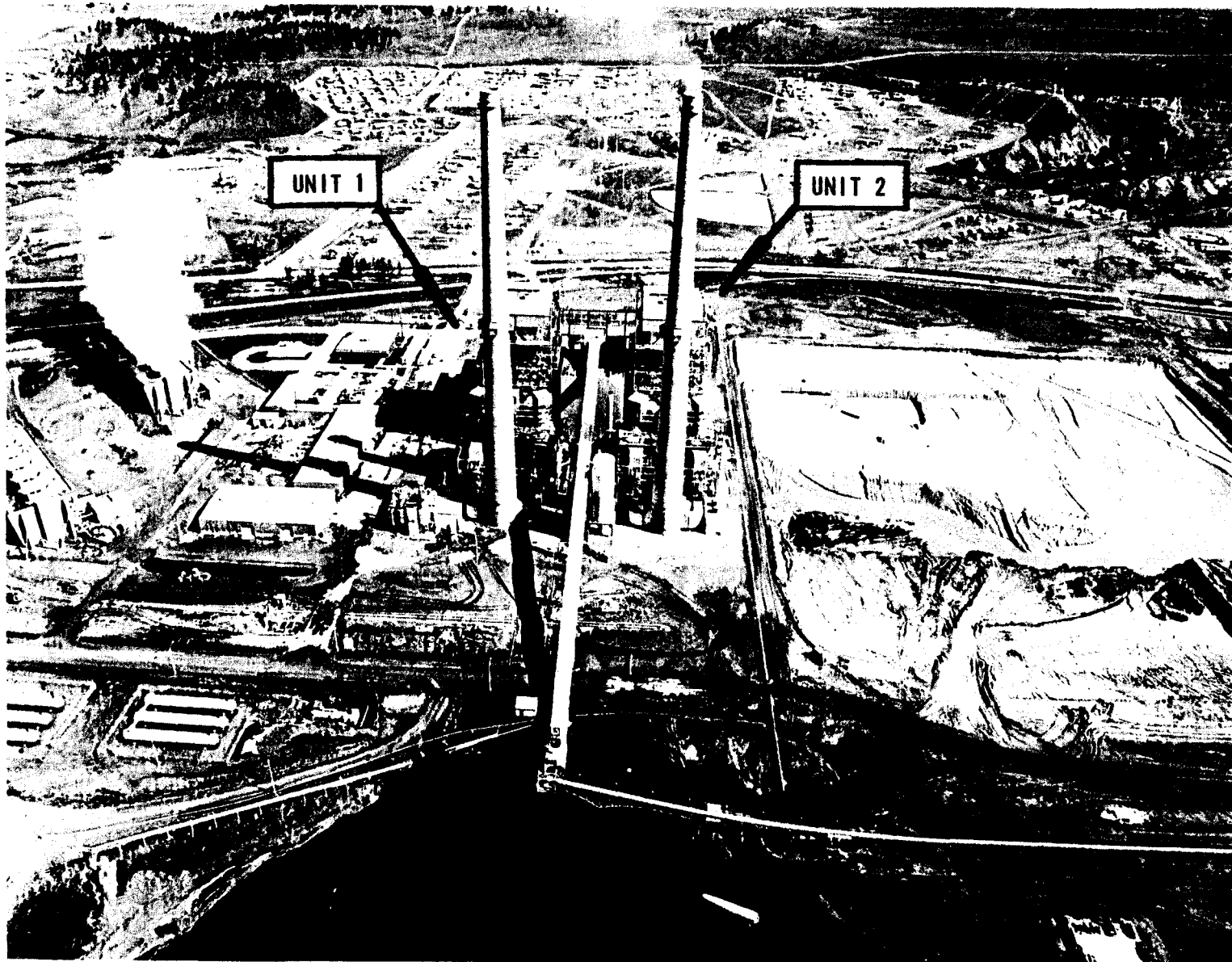
3.1 THE EXISTING PLANT

The Colstrip plant is located in Colstrip, Montana, one hundred miles east of Billings, the nearest population center. The facility is the largest fossil fueled power plant in Montana, with each of its two identical units contributing 350 MWe to the Montana Power Company grid. A subcritical power cycle with reheat is used with nominal operating conditions of 2,400 psig/1,000°F/1,000°F. Feedwater heating is accomplished with six extraction feedwater heaters. Firing is with subbituminous Rosebud coal transported by conveyor belt from a neighboring mine site. Construction of the plant was completed in 1976 showing that the plant is of fairly recent design. Wet cooling towers are used for heat rejection and precipitators and scrubbers for flue gas cleaning.

An aerial view of the plant site is shown in Figure 11. An open area to the east of Unit 2 (right side of figure) is currently used as an ash dump. Under MHD retrofit, the ash could be relocated to the north and the current dump site used as the location for MHD equipment. For this reason, Unit 2 of the plant was chosen for the retrofit application.

The main steam turbine, built by General Electric, is a 3,600 rpm, 2,400 psig/1,000°F/1,000°F, tandem compound, reheat unit with a double flow low pressure section. The turbine can accommodate five percent overpressure, valves-wide-open conditions of 2,535 psia/1,000°F/1,000°F with 2,465,000 lb/hr flow at the high pressure inlet and 1,608,000 lb/hr at the condenser. Higher inlet or outlet flows cannot occur without overloading the turbine or generator. The electric generator is hydrogen cooled and generates 360 MWe of electric power at a frequency of 60 Hz.

The Colstrip coal-fired boiler assembly was designed by Combustion Engineering. The assembly includes an economizer, evaporator, reheater, superheater, regenerative air preheater, forced and induced draft fans, and soot blowers. Design steam capacity is 2,465,000 lb/hr at superheater outlet



VIEW FACING NORTH

PHOTO COURTESY OF THE MONTANA POWER COMPANY

FIGURE 11
COLSTRIP POWER PLANT

conditions of 2,535 psia and 1,000°F. Thermal input capacity is 970 MWt of coal. The boiler feed pump is turbine driven, using steam drawn from the crossover point where the reheat turbine discharges to the low pressure turbine.

The coal feed for the Colstrip boiler is typical of conventional utility practice. A portion of the boiler combustion air heated by exhaust gas in a combustion air heater is used to dry the coal during pulverization. This air also carries the coal from the pulverizers directly into the boiler.

3.2 CYCLE ARRANGEMENT UNDER RETROFIT

The steam flow requirement for the Colstrip plant is approximately 3.5 times larger than that which can be supplied by heat recovered from either of the two MHD cycles. In References 3, 8, and 9, over 25 retrofit integration concepts were evaluated and the steam requirements of the steam cycle relative to the steam capability of the MHD cycle were studied over a considerable range. The conclusions from these retrofit evaluations concerning the most practical method of integration for a given application are summarized in Figure 12. Figure 12 depicts the compromises that can be made between turbine inefficiency due to reduced steam flow when only a limited amount of steam is available, and boiler inefficiency due to partial firing when only a limited amount of steam is required.

The top bar of Figure 12 shows that when the turbine capacity for steam flow is from slightly under one to slightly over 2 times the MHD capacity for steam generation, firing of the conventional boiler is not needed and may be eliminated. Whatever steam flow turndown is required can be tolerated by the turbine. The middle bar shows that for a capacity ratio of 1.5 and greater, it is practical to fire the existing boiler to avoid excessive turbine turndown. The proper amount of additional steam would be generated by partially firing the existing boiler to supply the turbine with approximately its design flow. The bottom bar shows that when the turbine capacity is 5 or more times the MHD capability, it may be advantageous to use the MHD heat for some purpose other than producing steam for the main turbine. In this case, steam may be generated for auxiliary turbines or other uses.

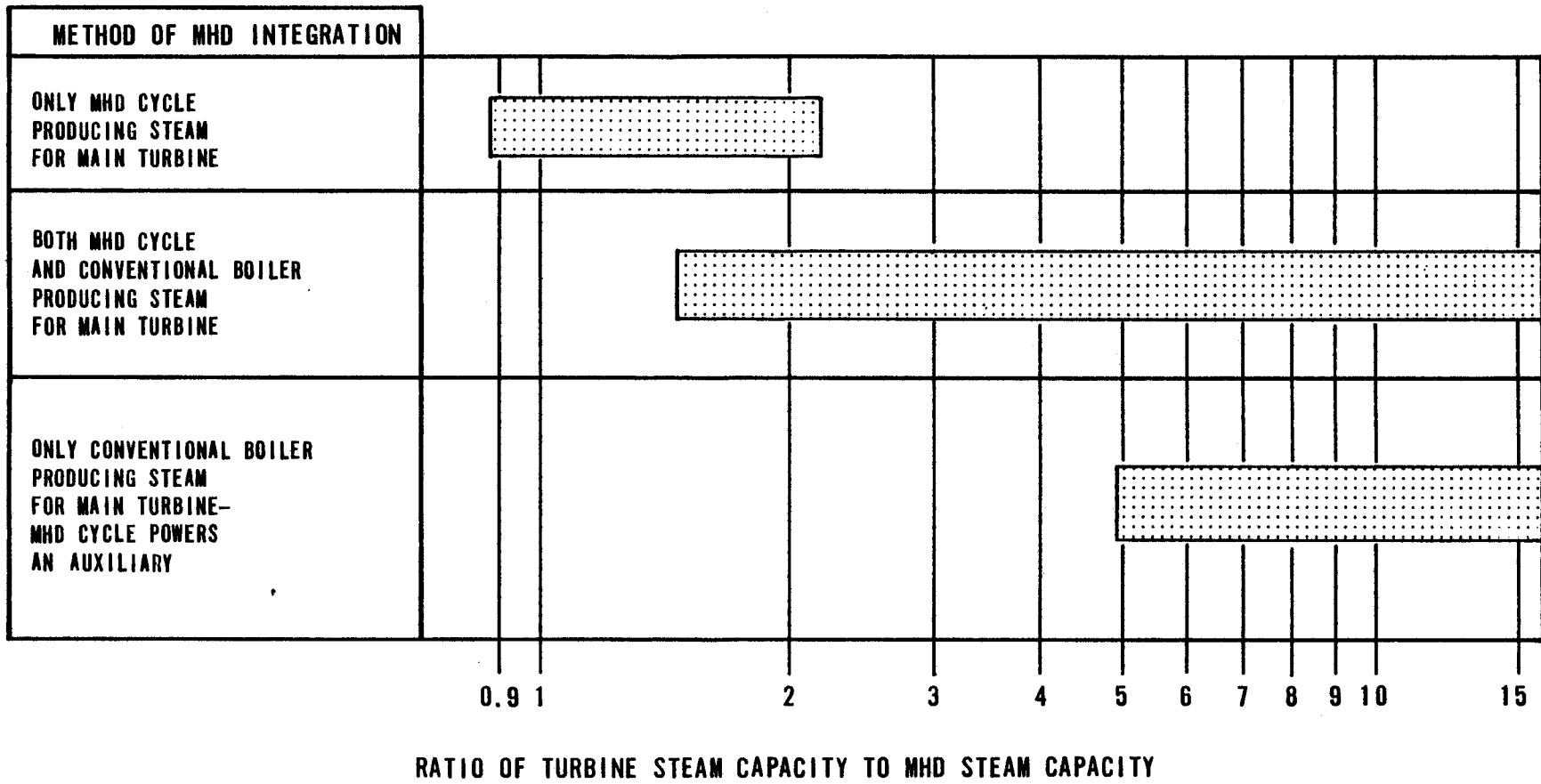


FIGURE 12
RANGE OF APPLICATION FOR
MHD INTEGRATION METHODS

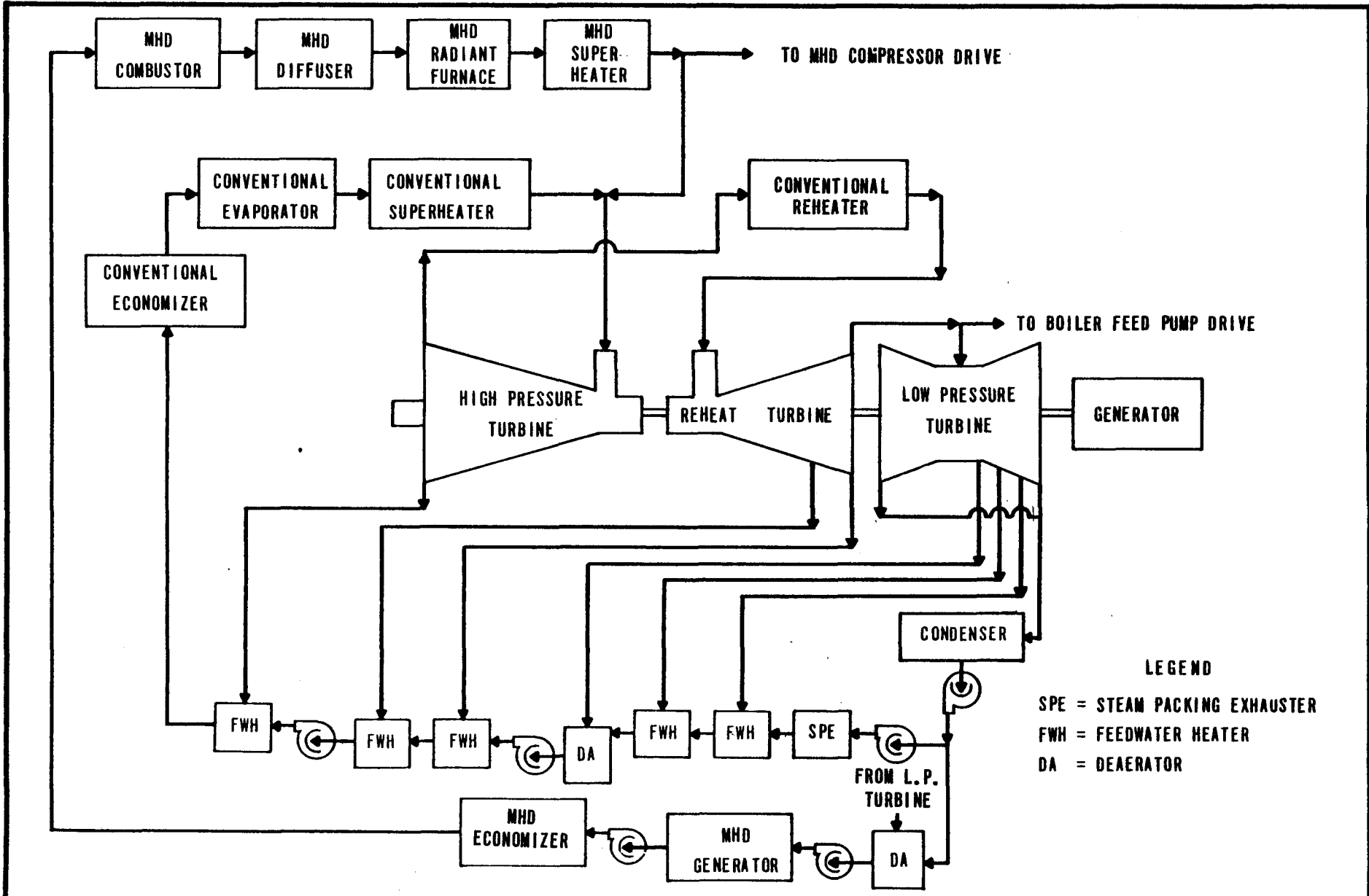


Since the Colstrip turbines were designed for 3.5 times the amount of steam that either of the two chosen MHD cycle sizes can raise, Figure 12 indicates that it is appropriate to obtain steam both from heat recovered from the MHD cycle and from partially firing the conventional boiler.

Figure 13 illustrates the steam flow path for retrofit operation. This sequence is the same for both MHD power cycles. Condensate is split just after the condenser into the topping cycle stream with about 25 to 30 percent of the flow, and the bottoming cycle stream. The topping cycle stream is first deaerated, then boosted to 100 psia pressure, demineralized, and circulated through the MHD generator as a coolant. It is then fully pressurized and receives heat in the MHD economizer, combustor, diffuser, radiant furnace, and superheater. All heat to this stream after the deaerator, both for feedwater heating and to raise steam at high pressure turbine throttle conditions, comes from the MHD components and the MHD heat and seed recovery system.

The bottoming cycle condensate stream undergoes the same process for feedwater heating in the same equipment that is currently in use at the Colstrip plant. This equipment consists of two low pressure extraction feedwater heaters, a primary deaerator, and three high pressure extraction feedwater heaters. The bottoming cycle feedwater stream is raised to high pressure throttle conditions by the existing conventional boiler system. Because of the reduced flows, the existing feedwater heater string operates at about 75 percent of its full capacity and the existing boiler at about 80 percent of its full capacity.

Steam for the turbine driving the topping cycle compressors is drawn from the discharge of the MHD superheater. Steam turbine drive, rather than electric motor drive, was chosen for the MHD compressors to avoid a large auxiliary drain from the plant electric output. The remainder of the MHD superheat stream is blended with the conventional superheat stream and fed to the Colstrip high pressure turbine. After expanding through the high pressure turbine, the steam flow is reheated solely in the reheat section of the Colstrip coal-fired furnace.



LEGEND
 SPE = STEAM PACKING EXHAUSTER
 FWH = FEEDWATER HEATER
 DA = DEAERATOR

FIGURE 13
RETROFIT STEAM CYCLE FLOW SCHEMATIC



With heat for feedwater heating of the topping cycle stream coming from the topping cycle itself, less extraction steam is drawn from the turbines. Steam flow into the Colstrip high pressure turbine section is reduced to avoid overloading the lower pressure turbine sections. Flow at the inlet of the high pressure section is set so that flow at the back end of the low pressure section is at the design value, for both the directly and separately fired MHD topping cycles.

When the MHD cycle is taken out of service, the topping cycle feedwater stream is cut off. The bottoming cycle feedwater stream then returns to full flow and the extraction feedwater heaters and the Colstrip coal-fired furnace revert back to full load operation to supply the original design steam flow rate to all parts of the turbine. Plant operation would then be the same as before retrofit.

The split between the topping cycle and bottoming cycle feedwater streams was made at the lowest possible temperature which occurs just after the condensate pump. This minimizes the temperature of the feedwater cooling the MHD channel.

SECTION 4.0
THE INTEGRATED SYSTEM

4.1 PERFORMANCE

Estimated performance at design conditions is given in Table 4 for three plant arrangements: 1) the oxygen enriched, direct fired combined MHD/steam retrofit system; 2) the nonenriched, separately fired combined MHD/steam retrofit system; and 3) the steam cycle standing alone, for either of the MHD cycles taken out of service. The stand-alone case is equivalent to the design performance of the Colstrip plant before retrofit. The table summarizes power outputs, power losses, fuel inputs, and net efficiencies. Table 5 gives a detailed breakdown of the auxiliary power losses. Performance of the three arrangements is compared in the discussion below.

4.1.1 MHD Out of Service

The analytical model of the Colstrip steam cycle under full design operation without MHD retrofit shows gross generator power to be 359.3 MWe, and fuel thermal input to be 971.0 MWt. Auxiliary losses amount to 6.5 percent of the gross plant output, giving a net plant output of 336.1 MWe and net plant efficiency of 34.62 percent. This performance will be the basis for comparing the two retrofit systems.

4.1.2 Oxygen Enriched System

For the oxygen enriched MHD retrofit system, electric output is 53.7 MW from the MHD generator and 346.4 MW from the turbine generator (a split of 13 percent MHD/87 percent steam turbine), for a total of 400.1 MWe of gross electric power. This gross power is 40.8 MWe or 11 percent higher than the original Colstrip cycle. Auxiliaries sum to 6.6 percent of gross plant output leaving net plant output at 373.6 MWe which is 37.5 MWe or 11 percent higher than the Colstrip plant in stand-alone operation.

TABLE 4

SYSTEM PERFORMANCE SUMMARY

		<u>Oxygen Enriched System</u>	<u>Separately Fired System</u>	<u>MHD Out of Service</u>
<u>Steam Turbine Power</u>				
Main Turbine Shaft	MW	351.4	351.3	364.4
Air Compressor Drive	MW	12.3	11.3	-
Oxygen Compressor Drive	MW	2.4	-	-
O ₂ Plant Compressor Drive	MW	10.0	-	-
Boiler Feedpump Drive	MW	5.5	5.4	7.3
Total Turbine Shaft Power	MW	<u>381.6</u>	<u>368.0</u>	<u>371.7</u>
<u>Generator Power</u>				
MHD Generator Gross	MW	53.7	35.5	-
Steam Turbine Generator:				
Shaft Input	MW	351.4	351.3	364.4
Mechanical Loss	MW	1.4	1.4	1.4
Generator Loss	MW	3.6	3.6	3.7
Turbogenerator Output	MW	<u>346.4</u>	<u>346.3</u>	<u>359.3</u>
Total Electrical Output	MW	<u>400.1</u>	<u>381.8</u>	<u>359.3</u>
<u>Auxiliary Losses</u>				
Topping cycle	MW	6.4	7.8	-
Bottoming cycle	MW	20.1	19.5	23.2
Total Losses	MW	<u>26.5</u>	<u>27.2</u>	<u>23.2</u>
<u>Net Plant Output</u>	MWe	373.6	354.6	336.1
<u>Heat Input</u>				
Oil/Separately Fired HTAH	MWt	-	74.3	-
Coal/MHD Combustor	MWt	287.0	182.8	-
Seed Regeneration	MWt	2.6	1.6	-
Existing Boiler Coal Input	MWt	776.1	757.0	971.0
Total Heat Input	MWt	<u>1,065.7</u>	<u>1,015.8</u>	<u>971.0</u>
<u>Net Performance</u>				
Net Plant Efficiency	%	35.06	34.91	34.62
Net Plant Heat Rate	Btu/kWh	9,735	9,777	9,860

TABLE 5

AUXILIARY LOSS BREAKDOWN

		<u>Oxygen Enriched System</u>	<u>Separately Fired System</u>	<u>MHD Out of Service</u>
<u>Topping Cycle Losses:</u>				
ID fan	kW	591	899	-
Gas blower	kW	-	1,220	-
Air blower	kW	48	1,180	-
Booster pump	kW	54	52	-
Boiler feed pump	kW	1,880	1,840	-
Fuel handling	kW	854	640	-
Ash handling	kW	222	141	-
Electrostatic precipitator	kW	926	590	-
Inverter	kW	537	355	-
MHD transformer	kW	1,070	710	-
Magnet	kW	86	57	-
Miscellaneous	kW	156	94	-
Total MHD losses	kW	<u>6,424</u>	<u>7,778</u>	<u>0</u>
<u>Bottoming Cycle Losses:</u>				
Condensate pump	kW	224	212	210
Booster pump	kW	861	835	1,130
Circulating water pump	kW	2,470	2,340	2,320
Forced draft fan	kW	1,810	1,760	2,260
Induced draft fan	kW	2,810	2,740	3,520
Fuel Handling	kW	2,310	2,250	2,890
Ash handling	kW	600	585	750
Electrostatic precipitator	kW	2,500	2,440	3,130
SO ₂ removal	kW	1,350	1,310	1,680
Transformer	kW	3,460	3,460	3,590
Miscellaneous	kW	<u>1,680</u>	<u>1,530</u>	<u>1,700</u>
Total steam plant losses	kW	<u>20,075</u>	<u>19,462</u>	<u>23,180</u>
Total Auxiliary Losses	MW	26.50	27.24	23.18

Total thermal input is 1,065.7 Mwt (split 27/73 percent between MHD combustor and existing boiler), which is 94.7 Mwt and 9.8 percent higher than Colstrip in stand-alone operation. The boiler is fired to 80 percent of design load. Net plant efficiency is 35.06 percent, up 0.44 percentage points from the calculated efficiency of the existing Colstrip plant.

4.1.3 Separately Fired System

The nonenriched retrofit system produces 35.5 MWe from the MHD generator and 346.3 MWe from the turbogenerator (split 9/91 percent), totaling 381.8 MWe of gross electric power. This gross is 22.5 MWe and 6.3 percent above Colstrip stand-alone. Auxiliaries total 7.1 percent of gross output putting net plant output at 354.6 MWe, or 18.5 MWe and 5.5 percent higher than the original Colstrip plant.

Thermal input totals 1,015.8 Mwt (split 18/7/75 percent between combustor, air heater, and boiler, respectively). This is 44.8 Mwt or 4.6 percent higher than Colstrip alone. Boiler firing is 78 percent of design load. Net plant efficiency is 34.91 percent up 0.29 points from Colstrip.

4.1.4 Retrofit Benefits

Both the oxygen enriched and the separately fired retrofit systems offer a small increase in output power over the present Colstrip power plant. Both retrofit systems also offer an increase in net plant efficiency. The oxygen enriched system is best in both regards, offering twice as much power increase as the separately fired system at 0.15 percentage points more efficiency rise.

Besides capital cost which is considered in Section 5, a performance benefit must be weighed against complexity, uncertainty, and reliability. The oxygen enriched direct fired option involves the complexity of an oxygen plant which potentially may be considered a disadvantage by a utility. However, oxygen plant technology introduces no uncertainty, even for the special process chosen by this study, and no problem with reliability. Instead, the oxygen enriched option removes the uncertainty associated with material durability

and fouling in the high temperature air heater. These are factors that will influence the selection of a retrofit concept.

The retrofit system designs produced by this study are preliminary. Each is presented as a system design that displays concept feasibility, but neither system is optimized completely.

4.2 OPERATING CONDITIONS

The detailed heat balance diagrams of the integrated system of the oxygen enriched MHD cycle, the separately fired MHD cycle, and the stand-alone steam cycle without an MHD cycle operating are presented in Figures 14, 15, and 16, respectively.

4.2.1 Oxygen Enriched System

The oxygen plant is integrated into the system by receiving compression power from a steam turbine operating with steam produced by the MHD heat recovery system. The oxygen plant is represented by the liquefaction compressor, aftercooler, and air separation unit. The air separation unit expands cool compressed air to obtain liquified air which is separated by fractional distillation into a stream of 95 mole percent oxygen and a stream of waste nitrogen. The oxygen is compressed and blended with compressed air to form the oxidizer for the MHD combustor.

The oxidizer is preheated to 1,100°F in the low temperature air heater which is directly fired by gas from the MHD generator. At 6.08 standard atmospheres (7.32 in local 12.2 psi atmospheres), the combustor burns coal at 95 percent stoichiometry, rejects slag and adds potassium carbonate and potassium sulfate seed to produce plasma at 4,547°F for the MHD channel. The plasma passes through the channel, generating electric power, and expands to essentially atmospheric pressure at the diffuser exit. Diffuser exit temperature is 3,686°F. While passing through the radiant boiler, the gas is injected with 300°F secondary air to attain 105 percent combustion stoichiometry. The cycle was balanced to hold the afterburner combustion temperature to 2,400°F. The

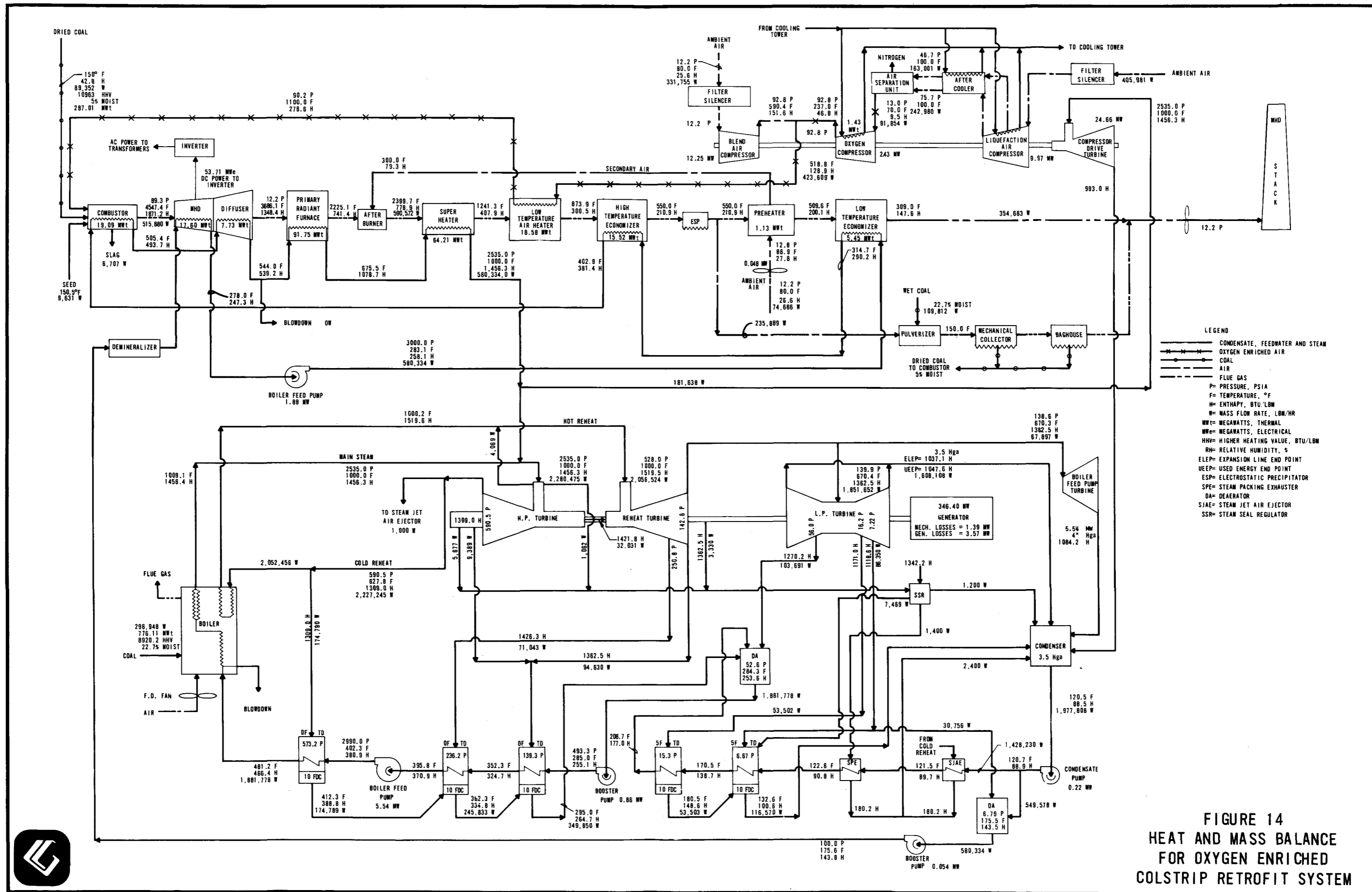
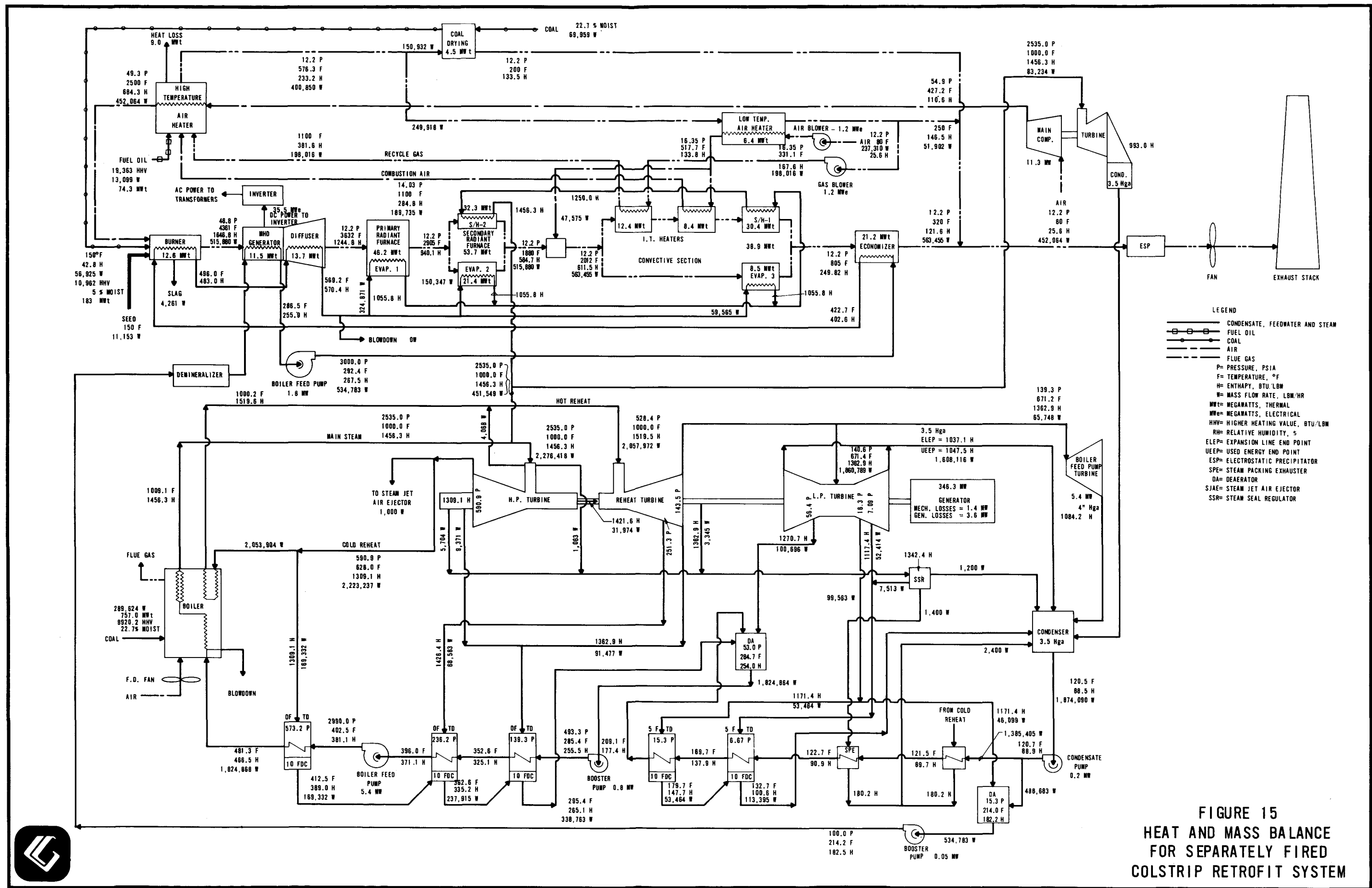
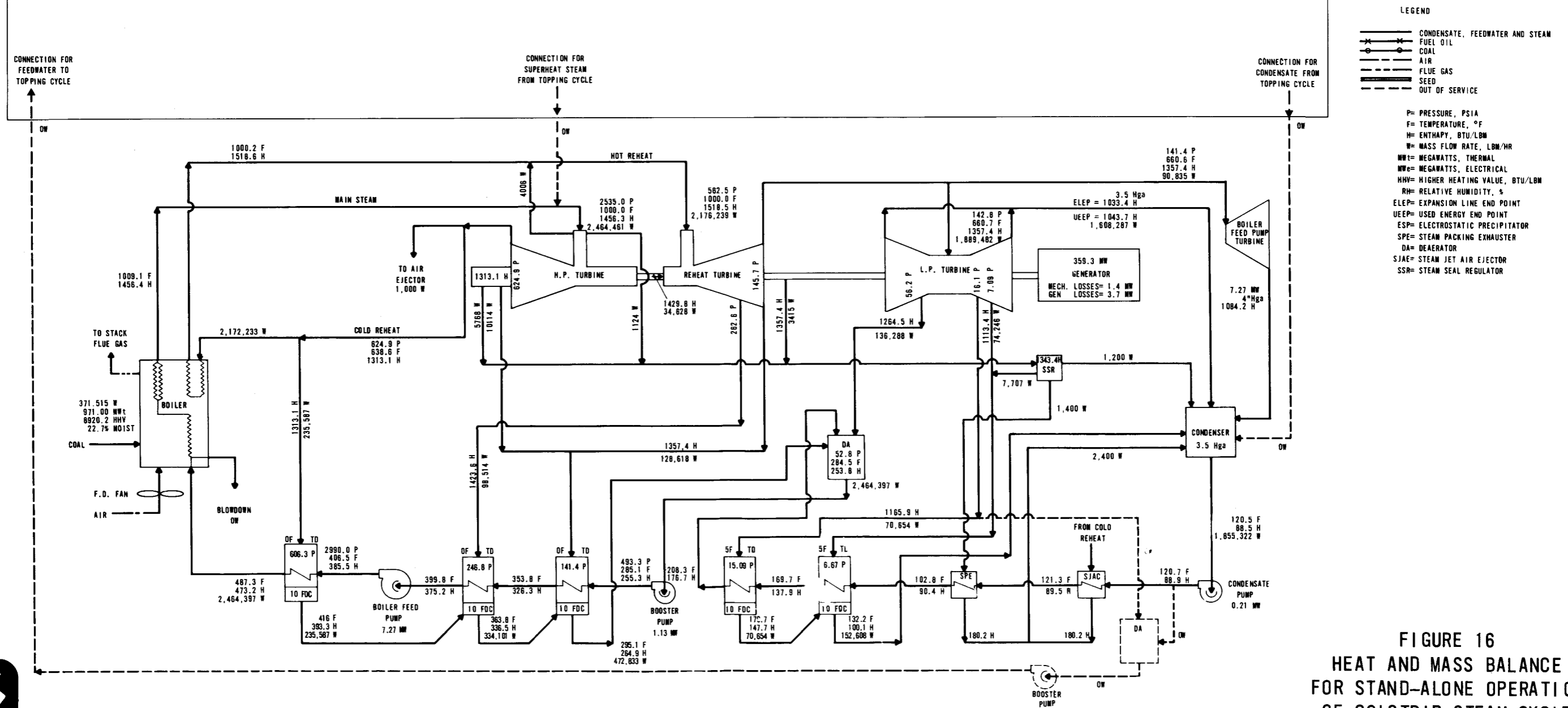


FIGURE 14
HEAT AND MASS BALANCE
FOR OXYGEN ENRICHED
COLSTRIP RETROFIT SYSTEM



DWG. NO. 373-016
 W.O. NO. 088230-037

MHD TOPPING CYCLE OUT OF SERVICE



**FIGURE 16
HEAT AND MASS BALANCE
FOR STAND-ALONE OPERATION
OF COLSTRIP STEAM CYCLE**

gas, now in an oxidizing state, passes through the superheater, low temperature air heater, and high temperature economizer to enter the electrostatic precipitator at 550°F where fly ash and remaining traces of seed are removed. Forty percent of the flow leaving the precipitator is split off and sent to the coal pulverizers at 550°F for drying coal. The remaining gas is used to preheat the secondary air and then cooled in a low temperature economizer to 309°F, the lowest stack temperature possible without going below a minimum approach temperature in the low temperature economizer.

The topping cycle feedwater stream is deaerated with the lowest pressure extraction steam available from the Colstrip turbines, which is subatmospheric at 6.8 psia. From the deaerator, the feedwater is pumped to 100 psia and demineralized to reduce its electrical conductivity before passing to the MHD channel to act as a coolant. Feedwater temperature leaving the channel is 278°F. The feedwater stream is then fully pressurized and passed through the low and high temperature economizers of the MHD heat recovery system, and then to the MHD combustor and diffuser, again to act as a coolant. Feedwater leaving the diffuser is subcooled by 104°F. The stream is then raised to saturated vapor in the radiant boiler and heated to high pressure turbine throttle conditions in the superheater. Provision for blowdown is made within the radiant boiler but blowdown will not need to be continuous because of the prior demineralization.

At the MHD superheater exit, 31 percent of the topping cycle superheat steam is split off to power the compressor drive turbines. The remaining MHD superheat steam is then blended with steam at the same state conditions from the existing Colstrip boiler and fed to the high pressure turbine. The MHD heat recovery system contributes 17.5 percent to the total high pressure turbine flow.

The main effect of the integration on the steam cycle is the reduced steam flow within the turbines. The reduction is necessary because the topping cycle feedwater stream bypasses the feedwater heaters, receiving none of its heating from extraction steam except for deaeration. Since the topping feedwater stream is 24 percent of the total feedwater flow, about the same percent less steam is extracted from the turbines. Turbine inlet flows must

be reduced accordingly to avoid back-end overloading of the turbines. Table 6 lists the major steam flow rates for the two retrofit systems and the original Colstrip steam cycle. The oxygen enriched case has reduced the high pressure inlet, reheat inlet, and low pressure turbine inlet flows by 7.5, 5.5, and 2.0 percent, respectively, in order to hold exhaust hood flow from the low pressure turbine at the original design level.

The oxygen plant requires 10 MW of power for its liquefaction compressor. Compression of the oxygen stream and compression of the blend air for combustion require 2.4 and 12 MW, respectively. All compression power is supplied by steam turbine drive. The additional boiler feed pump for the topping cycle is electric motor driven, as are all of the booster and condensate pumps. The only turbine driven pump is the original boiler feed pump.

TABLE 6
STEAM FLOWS

	<u>Oxygen Enriched System</u>	<u>Separately Fired System</u>	<u>MHD Out of Service</u>
High Pressure Turbine Inlet	2,280,000	2,276,000	2,464,000
Reheat Turbine Inlet	2,056,000	2,058,000	2,176,000
Low Pressure Turbine Inlet	1,852,000	1,861,000	1,889,000
Low Pressure Turbine Exhaust	1,608,000	1,608,000	1,608,000
Total Extraction Flow	584,000	582,100	743,900

4.2.2 Separately Fired System

The separately fired regenerative high temperature air heater requires a subsystem consisting of a low temperature air heater, an intermediate temperature air heater, the high temperature air heater itself, a recycle gas heater, gas and air blowers, and a fuel oil feed. MHD combustor air is heated from the main compressor discharge condition to 2,500°F entirely in the high temperature air heater. Air for the preheater combustion is heated to 1,100°F in the intermediate and low temperature heaters. The intermediate heater is fired with MHD gas and functions similarly to the direct fired air heater of

the oxygen enriched system. The low temperature air heater extracts its heat from the preheater combustion gas before discharging a portion of the gas to the stack. Some of this preheater combustion gas is recycled back to the combustion area of the high temperature air heater. This recycle gas also undergoes a reheating to 1,100°F in an intermediate temperature heat exchanger fired by MHD exhaust gas.

Coal drying in this system is similar to coal drying in the direct fired system, except that exhaust gas from the high temperature air heater subsystem is used rather than MHD gas.

MHD combustor pressure is 3.32 standard atmospheres (4.0 local atmospheres), and flame temperature is 4,361°F, 186°F lower than in the oxygen enriched case. Diffuser exit temperature is 3,632°F, 54°F lower than the enriched case.

The schematic of the heat and seed recovery system in Figure 15 shows more detail of the feedwater and steam flow paths by showing boiling in both the radiant furnace and in additional evaporators to represent feedwater cooling of furnace walls. The superheater sections are shown as two sections, an initial and a finishing section, at different locations in the gas flow path.

Secondary combustion takes place after the finishing superheater section. A single economizer is used, which cools the MHD gas to 320°F before discharging it to the electrostatic precipitator and the stack.

Topping cycle feedwater in the separately fired system follows a flow path from the condenser to the high pressure turbine that is nearly identical to that of the oxygen enriched system. Deaeration of the topping cycle feedwater stream is done with extraction steam from the second, rather than first, lowest extraction point on the Colstrip turbines. This pressure is 15.3 psia, just above atmospheric. Feedwater temperature leaving the MHD channel is 287°F, slightly higher than in the oxygen enriched system. The state at the diffuser exit is 120°F subcooled. Steam flow to the compressor drive turbine is 15.6 percent of the steam produced by the MHD heat and seed recovery system. This is significantly less than in the oxygen enriched

system because no air separation compressors are involved. MHD contribution to the total high pressure turbine steam flow is 19.8 percent, slightly higher because of the reduced compressor power requirement.

Steam flows within the main turbine set are reduced in the same way as in the oxygen enriched system due to the smaller amount of extraction steam required. The topping cycle feedwater stream is 23 percent of total feedwater flow, and the reduction in steam flow to the high pressure, reheat, and low pressure turbine is 7.6, 5.4 and 1.5 percent, respectively, as can be determined from Table 6.

4.2.3 MHD Out Of Service

The steam cycle heat balance in Figure 16 represents either retrofit system with the MHD cycle shut down. It is equivalent to the design conditions of the original Colstrip plant before MHD retrofit.

4.3 PLANT LAYOUT

A preliminary plot plan was prepared to illustrate how each MHD configuration could be arranged on the Colstrip plant site. Figure 17 shows the oxygen enriched system and Figure 18 the separately fired system. Both topping cycles are integrated with Unit 2 of the Colstrip plant with the MHD equipment located on the land adjacent to Unit 2.

4.4 OPERATING CONCERNS

Some items of concern to the practicability of the MHD retrofit facility are discussed briefly in this section.

4.4.1 MHD Shutdown

Neither MHD retrofit system will hinder plant operation when the MHD cycle is taken out of service because the steam connection is easily broken by the closing of valves. The main effect on stand-alone steam plant operation is the delay involved in getting the existing boiler into full operation should

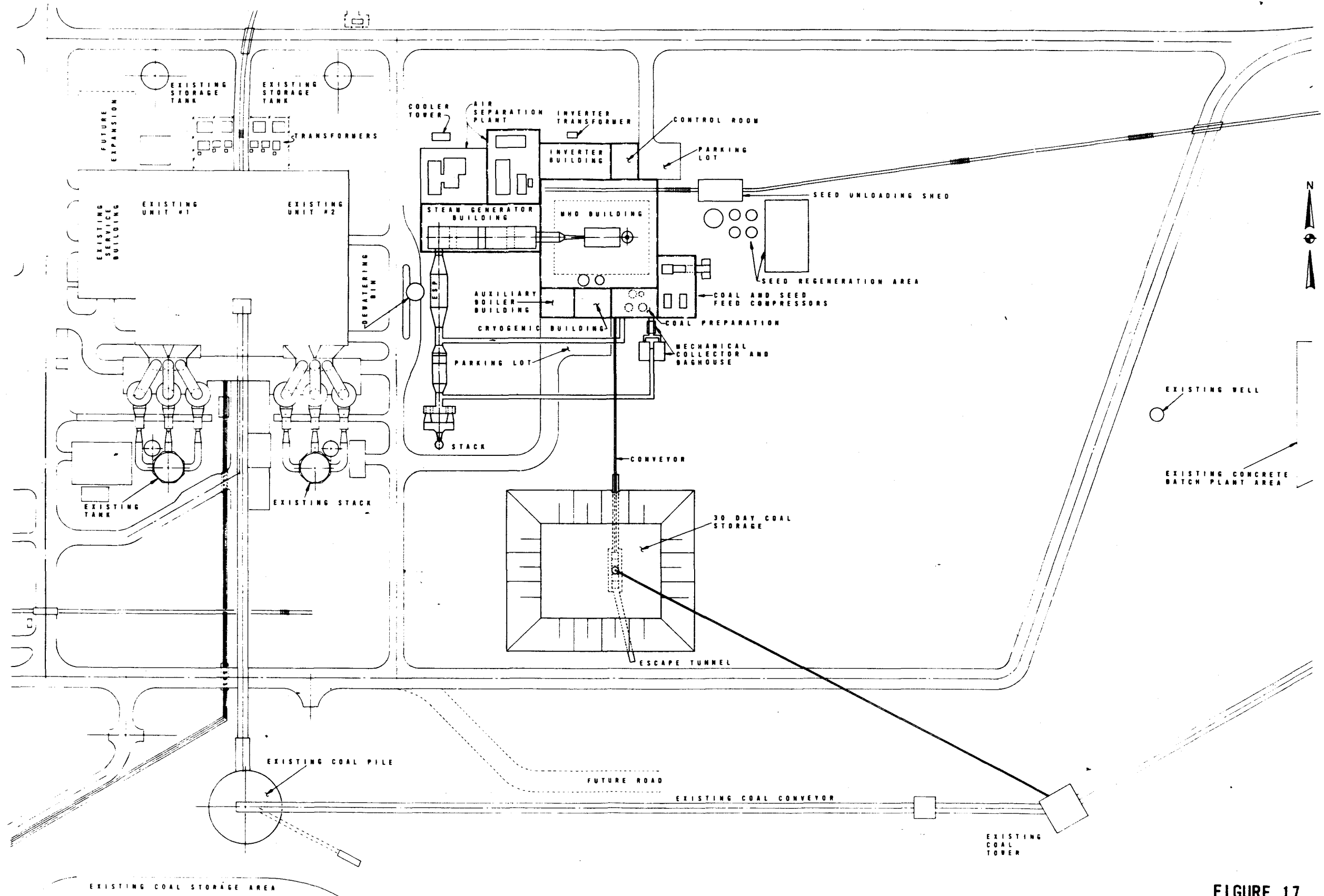


FIGURE 17
 PLOT PLAN OF OXYGEN ENRICHED
 COLSTRIP RETROFIT PLANT

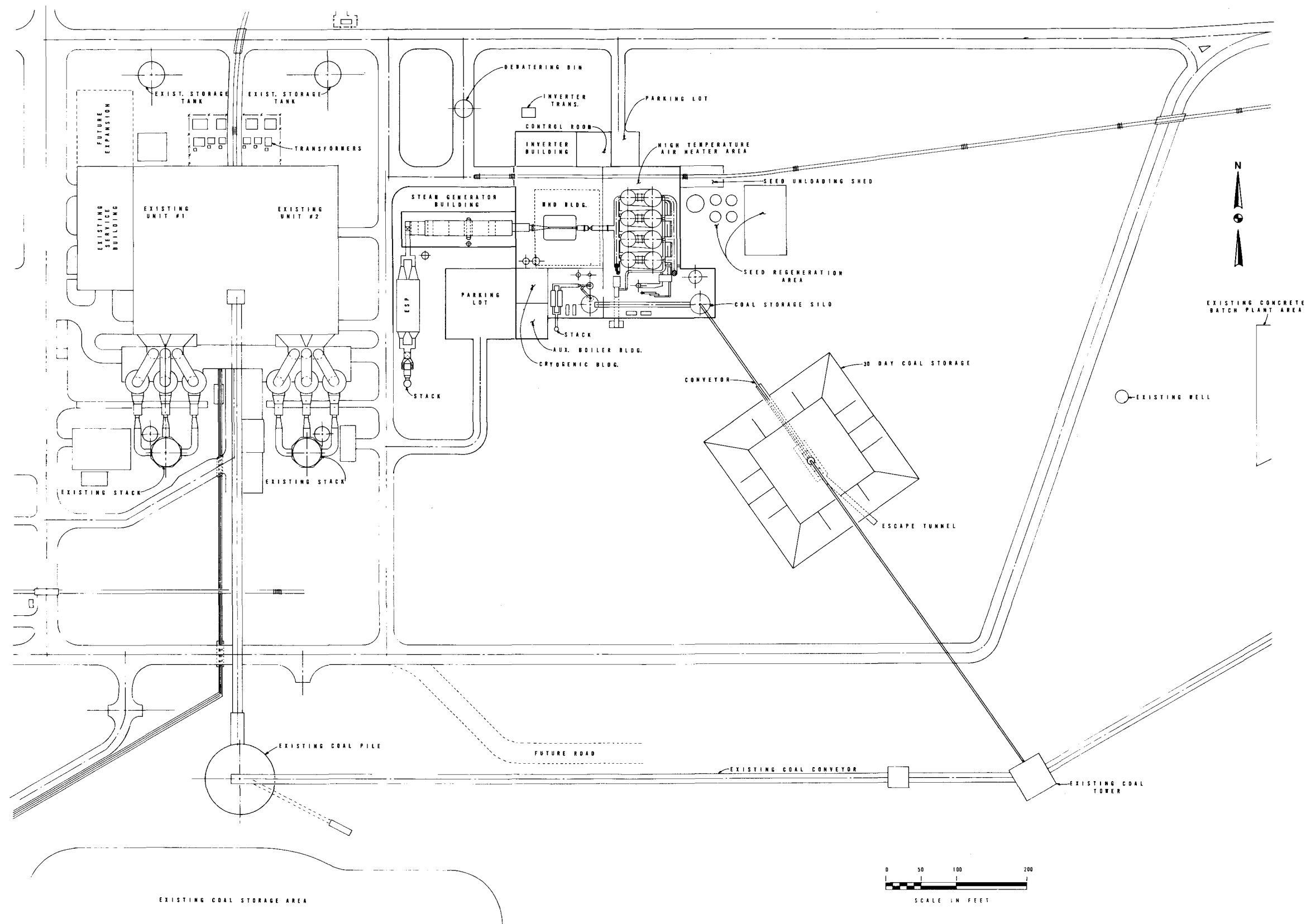


FIGURE 18
 PLOT PLAN OF SEPARATELY FIRED
 COLSTRIP RETROFIT PLANT

DWG. NO. 073-017
 W.O. NO. 088230-037

the MHD cycle be shut down suddenly. The delay should be small because the steam plant boiler will always be fired to about 80 percent of its capacity and will be up to operating temperature with correct water chemistry. Neither a planned nor an emergency outage should cause any serious interruption of plant output.

4.4.2 Control of Steam Blend

Operation of the MHD steam generator in parallel with the conventional steam generator should require only minor modifications to the present single boiler control system. The MHD steam generator should be controlled by the MHD cycle only, and not by the remainder of the plant. Changes in steam flow to the main turbine should be obtained by controlling the conventional steam generator.

A conventional turbine load-runback control would be needed to prevent runaway of the steam turbine after an emergency trip of the MHD cycle. Interlocks protecting the MHD cycle from a trip of the steam cycle also deserve attention.

4.4.3 Oxygen Plant Considerations

For short MHD outages, the oxygen plant should continue operating on maximum turndown with its product oxygen vented. Shutting down the oxygen plant requires subsequent cooldown time, as much as three days, before the plant can resume full production.

Storing liquid oxygen in compact containers can be a means to increase power plant peak output. Liquid oxygen would be stored during off-peak periods and added to the output from the oxygen plant during peak periods. Oxygen plant power consumption at the time would be reduced and oxygen compression power would also be reduced by pumping as a liquid. However, oxygen plant design must be modified to allow product oxygen to be discharged as a liquid rather than a gas, and heat must be supplied to vaporize the oxygen liquid. These effects were not evaluated for the test facilities in this study.

SECTION 5.0
CONSTRUCTION TIME AND COST

The time and capital cost involved in constructing the oxygen enriched direct fired MHD retrofit power plant and the separately fired retrofit power plant are discussed in this section.

5.1 CONSTRUCTION TIME

A construction time of five and one half years was estimated for the integration of either the oxygen enriched direct fired or the separately fired MHD power cycles with the Colstrip plant. A construction schedule was prepared based on conventional power plant scheduling experience and the assumption that procurement of critical MHD components is started during the design phase. It was assumed that developments in MHD technology would be achieved by the time they were needed to satisfy manufacturing, final design, and construction requirements. The construction schedule corresponds to normal practice of the electric utility industry and does not take into account the effect of government funding commitments and allocations.

5.2 CONSTRUCTION COST

5.2.1 System Cost

Construction cost estimates for the two MHD power cycles, based on equipment requirements analogous to those used in the retrofit studies of Reference 3, are shown in Tables 7 and 8. These estimates are arranged in accordance with the standard DOE/MHD format. They include design, procurement, fabrication, construction, installation, and checkout. The power train costs include the MHD topping subsystems and interface items such as adaptors, isolation valves, and bypass piping.

As shown in Table 7, the estimated overnight construction cost in mid-1978 dollars of the oxygen enriched MHD power train is \$171.0 million. The separately fired MHD power train would cost \$197.5 million, as shown in

TABLE 7
ESTIMATED CONSTRUCTION COST FOR RETROFITTING AN OXYGEN ENRICHED MHD CYCLE TO THE COLSTRIP POWER PLANT
 Costs in Thousands of Mid-1978 Dollars and Based on Overnight Construction

Account Number	Account Description	Material		Installation	Indirect Cost	Contingency*** Cost	Total*** Cost
		Major Components	Balance Of Plant				
311	Structures and Improvements	-	7,200	4,500	3,300	1,500	16,500
312	Boiler Plant Equipment	23,400	10,800	9,000	5,800	5,400	54,400
314	Turbogenerator Unit Equipment	-	1,000	400	300	100	1,800
315	Accessory Electric Equipment	4,100	6,000	3,100	2,000	1,600	16,000
316	Miscellaneous Power Plant Equipment	90	320	80	50	60	600
317	MHD Topping Cycle	18,100	13,300	3,800	2,400	5,300	42,900
350	Transmission Plant	900	600	600	400	300	<u>2,800</u>
	Subtotal Direct Accounts						135,800
381*	Engineering						13,600
- **	Oxygen Plant and Delivery System						<u>21,600</u>
	Total Estimated Construction Cost						171,000

NOTES:

* Includes 2% A/E fee on total direct costs.

** Includes liquefaction compressor, blend air compressor, oxygen compressor, and oxygen plant.

*** Based on GAI normal contingency factor for construction.

TABLE 8
ESTIMATED CONSTRUCTION COST FOR RETROFITTING A SEPARATELY FIRED MHD CYCLE TO THE COLSTRIP POWER PLANT
 Costs in Thousands of Mid-1978 Dollars and Based on Overnight Construction

Account Number	Account Description	Material		Installation	Indirect Cost	Contingency**	Total** Cost
		Major Components	Balance Of Plant				
311	Structures and Improvements	-	6,378	5,410	2,705	1,447	15,940
312	Boiler Plant Equipment	18,918	8,107	8,555	4,278	3,782	43,840
314	Turbogenerator Unit Equipment	-	923	403	202	152	1,680
315	Accessory Electric Equipment	4,144	6,216	3,525	1,763	1,562	17,210
316	Miscellaneous Power Plant Equipment	78	306	78	39	49	550
317	MHD Topping Cycle	55,440	4,274	7,448	3,724	7,094	78,030
350	Transmission Plant	814	542	569	285	220	<u>2,430</u>
	Subtotal Direct Accounts						159,680
381*	Engineering						<u>19,820</u>
	Total Estimated Construction Cost						197,500

NOTES:

- * Includes 2% A/E fee on total direct costs.
- ** Based on GAI normal contingency factor for Construction.

Table 8. Reference 3 shows that a newly constructed (both topping and bottoming cycle) MHD power plant with a steam cycle fully fired by the separately fired MHD cycle considered in this study would cost \$233.3 million and take 6.5 years to build.

These retrofit plant designs were not developed for minimum cost. Flexibility during operation was considered more important. As test facilities, the plants contain redundancy which increases cost compared to commercial MHD plant design. The major redundant item is the separate MHD heat and seed recovery boiler which effectively duplicates a portion of the conventional boiler. The expense of unused conventional boiler capacity is exchanged for construction time and cost savings and for the flexibility to revert back to stand-alone operation when the MHD cycle is taken out of service. Cost of these retrofit facilities is therefore not representative of commercial MHD plant designs.

5.2.2 Cost Basis

These estimates are based upon more detailed studies. The separately fired MHD cycle was unchanged from the cycle used for the retrofit feasibility study of Reference 3. Direct costs for the separately fired system consisting of materials, installation, and balance of plant, were taken from this study. However, more recent contingency factors and engineering cost factors were applied consistent with the costing techniques employed in current Gilbert/Commonwealth studies. Costs for the oxygen enriched case were obtained from the 500 MWt MHD cycle of Reference 7 by simple scaling on the basis of thermal input.

SECTION 6.0
CONCLUSIONS

The following conclusions may be drawn from this study:

1. It is technically feasible to retrofit a unit of the Colstrip power plant with either an oxygen enriched or a separately fired MHD cycle with MHD channel size equivalent to that in the AVCO separately fired ETF design (gas flow equal to 143 lb/s).
2. Either type of retrofit system with an AVCO size channel should employ partial firing of the Colstrip boiler at approximately 80 percent of the design capacity of the boiler.
3. Plant operation may be restored to normal with the MHD cycle shut down, if the MHD and steam cycles are integrated through steam blending. Steam blending confines the MHD gas to a new system of heat and seed recovery heat exchangers separated from the original plant boiler.
4. During retrofit operation with either type of MHD channel, inlet flows to the high pressure, intermediate pressure, and low pressure turbine sections must be decreased by approximately 7.5, 5.5, and 2 percent, respectively, in order to avoid back-end overloading at the low pressure turbine.
5. An oxygen enriched retrofit system can increase net plant output by almost 40 MWe and increase net plant efficiency by 0.44 percentage points.
6. A separately fired retrofit system can increase net plant output by almost 20 MWe and increase net plant efficiency by 0.3 percentage points.
7. Construction time for either type of retrofit system would be 5.5 years.

8. Capital cost is estimated to be \$171 million for the oxygen enriched retrofit system and \$198 million for the separately fired retrofit system, based on overnight construction and mid-1978 dollars.

9. An all-new MHD/steam power plant with the same separately fired MHD cycle used in this study, but with a smaller steam cycle that would be fully fired by the MHD exhaust gas, would cost \$35 million more and take at least one year longer to build than the separately fired Colstrip retrofit plant. Such a plant would have approximately one-fourth the electrical output of the separately fired Colstrip retrofit plant.

SECTION 7.0
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