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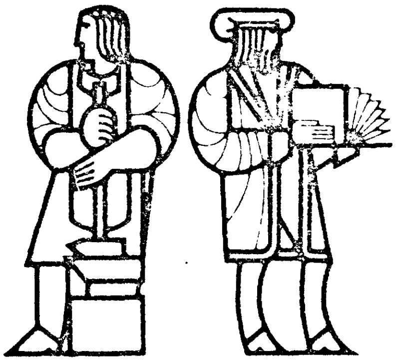

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ABSTRACT

This study is a review of projected emissions and energy efficiencies of coal-fired open cycle MHD power plants. Ideally one would like to develop empirically-based probabilistic models of MHD performance. However, with the lack of empirical information about full-sized facilities this survey concentrates on modeling analytically developed data. Also presented are discussions of unresolved MHD issues of importance, comprehensive lists of recent and ongoing research, and a bibliography of material related to emissions and efficiencies of coal-fired open cycle MHD power plants.

TABLE OF CONTENTS

1. Introduction

Recent reports (Pomeroy, et al., 1978) show open cycle (or binary) coal-fired magnetohydrodynamics, OCMHD, playing an extremely important role in our nation's energy future. Under certain assumed scenarios, such as no breeder reactors, open cycle MHD is overwhelmingly preferred once it is available (about the year 2003). That same study shows the large size (1932 MW) to be somewhat of a disadvantage that makes earlier penetration, if available, unlikely. Once available, however, the share of the market for OCMHD could be as large as 90% (Pomeroy, et al., 1978). Most forecasts show MHD dominating future coal-fired power plant markets, especially in scenarios where coal prices escalate rapidly.

Clearly this is an important advanced energy technology, yet there is currently not enough performance data to precisely assess the emissions or efficiency capabilities of OCMHD power plants. Appendix A displays the large uncertainties that exist concerning this information. The theoretically very high performance potential, meeting emissions standards with 50 to 60% conversion efficiency, and absence of moving parts and heat exchanges in the MHD cycle, have been the principal justifications for continued research and development. With the absence of full-sized facilities, this study concentrates on analytically derived data, ongoing research efforts, and problems and potential solutions for meeting the theoretical performance potential.

MHD is envisioned as a topping cycle to be operated in series with a steam cycle, see Figure 1-1. Coal is first processed then sent into a combustor where it is burned at very high temperatures, 2756 K to 3033 K (4500^{o}F to 5000^{o}F) and at high pressure, 7 to 15 atm. The gaseous

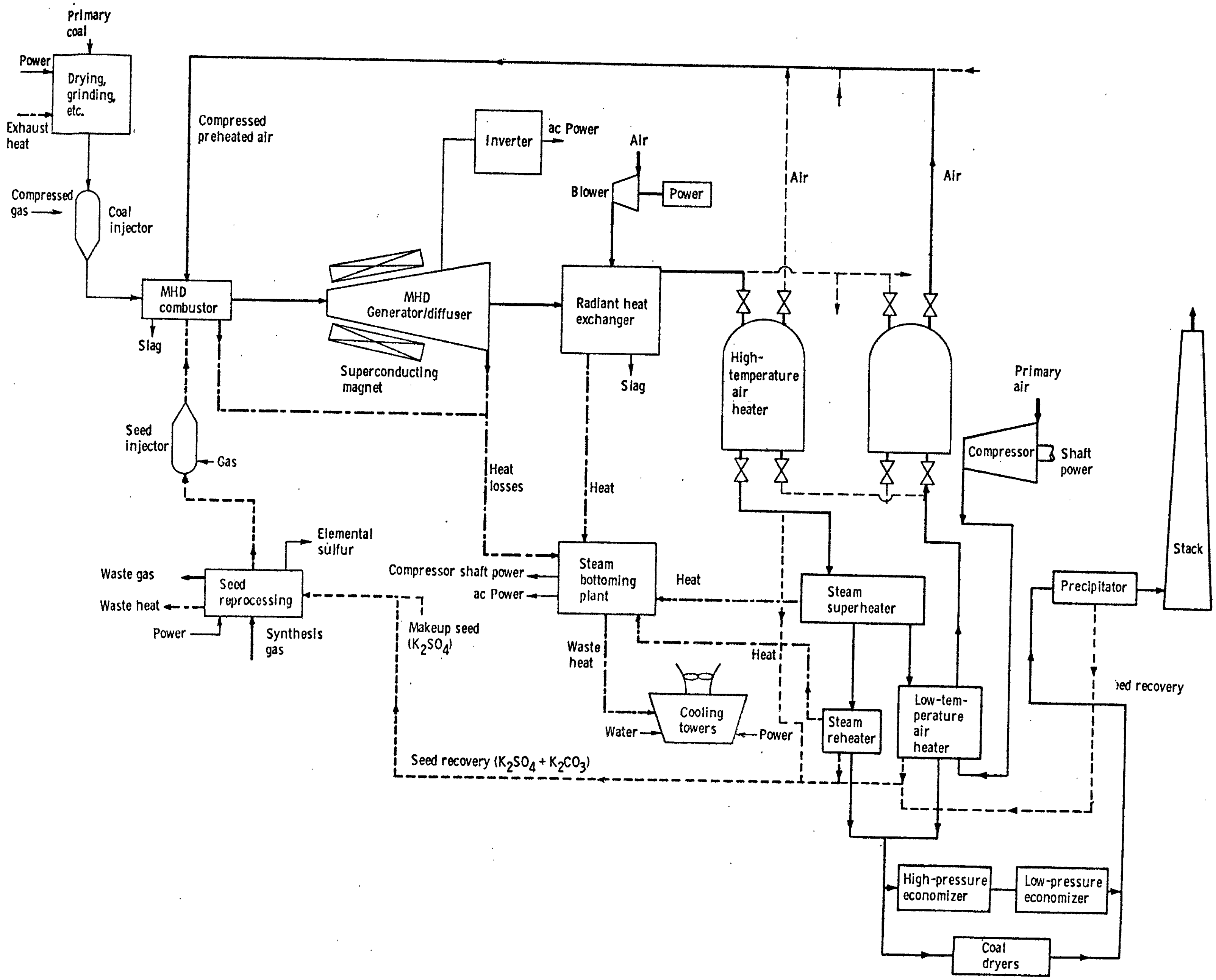


Figure 1-1 Basic Schematic of Open Cycle MHD (NASA, 1977)

combustion products are made electrically conductive, about 10 to 12 mhos/m, by injection of a small fraction, about 1%, of seed material such as potassium carbonate. The conductive gas is then expanded at high velocity, about 1000 m/s, through a high magnetic field, about 5 to 8 Tesla, thus producing direct current at electrodes perpendicular to the flow field and magnetic field. The still hot gases, about 2256 K (3600°F), are then sent to a bottoming steam turbine. Before or after this turbine the gases usually will preheat the coal and/or air. In an open-cycle system the steam turbine exhaust usually goes to a water heater and then eventually up the stack. Some of the possible design variations that have been studied are outlined in Chapter 3.

Even considering nearly identical conditions, about 1617 K (2450°F) direct air preheat and a 24.1 MN/m^2/811K/811K (3500° psi/1000°F/1000°F) supercritical single reheat steam bottoming cycle, performance estimates are widely scattered, (see Table 1-1 and several others in this report) sometimes almost a factor of two variation on certain estimates ($642 versus $1102 investment cost per kWe). This large uncertainty in projected performance is the first major issue discussed in each of the following chapters.

The second issue elaborated is that of barriers that must be hurdled before commercialization of OCMHD. These technological problems are indirectly related to the issues of this paper. Thus they are only roughly summarized in Table 1-2, are listed in order of severity in Chapter 5, and are briefly mentioned in the sections of this report where they bear upon aspects of performance.

TABLE 1-1

AVAILABILITY AND COST COMPARISONS OF PROJECTED FULL-SIZE OPEN CYCLE COAL MHD DESIGNS

Capital Cost	
(Pomeroy, *et al.*, 1978)	\$805/kWe
(NASA, 1977)	\$1103/kWe (Westinghouse)
(NASA, 1977)	\$642/kWe (GE Co.)
(Seikel, Harris, 1976)	\$718/kWe
(General Electric, 1975)	\$910-\$1440/kWe
(Pepper, Yu, 1975)	\$340-\$440/kWe
(Rosa, *et al.*, 1970)	\$35-\$55/kWe (peaking)
(Hals, Jackson, 1969)	\$90-\$120/kWe
Cost of Electricity	
(Levi, 1978)	32 mills/kWh
(Pomeroy, *et al.*, 1978)	34-43 mills/kWh (baseload)
(Pomeroy, *et al.*, 1978)	130 mills/kWh (peaking)
(NASA, 1977)	27.1-43.9 mills/kWh
(Seikel, Harris, 1976)	42-49 mills/kWh (GE Co.)
(Seikel, Harris, 1976)	32-50 mills/kWh (WE Co.)
(Seikel, Harris, 1976)	31.8 mills/kWh (GE Co.)
(General Electric, 1975)	41.5-55.5 mills/kWh
(NASA, 1975)	41-48 mills/kWh (GE Co.)
(NASA, 1975)	27-35 mills/kWh (Westinghouse)
(NASA, 1975)	34-42 mills/kWh (low Btu, Westinghouse)
(Hals, Jackson, 1969)	3.34-4.26 mills/kWh
Construction Time	
(Pomeroy, *et al.*, 1978)	5-6.5 years
(Seikel, Harris, 1976)	6.5 years
Date of Commercialization	
(Pomeroy, *et al.*, 1978)	2003
(Penny, Bourgeois, Cain, 1977)	2000
(Seikel, Harris, 1976)	1996-1999
(Pepper, Yu, 1975)	1988

TABLE 1-2

SUMMARY OF MHD PROBLEM AREAS

Problems	Potential Solutions
Particulate Removal	
- submicron sizes	. facility testing
- high quality plasma with low ash	
Seed Recovery	
- efficiencies of recovery from solids	. seed collection . combustion modeling
- suitability for reuse	
- economic problems and energy costs	. thermal regeneration
- water contamination	
- ash composition peculiarities	
- atmospheric releases	
Nitrogen Oxide Control	
- may not meet standards	. minimize during combustion . reduce oxygen in high-temperature areas and inject air in low-temperature regions . post-combustion control . two-stage combustion . use different pressures . use different air/fuel ratios
Sulfur Oxide	
- potassium sulfate emissions	. facility testing
Properties of Coal	
- some fundamentals are important but not known or are widely varying	. kinetic conditions testing . devolatilization kinetics studies
- conductivity, ignition, devolatilization, combustion, gasification, slag vaporization, slag agglomeration	. ash vaporization studies
Moisture	
- in low-grade coals	. coal drying

TABLE 1-2 (continued)

SUMMARY OF MHD PROBLEM AREAS

Durable Materials, especially insulators, electrodes and heat exchangers	
- extremely high temperatures	. develop high grade materials
- corrosive exhaust gases	. develop predictive techniques for optimizing conditions and materials
- short life of nozzles, valves, boiler tubes and duct materials	. study high temperature and corrosion effects
- ash and seed corrosion of ceramic and metal parts	. study of thermal cycling and long duty cycle effects
Generator, Duct and Diffuser Life	
- effects of combustion products and slag on walls	. studies of properties of combustion products
- multiplicity of load circuits	. long duration tests
- axial breakdown limitation	. disk generators
Other Component Problems	
- demonstrate air preheaters	. facility testing
- slag coating of heat exchangers	
- high temperature heat exchangers	
- superconducting magnetic system cost, size, and temperature problems	
Combustors	
- 5000°F	. facility testing
- reasonably free of slag vapor 10-20% original ash	. more direct measurements and analytic modeling
- sufficient rate and uniform coal feed	
- good mixing with low pressure drop	
- high slag rejection and topping	
Large Facility Sizes	
- effects of components on each other	. development of smaller modules
- 2000 MW minimums	. testing of component interfaces
- reliability problems associated with large blocks of power	
- scale-up problems	
Turndown and Load Follow	. use several smaller modules

TABLE 1-2 (continued)

SUMMARY OF MHD PROBLEM AREAS

Demonstrate Enthalpy Extraction and Isentropic Efficiency	. short duration experiments
Absolute and Convective Instabilities	. large facility testing
Stable Electrical Loading	. large facility characteristics . analytic stability studies
Accurate Performance Estimates	
- efficiency and coal consumption	. optimum design specification
- capital cost and cost of electricity	. facility testing
- availability	. forecast of R&D funding levels
- adaptability to base load	
- likelihood and expected year of commercialization	

It is easy to be optimistic about the future of OCMHD, one just has to review the system's simplicity, the fallback positions, the time and funding available, and the progress to date (compared to the competing technologies, particularly the operating experimental facilities). However, it is also easy to be pessimistic, there are considerable technical problems associated with virtually <u>every</u> major power plant design component. Efficiencies and emissions will be significantly affected by the trade-offs and design changes resulting from future solutions for these technical problems, and this is a major reason for the significant uncertainties in the values reported in the following chapters.

2. MHD Programs in Progress

Research and development programs in MHD cycles have progressed erratically for more than a century (Levi, 1978), initially being linked to the work of Michael Faraday in 1831. Translation of the MHD concept into commercial application has been motivated recently by the need for efficient, clean methods of converting coal energy into electricity. Modern efforts began at Westinghouse starting in 1938 and were continued into the 1950's at Cornell University. Feasibility experiments were conducted in the 1960's first at Westinghouse, GE, and Avco and later at University of Tennessee and Stanford University.

Internationally, the Soviet Union has advanced, first in closed-cycle, later in open-cycle, facilities fueled by natural gas. The Japanese have been concentrating on use of heavy oils as fuels, primarily to reduce amounts of petroleum to be imported. In addition to the U.S. and U.S.S.R., Poland and India because of their significant fossil fuel resources have continued to conduct MHD research. The United Kingdom, France, and West Germany have essentially stopped their MHD programs although they have joined an international cooperative with the other principal research countries and some countries with relatively new interests: Australia, Austria, Belgium, Canada, Czechoslavakia, Hungary, Italy, Netherlands, Rumania, Sweden and Switzerland.

A summary of the more recent history of MHD development is shown in Figure 2-1. Excellent further historical discussions are contained in (Kantrowitz, 1977), (Way, 1971), and (Tager, Henry, 1976).

It would take a considerable effort to describe all the current and future plans for MHD in the U.S. Instead Table 2-1 lists the

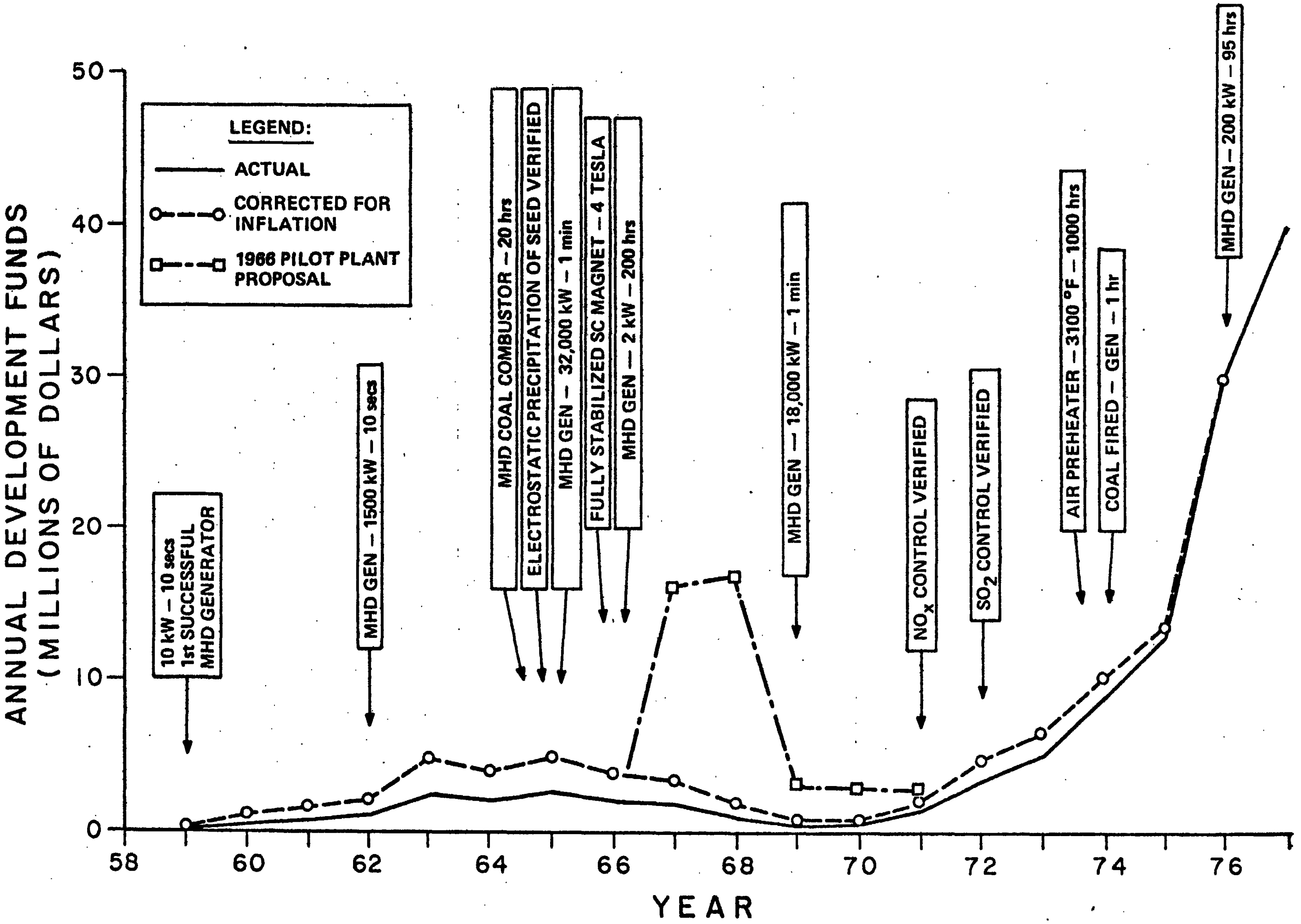


Figure 2-1 General Description of the Evolution of Recent MHD Developments (Kantrowitz,1977)

TABLE 2-1

RECENT AND ONGOING MHD RESEARCH

Argonne National Lab	- generator phenomena - combustion studies and modeling - project planning and definition - systems studies - magnets
Arnold Engineering Development Center	- component and materials experiments - high enthalpy extraction - magnet testing and building - test facility
Avco-Everett Research Lab	- component and materials experiments - seed recovery - generator design - economic and environmental assessments - auxiliary component development - peaking plants - pollution control by gas cleaning - NO_x control experiments
Battelle Pacific Northwest Lab	- electrode development
Bechtel	- design evaluation - labor and materials studies - cooling water evaluations
British Coal Utilization Research Association	- combustion modeling
Brookhaven National Labs	- comparative assessments
Burns and Roe	- design
California Institute of Technology	- performance studies
Central Electricity Generating Board, Great Britian	- slag buildup on heat exchangers
Eindhoven, Holland	- closed-cycle facility
Electrotechnical Lab of Japan	- oil-fired MHD -Mark V, VI

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

EPRI	- market penetration - R&D funding
Exxon Research & Engineering Co.	- evaluation of designs
Flinders University of South Australia	- comparative assessments
Fluidyne Corporation	- air preheaters - facility design and evaluation
Foster-Wheeler	- design evaluation - evaluation of auxiliaries
Gilbert Associates Inc.	- design studies
General Electric Co.	- MHD market penetration - design and evaluation of facilities - preheater development
Hercules Powder Corp	- support studies
Hittman Associates Inc.	- comparative assessments
Institute of Gas Technology	- comparative assessments
International Atomic Energy Agency, Vienna	- MHD commercialization potential
Krzhizhnavosky Power Institute	- prototype MHD plant
Laboratory of Direct Conversion of Italy	- closed-cycle facility
Arthur D. Little, Inc.	- comparative assessment
Lockheed-Huntsville Research & Engineering	- environmental assessments
Max Planck Institute of Plasma Physics of Germany	- combustion modeling - closed-cycle facility
Maxwell Labs	- support studies

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

MEPPSCO	- generator design - magnet design
Mississippi State University	- corrosion studies
M.I.T.	- magnet design - emission modeling and control - combustion modeling - modular design tool - generator performance - disc generator experiments - materials problems - seed recovery experiments
Montana Energy and MHD R&D Institute	- research facilities
Montana State University	- air preheaters
National Bureau of Standards	- materials problems - electrodes - slag characteristics
National Science Foundation	- basic research funding - comparative study funding
North Carolina State University	- electrode materials
Nuclear Energy Agency (OECD)	- international cooperation
Oak Ridge National Labs	- comparative assessment
Parsons	- design studies
Rand Corporation	- closed-cycle examination - overview studies
Reynolds Metals	- gaseous electrode development
Rockwell International	- design studies - space applications
Stanford Research Institute	- comparative assessments

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

Stanford University	- test facility - generator phenomena - magnet design and effects - NO_x modeling and control - cooling requirements
STD Research Corporation	- design and systems studies - coal drying - retrofit to older plants
Systems Research Labs	- support studies
Teknekron, Inc.	- comparative assessments
Tokyo Institute of Technology	- NO_x modeling
TRW Energy Systems	- evaluation of designs - prototype combustors
University of Illinois at Chicago	- combustion modeling
University of Mississippi	- performance studies
University of Montana	- support studies
University of Pittsburgh	- seed regeneration - slag effects - downstream components
University of Tennessee	- seed recovery - experimental facility
University of Tokyo	- systems studies
U.S. Bureau of Mines, Morgantown	- seed regeneration - seeded coal combustion properties
U.S. DOE	- R&D funding - experimental programs - commercial demonstration
U.S. DOE Pittsburgh Energy Research Center	- seeding and seed recovery and regeneration - environmental emissions - combustion experiments - coal drying

TABLE 2-1 (continued)

RECENT AND ONGOING MHD RESEARCH

U.S. EPA	- environmental assessments
U.S. NASA	- comparative study funding - design and evaluation
U.S. Senate, Office of Technology Assessment	- overview of government role in MHD - comparison with other energy cycles
U.S.S.R.	- sponsoring MHD research and development
USSR Atomic Energy Institute	- systems studies
USSR Institute for High Tempertures	- MHD research - facilities
Westinghouse Research Labs	- design and evaluation of facilities - systems studies - experimental facility
Whittaker Corporation	- unconventional designs - systems studies
Wright-Patterson AFB	- systems studies

organizations involved and the general research and development areas to which they are contributing. In addition to EPRI sponsorship, a recent tally of <u>government</u> funding of MHD studies (Penny, Bourgeois, Cain, 1977) showed DOE with 81%, DOD 13%, and NSF 6%, of the $8.15 million being spent on 37 projects. Current facilities are listed in Table 2-2 and some of the future U.S. facilities are listed in Table 2-3. The approximate timing of these future facilities is shown in the ECAS study in Figure 2-2 and in an accelerated forecasted from DOE and EPRI in Figure 2-3. Two ideas about the logical process of the research and development necessary to support this facility timetable are shown in Figures 2-4 and 2-5.

Table 2-2 Main Parameters of Some Open Cycle MHD Genrators Presently in Use (Argyropolis, 1976, pp 64-66)

FACILITY	OPERATION TIME	THERMAL POWER MW	ELEC. POWER MW	MASS FLOW (Kg/s)	SPECIFIC ELEC. POWER (MJ/kg)	EHTHALPY EXTRACTION η_{ent}	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	ELEC. POWER DENSITY (MW/m^3)	T_0 (°K)	P_0 (atm)	M inlet	ELECTRODES	B (T)	SEED
USSR IED Kiev	3 h	8.35	0.015	2	0.0075	0.0016	natural gas	O_2/N_2=2/3	-	-	2850	-	0.7	Sic 6 pairs	1.5	KOH in alcohol
USSR (ENIN-II	10 min	140-160	0.2-1.5	12-14	0.014-0.1	0.0013-0.01	-	O_2	20x20 20x50 L=300	1-7.5	3200	10-12	2	brass 116 pairs	1.5	K_2CO_3 in water
USSR IHT (U-02)	200 h	5	0.075	1	0.075	0.015	-	O_2/N_2=1 T_{ox}=1100°C	20x6.4 40x6.4 L=300	1.32	2900	1.2	0.8	ZrO_2, Sic 52 pairs	1.7	Cs_2CO_3 in water
USSR IHT (U-25)	1000 h	300	20	50	0.4	0.066	-	O_2/N_2=2/3 T_{ox}=1200°C	38x77 38x138 L=500	12	2900	3.2	0.8	copper; ceramics	2	K_2CO_3 in water 65%
POLAND Tech.Univ. Poznan	long term	4	-	0.8	-	-	liquid hydrocarbon	O_2 or preheated air	3x10x50	-	3100	1	1	various materials	3.5	KOH in alcohol
POLAND IBJ	1 h	30	-	3	-	-		O_2	-	-	-	-	-	-	-	KOH in alcohol
JAPAN ETL (Mark-II) hot wall	10 min	10	0.251	2.5	0.10	0.025	gas, oil	O_2/N_2=1 T_{ox} = 1320°C	9x15 9x25 L=120	11.6	2780	2.8	>1	graphite 30 pairs	3.3	K_2SO_4 power 1% K in fuel
JAPAN ETL (Mark-II semi-hot wall	-	-	0.019	-	0.0076	0.0019	-	-	-	0.88	-	-	-	ZrB_2(80%)	-	-

Table 2-2 Main Parameters (cont.)

FACILITY	OPERATION TIME	THERMAL POWER	ELEC. POWER	MASS FLOW (Kg/s)	SPECIFIC ELEC. POWER (MJ/kg)	ENTHALPY EXTRACTION η_{ent}	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	ELEC. POWER DENSITY (MW/m^3)	T_0 (°K)	P_0 (atm)	M inlet	ELECTRODES	B (T)	SEED
JAPAN ETL (Mark III)	100 h	3.6	-	0.5	-	-	diesel oil	air + O_2	3x12x90	-	-	-	0.8	12 pairs	1.9	KOH
JAPAN ETL (Mark VI)	100 h	1	-	0.66	-	-	light oil	enriched air, T_{ox}=1400°C	3x12x90	-	-	-	1.9	-	-	ag KOH
JAPAN ETL (Mark V)	1 h	25	0.5	1.5-3.5			light oil	oxygen	F_1=140 cm^2 F_2=250 cm^2 L =192 cm				~1.	anode: stainless steel cathode: Cu-W 50 pairs	3.9	aq KOH
USA AVCO (Mark VIC)	~~100~~ 250 h	20	0.5	2.8	0.17	0.05	oil or kerosene, slag	O_2/N_2=2	F_1=400 cm^2 F_1=800 cm^2 L=200 cm	12.5	3200	8	2	Inonel	3.2	K_2CO_2 [STET].
USA AVCO Mark V	**1 min**	**-**	**50**													
USA WPAFB (KIVA-I)	1 min	6	0.2	0.6	0.5	0.05	toluene, JP4	O_2	2.6x10 7.2x11 L=85	80	3300	10	2	50 pairs	2.7	Cs_2CO_3
USA Stanford U. (M-2)	3 h	2-3	-	-	-	-	CH_3OH	N_2/O_2=1/2	3x10x61	-	2900	1.5	8	stainless steel 13 pairs	2.5	1% K
USA Stanford U. (M-8)	3 h	8	0.1	0.5	0.125	-	kerosene	O_2	3.9x10 6.3x10 L=70	20	3300	5	1.7	various materials 22 pairs	2.5	KOH in alcohol
USA AEDC (HPDE)	~~15~~ 30 sec.	320-460	45-65	50-65	-	.16	toluene, later with slag	N_2/O_2= 1.25	26x51 102x128 L=920	-	3100	5.4	0.8	copper w/ granite caps 173 pairs	6	KOH in CH_3OH

Table 2-2 Main Parameters (cont.)

FACILITY	OPERATION TIME	THERMAL POWER	ELEC. POWER	MASS FLOW (Kg/s)	SPECIFIC ELEC. POWER (MJ/kg)	ENTHALPY EXTRACTION η_{ent}	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	ELEC. POWER DENSITY (MW/m^3)	T_0 (°K)	P_0 (atm)	M inlet	ELECTRODES	B (T)	SEED
USA AEDC LORHO	**1 min**	-	20													
USA Westinghouse	100 h	4-5	.1	1.5	-	-	toluene, char, later with slag	air $T_{ox} \approx 900^\circ C$	8x11x100	-	2600	4	0.9	various mat'ls. 50 pairs	3	K_2CO_3
USA (UTSI-I)	8 s	8.35	0.07	0.8	0.09	0.0084	kerosene & powerful additives	O_2	9.5x20.5x 120	2.8	3200	3-4.5	2	copper 60 pairs	2.2	KOH and KNO_2 in alcohol Cs_2CO_3
USA (UTSI-II)	8 s	8.35	0.04	0.8	0.04	0.0047	coal	O_2	5.8x15x90	-	3200	3-5	2	copper 40 pairs	2.2	K
USA (UTSI-III)	long term	8.35	0.09	0.8	-	-	coal	O_2	5.8x30x90	-	3000	4.5	1.4	copper	2.2	K
USA Reynolds Metals	long term	-	-	-	-	-	diesel fuel	$N_2/O_2=1$	2.6x5.1x26	-	2200	-	<1	-	2	K
USA Reynolds Metals	long term	-	-	4.4	-	-	diesel fuel	$N_2/O_2=1$	21x36x154	-	2200	-	<1	-	4.2	K
USA PERC	-	5.0														

Table 2-3 Main Parameters of Some Planned Open Cycle MHD Generators (Argyropolis, 1976, p. 67)

FACILITY	EXPECTED DATE OF OPERATION	THERMAL POWER	MHD ELEC. POWER	STEAM ELEC. POWER	MASS FLOW (Kg/s)	FUEL	OXIDIZER	GENERATOR VOLUME (cm^3)	T_0 (°K)	P_0 (atm)	M inlet	B (T)	SEED
USA (CFFF)	1978	20	-	-	3.6	coal							
USA (CDIF) MEMRDI	1978	50	9	9	10	coal	air T_{ox}=2125-2250°C	-	-	8-10	.9	3.5	K_2CO_3
USA (ETF) MEMRDI	1981	250	70	70	46	coal	air T_{ox}=2125-2250°C	-	-	8-10	.9	3.5	K_2CO_3
USA (CDP)	1980's	1000	-	500	-	coal							

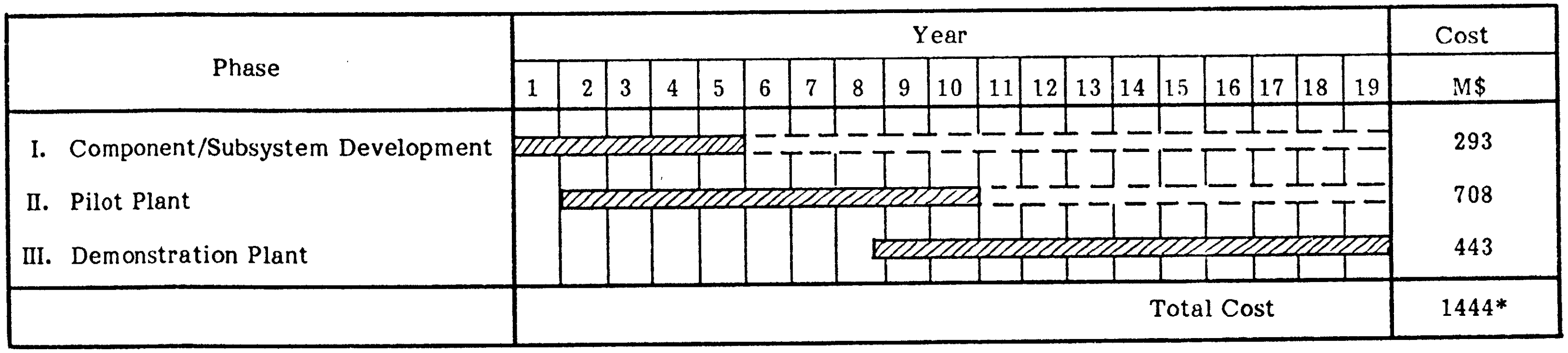


Figure 2-2 Schedule and Costs For Development Plan - Open Cycle MHD (General Electric, 1976)

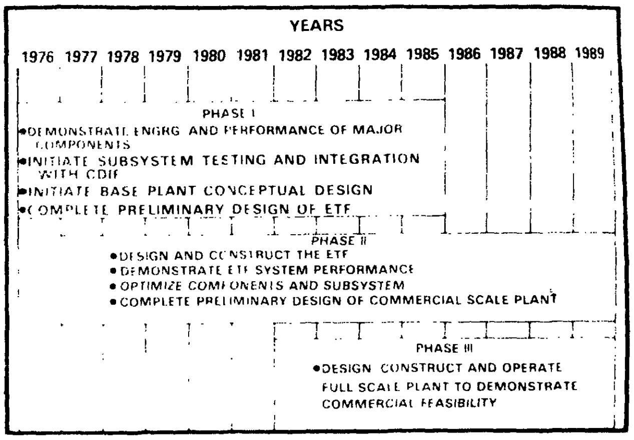


Figure 2-3 Major MHD Program Phases (Jackson, et al., 1976)

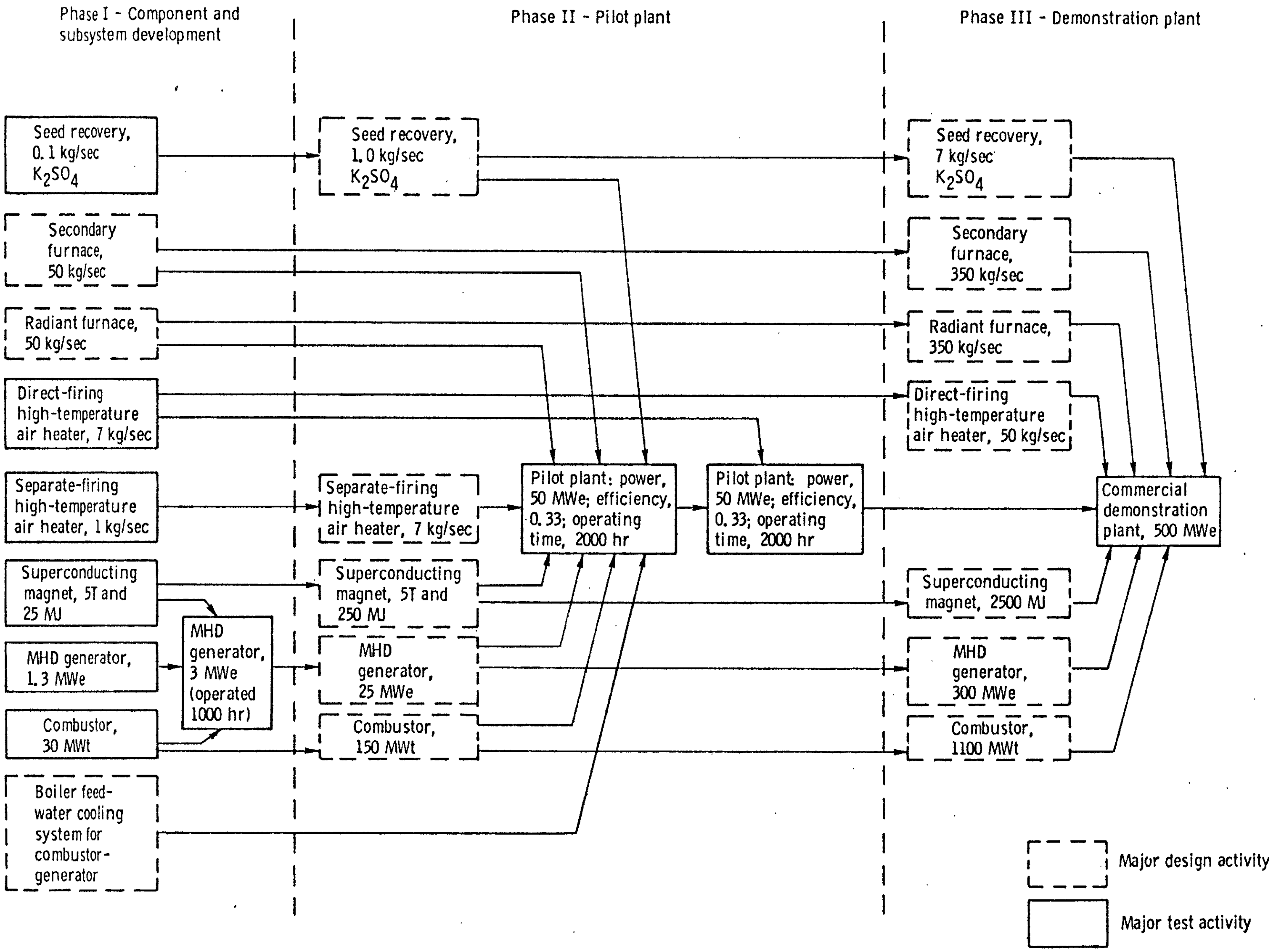


Figure 2-4 Avco Logic Flow Diagram for Coal/Open-Cycle MHD/Steam System Development Plan (NASA, 1977)

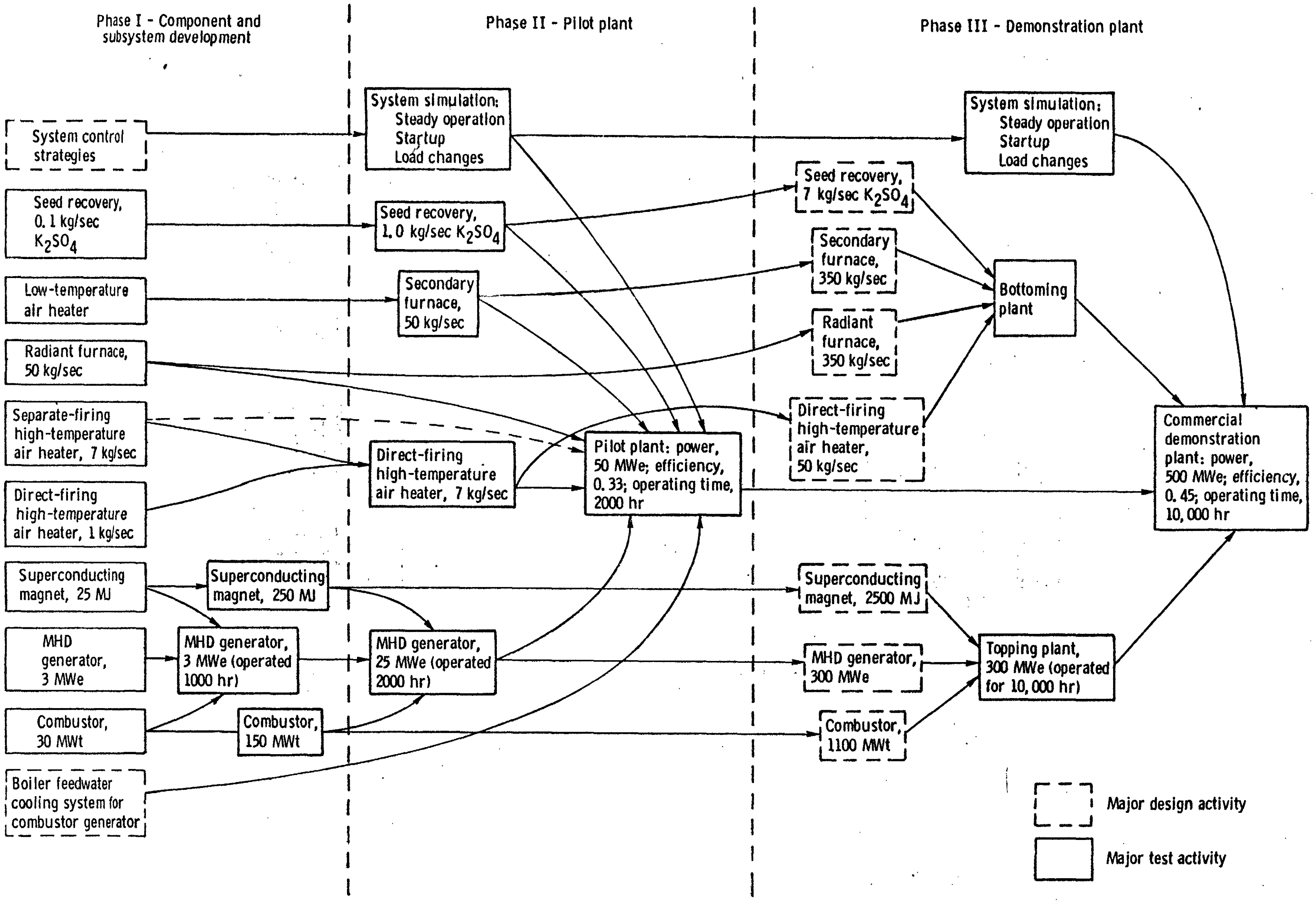


Figure 2-5 General Electric's Revised Logic Flow Diagram for Coal/Open-Cycle MHD/Steam System Development Plan (NASA, 1977)

3. Plant Design Configurations

In addition to choices between open-cycle and closed-cycle there are a tremendous number of possible MHD design variations. In Phase I of the ECAS study the open-cycle variations included:

(1) coal, solvent refined coal, or coal gasifier products as fuels;
(2) air or oxygen-enriched air as oxidant;
(3) direct air preheat using MHD exhaust, or indirect (separate) preheating using coal volatiles or a coal gasifier product, or combinations of direct and indirect preheats; and
(4) steam bottoming cycles or gas-turbine bottoming cycles.

An excellent display of the MHD configuration options is shown in Figure 3-1 from (Jackson, et al., 1976). This diagram shows that for coal-fired OCMHD the principal distinguishing feature is the high-temperature preheat or regeneration procedure. The regeneration procedures could involve anything from using the MHD exhaust heat to produce a clean fuel for indirect air preheaters, to using direct air preheaters with the MHD exhaust heat utilized to generate heated, clean fuel for the MHD combustor. The simplicity of the MHD process and the relatively early stage of its development are the reasons for the tremendous variety of designs.

Receiving the most attention lately (due to low expected cost of electricity) is the OCMHD design suggested in Phase II of the ECAS study (General Electric, 1976), called NASA Case 1. This configuration uses direct air preheating at 1316 K to 1371 K (2400°F to 2500°F), direct coal-fired combustor, and a 24.1 MN/m^2/811 K/811 K (3500

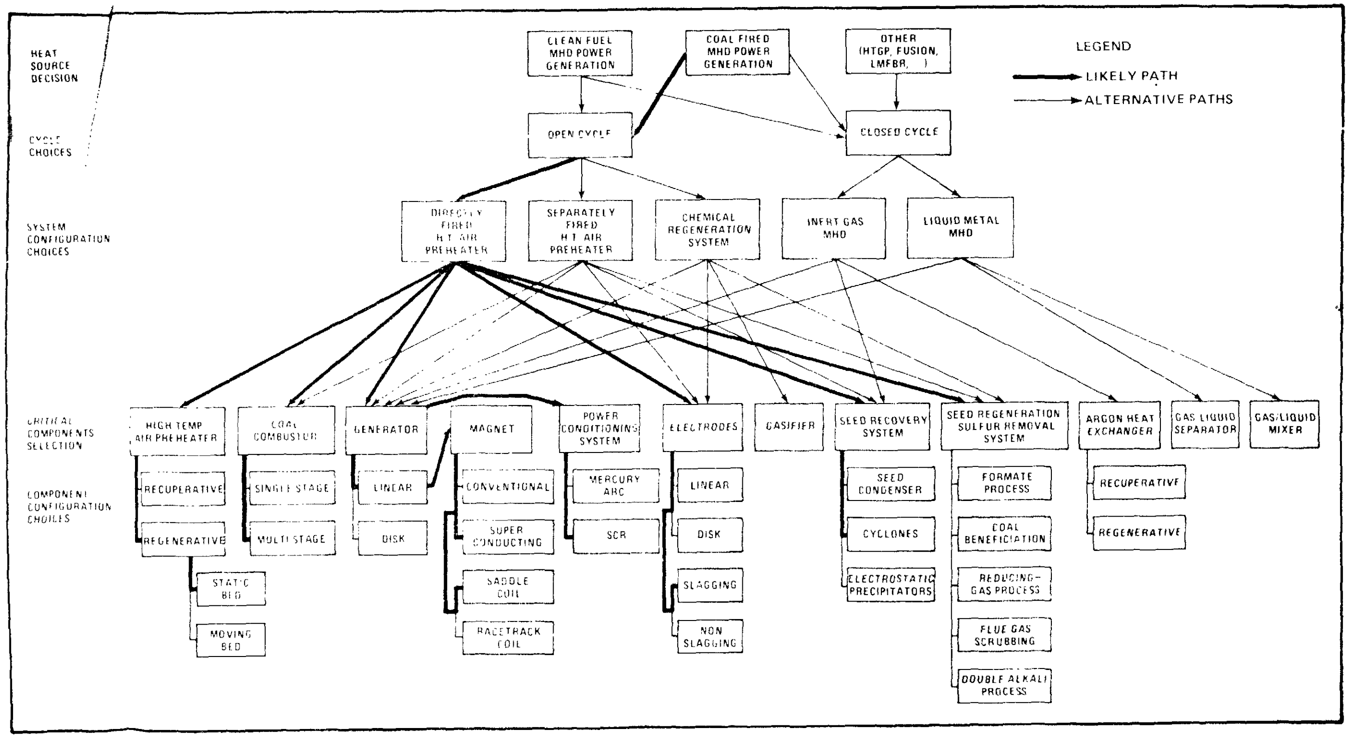


Figure 3-1 MHD System Decision Tree (Jackson,et al.,1976)

psi/1000°F/1000°F) steam bottoming cycle. In this system the coal processor feeds dried crushed coal to a single-stage cyclone combustor. The preheated air is mixed with the coal at a 95% stiochiometric air fuel ratio and is fired to 2700 K (4400°F). The cyclone combustor is assumed to remove 80% of the coal ash. Potassium carbonate is the seeding material. The MHD generator conditions (Beecher, et al., 1976) include a .62MPa (6 atm) pressure, .75 Mach flow rate, and 6 T magnetic field (in the equivalent Westinghouse ECAS Base Case). The MHD exhaust is at 1650 K (2511°F) and passes to the steam generator. Seed-ash is collected on the superheater surface and in the stack gas cleanup system. The seed is recycled through a Claus plant that converts part of the potassium sulfate to potassium carbonate before reuse. These are the most important features of the frontrunning configuration, additional important parameters are listed in Section 3.1.

3.1 Operating and Design Parameters

Even given the exact design configuration there is still a significant variation in system performance that is due to variations in operating and design parameters. For example, the air preheat temperature can play a major role in system efficiency and cost, and values of 1089 K, 1366 K, 1589 K, 1644 K, 1922 K, and 2200 K (1500°F. 2000°F, 2400°F, 2500°F, 3000°F, and 3500°F) have been explicitly investigated. This section begins with a listing of the important operating and design parameters, Table 3.1-1. This list is separated into the parameters related to the various system components, and is further segregated into the independent parameters and the

TABLE 3.1-1

MAJOR PARAMETERS DETERMINING OCMHD PERFORMANCE

MHD Generator

Independent Parameters
- generator type and channel connection; linear Faraday, Hall, diagonal wall, and cylindrical configurations
- generator size and geometry
- materials
- temperatures and pressures
- working fluid
- magnetic flux density
- seed type and feed rate
- flow rate

Dependent Parameters
- enthalpy extraction ratio
- plasma flow rate
- electrical conductivity of fluid
- electron affinities of OH, CO_2 and AlO_2
- electron-atom collision cross sections
- emissions
- power output
- Hall parameter nonuniformities
- pressure drop
- electrical loading parameter
- heat leak fraction
- enthalpy

Fuel and Combustor

Independent Parameters
- combustor type, design and stages
- combustor pressure and temperature-time history
- coal feed rate and configuration
- coal type and size, or solvent refined or gasified coal characteristics
- oxidizer type and feed rate
- air feed rate and temperature
- coal properties; ash, volatiles, moisture and so on
- drying of coal

Dependent Parameters
- air/fuel ratio
- percent slag rejection
- percent ash in flue gas
- coal moisture
- enthalpy
- pressure drop
- radioactive heat loss
- overall efficiency of combustor
- combustor residence time
- carbon burnout
- uniformity of product distribution

TABLE 3.1-1 (continued)

MAJOR PARAMETERS DETERMINING OCMHD PERFORMANCE

Nozzle, Diffuser, Inverters, Electrodes, Insulators, Compressor

Independent Parameters
- size and geometry of channel, etc.
- materials
- nozzle area, contour
- pressure and temperatures

Dependent Parameters
- lifetimes
- pressure and temperature drops
- thermal losses
- electrical losses
- diffuser exit temperature
- diffuser recovery factor
- duct wall temperature
- heat transfer coefficients
- nozzle heat loss
- channel loft
- efficiencies
- enthalpy
- flow rates

Magnets

Independent Parameters
- magnet size and strength
- support
- magnet shape and orientation

Dependent Parameters
- bending stress
- magnetic flux density

Air Preheater

Independent Parameters
- design and type
- temperatures at stages
- pressure

Dependent Parameters
- lifetime
- air preheater losses
- enthalpy
- pressure drop

TABLE 3.1-1 (continued)

MAJOR PARAMETERS DETERMINING OCMHD PERFORMANCE

Seed and Slag Recovery

Independent Parameters
- combustor designs
- reactor, absorption tower, heat exchanger types and sizes
- coal propertes

Dependent Parameters
- recovery percent
- seed form
- cost and energy losses

Seed Regenerator

Independent Parameters
- reducing process
- design and type

Dependent Parameters
- efficiency and cost
- seed form

Steam Cycle

Independent Parameters
- type and design
- pressures and temperatures
- heat rejection type

Dependent Parameters
- boiler lifetimes
- heat rejection
- heat transfer coefficients
- power turbine heat rate
- compressor turbine heat rate
- power output

dependent parameters, that is those values that can only be controlled through changes in independent parameters. It should be noted that dependent parameters for some components are independent choices for others.

The values for many of the parameters that are expected to be selected for the first commercial design are shown in Table 3.1-2. The Base Case ECAS OCMHD cycle parameters for (Phase I General Electric) are shown in Table 3.1-3. A comparison of major features of the Base Case with the solvent refined coal case is shown in Table 3.1-4; a comparison of magnet designs in Table 3.1-5 and 3.1-6; and a comparison of preheaters in Tables 3.1-7 and 3.1-8.

Phase I ECAS Base Cases for General Electric and Westinghouse are compared to the General Electric Phase III Base Case in Table 3.1-9. Additional Phase II OCMHD Base Case parameters are shown in Table 3.1-10 and performances in 3.1-11. Finally some interesting miscellaneous performance factors are collected in Table 3.1-12.

3.2 Mass Balances of Specific Designs

First it should be reiterated that no large coal-fired OCMHD's are operational. Mass balance computations to date have therefore been calculated analytically not empirically. Computer programs for these computations exist at Westinghouse, General Electric, and elsewhere, and are also being developed at MIT. Thus there is no reason to duplicate these efforts for this study, instead some already published mass balances of important specific OCMHD designs are presented here.

Table 3.1-2 Input Parameters Projected for First Commercial Sized Facility (Jackson, et al., 1976)

POWER INPUT - GROSS	2000 MWth
COMBUSTION	
Coal	Montana, Rosebud Seam
Combustor	Direct, 2-stage, 90% slag-rejection
Seed rate	K - 1% of total combustion products
PREHEATER	
Type	Direct fired, regenerative
Oxidizer temp. (K)	1644
MHD GENERATOR	
Type	Diagonal connected, 15 meter nominal
Load factor	0.7 (variable)
Magnet	Maximum field 6 tesla, superconducting
Flow	High subsonic
DIFFUSER	
Exit pressure (psia)	16.25
Recovery factor	0.8
STEAM BOTTOMING CYCLE	
Steam conditions	3500 psia (1000°F/1000°F)
Heat rejection	wet cooling tower
ENVIRONMENTAL EFFECTS	
SO_2	< 1.2 lb/10^6 Btu
NO_x	< 0.7 lb/10^6 Btu
Particulates	< 0.1 lb/10^6 Btu

Table 3.1-3 Major System Parameters for Open Cycle MHD General Electric Base Case (Harris, Shah, 1976)

PARAMETER	VALUE OR DESCRIPTION
FUEL COAL	
TYPE	ILL #6, 10788 Btu/LB HHV
SIZE, PULVERIZED	70% THROUGH 200 MESH
MOISTURE CONTENT, DRIED	2%
OXIDIZER	AIR
FURNACE, GASIFIER OR FUEL PROCESSING	
COMBUSTOR TYPE	SPECIAL
COMBUSTION PRESSURE (ATM)	9
COMBUSTION TEMPERATURE (°F)	4634
AIR PREHEAT TEMPERATURE	2500
F/A RATIO RELATIVE TO STOICHIOMETRIC F/A	1.07
SLAG REJECTION	85%
PRIME CYCLE MHD	
TYPE	DIAGONAL
WORKING FLUID	COMBUSTION GASES
AVERAGE MAGNETIC FLUX DENSITY (TESLA)	5
COMPRESSOR PRESSURE RATIO	10.75
DIFFUSER OUTLET PRESSURE (ATM)	1.14
ELECTRIC LOAD PARAMETER	0.80
POTASSIUM SEEDING	1%
HEAT EXCHANGER(S)	
HIGH TEMPERATURE AIR HEATER	
TYPE	REFRACTORY CERAMIC STORAGE
GAS $\Delta P/P$	0.07
AIR $\Delta P/P$	0.02
RADIANT FURNACE	
GAS $\Delta P/P$	0.01
WATER ΔP (PSI)	570
SECONDARY FURNACE	
GAS $\Delta P/P$	0.03
STEAM ΔP (PSI)	854
AIR ΔP (PSI)	21
ECONOMIZERS	
GAS $\Delta P/P$	0.02
WATER ΔP (PSI)	21
STEAM BOTTOMING CYCLE	
TYPE	psi 3500[illegible]/1000F/1000F
HEAT RATE FOR POWER TURBINE (BTU/kW-HR)	8160 ($\eta = 42$)
HEAT RATE FOR COMPRESSOR TURBINE (BTU/kW-HR)	8270 ($\eta = 41$)
CONDENSING PRESSURE (IN. Hg)	2.3 (106°F)
HEAT REJECTION	
WET MECHANICAL DRAFT COOLING TOWERS	25 CELLS
STACK GAS TEMPERATURE	251°F

Table 3.1-4 Summary of Important Parameters for ECAS OCMHD Cases (General Electric,1976)

Base Case

CYCLE PARAMETER

Power Output (MWe)	1932
Combustion	
Coal	Solvent refined coal
Oxidizer	Air
Combustor slag rejection (percent)	0
Preheater	
Firing	Direct
Oxidizer temperature (°F)	3100
MHD Generator	
Type	Faraday
Inlet pressure (atm)	15
Average magnetic field (T)	6
Potassium seed (percent)	1.0
Electrical load parameter	0.8
Heat Exchangers	
Gas (Δp/p)	0.15
Air (Δp/p)	0.10
Steam Bottoming Cycle	
Turbine inlet temperature (°F)	1000/1000
Turbine inlet pressure (psi)	3500
Maximum feedwater temperature (°F)	232
Air Bottoming Cycle	
Turbine inlet temperature (°F)	--
Pressure ratio	--
Heat Rejection	Wet cooling tower

MAJOR COMPONENT CHARACTERISTICS

Major Component	Unit or Module			Units Required	Total Cost ($ x 10⁶)	$/kW Output
	Size (ft) (W x L (or D) x H)	Weight (lb) (x 10⁶)	Cost ($ x 10⁶)			
Combustor	5.7 dia x 11 long	0.022	2.2	1	2.20	1.14
Nozzle/generator/diffuser	Inlet area 22 ft² Exit area 4100 ft² } x 250 long	2.92	7.90	1	7.90	4.09
Magnet and dewar	44 dia x 91 long	9.0	43.00	1	43.00	22.26
Radiant furnace	80 x 58.5 x 100	0.76	2.44	1	2.44	1.26
Superheater/reheater	80 x 36.5 x 56.2	8.04	19.91	1	19.91	10.31
Economizer	80 x 28.8 x 6.1	1.50	1.13	1	1.13	0.58
High-temperature air heater	34 dia x 75 high	5.29	2.67	6	16.00	8.28
Low-temperature air heater	80 x 29.0 x 26.4	2.61	10.75	1	10.75	5.56
Seed recovery system	--	--	1.00	1	1.00	0.52
Steam turbine-generator set	30 x 174 x 25	4.30	12.90	1	12.90	6.68
Inverters	--	--	97.40	1	97.40	50.41

SRC Base Case

CYCLE PARAMETER

Power Output (MWe)	1895
Combustion	
Coal	Illinois No. 6
Oxidizer	Air
Combustor slag rejection (percent)	90
Preheater	
Firing	Direct
Oxidizer temperature (°F)	2500
MHD Generator	
Type	Faraday
Inlet pressure (atm)	9
Average magnetic field (T)	5
Potassium seed (percent)	1.0
Electrical load parameter	0.8
Heat Exchangers	
Gas (Δp/p)	0.15
Air (Δp/p)	0.10
Steam Bottoming Cycle	
Turbine inlet temperature (°F)	1000/1000
Turbine inlet pressure (psi)	3500
Maximum feedwater temperature (°F)	232
Air Bottoming Cycle	
Turbine inlet temperature (°F)	--
Pressure ratio	--
Heat Rejection	Wet cooling tower

MAJOR COMPONENT CHARACTERISTICS

Major Component	Unit or Module			Units Required	Total Cost ($ x 10⁶)	$/kW Output
	Size (ft) (W x L (or D) x H)	Weight (lb) (x 10⁶)	Cost ($ x 10⁶)			
Combustor	9 dia x 27 long	0.051	5.00	1	5.00	2.64
Nozzle/generator/diffuser	Inlet area 22 ft² Exit area 4100 ft² } 250 long	2.92	7.90	1	7.90	4.17
Magnet and dewar	44 dia x 100 long	8.20	44.00	1	44.00	23.22
Radiant furnace	80 x 60 x 100	0.98	3.15	1	3.15	1.66
Superheater/reheater	80 x 38.7 x 70	9.50	22.72	1	22.72	11.99
Economizer	80 x 32.7 x 7.9	2.20	1.64	1	1.64	0.87
High-temperature air heater	34 dia x 75 high	4.85	2.07	6	12.4	6.54
Low-temperature air heater	80 x 36.5 x 29.6	3.30	12.26	1	12.26	6.47
Seed recovery system	--	--	[illegible]	1	8.00	4.22
Steam turbine-generator set	30 x 174 x 25	4.5	20.08	1	20.08	10.55
Inverters	--	--	86.60	[illegible]	86.60	45.70

Table 3.1-5 Magnet Design Data for Base Case MHD Generator Case 1 - 2000MWE Plant Size (General Electric, 1976)

<u>Channel Specifications</u>

Inlet		1.4297 m × 1.4297 m
Exit		3.653 m × 3.653 m
Active Length		25m
Field:	Inlet	2.496 T
	Bo max.	5.992 T
	Exit	3.12 T
$VB^2 = \int_0^{25} AB^2\, dl$		11,600 m^3T^2

<u>Magnet Design Data</u>

Warm bore (circular)	Inlet	2.87 m
	Exit	6.50 m
Active length		25 m
Ampere turns		50.8×10^6
Ampere meters		34.2×10^8
Stored energy		15,200 megajoules
Current density, winding, average		2.0×10^7 A/m^2
Dewar O.D.		
Inlet end		9.3 m
Exit end		13.6 m
Dewar length, overall		31 m
Conductor weight		900,000 kg
Main structure weight (design stress 25,000 psi)		1,900,000 kg
Internal structure & miscellaneous weight		180,000 kg
Dewar weight		750,000 kg
	Total	3,730,000 kg

Table 3.1-6 Magnet Design Data for Base Case MHD Generator Case 24 - SRC As Fuel (General Electric, 1976)

Channel Specifications

Inlet		1.067 m sq.
Exit		3.499 m sq.
Active length		∿20 m
Field:	Inlet	3.21 T
	Peak	7.72 T
	Exit	2.40 T

Magnet Design Data

Warm bore (circular):	Inlet	2.60 m
	Exit	6.36 m
Active length		20 m
Field: Inlet		3.2
Peak		7.9
Exit		2.4
$VB^2 = \int_0^{20} AB^2\,dl$		13,200 m^3T^2
Ampere turns		76.4×10^6
Current density, average		2.0×10^7 A/m^2
Dewar O.D.		
Inlet end		9.8 m
Exit end		13.7 m
Dewar length		28 m
Conductor weight		1,036,000 kg
Main structure weight		2,100,000 kg
Intermediate structure & miscellaneous weight		200,000 kg
Dewar weight		750,000 kg
	Total	4,086,000 kg

Table 3.1-7 Air Preheater Design Data for GE OCMHD Cases 1, 2 and 3 (General Electric, 1976)

	Case 1	Case 2	Case 3
Plant Size MWe	2000	1200	600
Air preheat temp (°F)	2500	2500	2500
Air pressure (atm)	10.5	10.5	10.5
Number of Heaters	6 2 blowdown 3 reheat 1 spare	6 2 blowdown 3 reheat 1 spare	6 2 blowdown 3 reheat 1 spare
Heater bed dia. (ft)	30	24	17
Heater bed height (ft)	40	40	40
Heater total height (ft)	75	70	60
Heater bed weight (tons)	1400	900	450
Heater total weight (tons)	2400	1650	1000
Pressure drop			
Air side (atm)	0.01	0.01	0.01
Gas side (atm)	0.06	0.06	0.06

Table 3.1-8 Air **Preheater** Design Data for GE OCMHD **Case 24 - Base Case** with SRC **As Fuel** (**General Electric**, 1976)

Air preheat temperature (°F)	3100
Air pressure (atm)	16
Number of Heaters	6 2 blowdown 3 reheat 1 spare
Heater bed diameter (ft)	30
Heater bed height (ft)	40
Heater total height (ft)	75
Heater bed weight (tons)	1600
Heater total weight (tons)	2600
Pressure drop	
Air side (atm)	0.01
Gas side (atm)	0.10

Table 3.1-9 Comparison of Performance Data for Coal/Open Cycle MHD/ Steam Systems Between ECAS Phases 1 and 2 (NASA, 1977)

	Phase 2 G. E. conceptual powerplant	Phase 1	
		Westinghouse base case 2, point 17	G. E. base case 1
Net output power, MWe	1932	1988	1895
Coal thermal input to combustor, MWt	3688	3870	3700
Air preheat temperature, °F	2500	2400	2500
MHD inlet temperature, °F	4634	4503	4634
MHD diffuser exit temperature, °F	3662	3655	3625
MHD inlet pressure, atm	9.0	7.0	9.0
Compressor exit pressure, atm	10.7	7.6	10.5
Airflow, lb/sec:			
Primary	2492	2653	2486
Secondary	189	279	187
MHD inverter output power, MWe	1406	1230	1399
Compressor power required[a], MWe	377	307	361
Steam turbine-generator output, MWe	587	821	555
Powerplant gross power output, MWe	1993	2051	1954
Ratio of the difference of MHD power and compressor power to plant gross power	0.52	0.45	0.53
Auxiliary power required, MWe	50.7	63	55.6
Ratio of auxiliary power to powerplant gross power	0.025	0.031	0.028
Coal thermal input to seed-reprocessing system, MWt	311	213	231
Ratio of coal for seed reprocessing to total coal	0.078	0.052	0.059
MHD efficiency, MHD power minus compressor power divided by amount of coal to combustor	0.279	0.238	0.281
Steam-cycle efficiency (including generator)	0.420	0.420	0.400
Thermodynamic efficiency, ratio of gross power to amount of coal to combustor	0.540	0.530	0.528
Overall efficiency, ratio of net power to total coal used	0.483	0.487	0.483

[a] Given in electric power even if shaft driven.

Table 3.1-10 Major Design Parameters of Coal/Open Cycle MHD/ Steam System - ECAS Phase 2 (NASA, 1977)

Coal type	Illinois #6
Moisture content of coal delivered to combustor, percent	2
Air preheat temperature, °F	2500
Combustion pressure, atm	9
Combustion temperature, °F	4634
Combustor fuel-air ratio relative to stoichiometric	1.07
Combustor slag rejection, percent	85
Slag carryover to channel, percent	15
Generator type	Diagonal wall
Average magnetic flux density, T	5
Electrical load parameter	0.8
Potassium seed, percent	1
Steam-bottoming-cycle conditions, psig/°F/°F	3500/1000/1000
Cooling tower type	Wet mechanical draft
Stack-gas temperature, °F	251

Table 3.1-11 Summary of Performance and Cost for Coal/ Open Cycle MHD/Steam System - ECAS Phase 2 (NASA, 1977)

Net powerplant output (60 Hz; 500 kV), MWe	1932.2
Thermodynamic efficiency, percent	54.0
Powerplant efficiency, percent	49.8
Overall energy efficiency, percent	48.3
Coal consumption, lb/kW-hr	0.655
Total wastes, lb/kW-hr	0.082
Powerplant capital cost, dollars	1391.1×10^6
Powerplant capital cost, $/kWe	720.0
Cost of electricity (capacity factor, 0.65), mills/kW-hr:	
Capital	22.7
Fuel	7.3
Operation and maintenance	1.7
Total	31.8
Estimated time of construction, yr	6.5
G. E. estimate of approximate date of first commercial service	1996-1999

TABLE 3.1-12

PROJECTED OCMHD OPERATING CHARACTERISTICS

Full Load Heat Rate	
(Pomeroy, *et al.*, 1978)	7068 Btu/kWh
(Pepper, Yu, 1974)	6600 Btu/kWh
Forced/Planned Outage Rate	
(Pomeroy, *et al.*, 1978)	20%/15%
(Jackson, *et al.*, 1976)	20% total unavailability
Minimum Load	
(Pomeroy, *et al.*, 1978)	60% full capacity
(Pomeroy, *et al.*, 1978)	85% of full efficiency
Lifetime	
(Beecher, *et al.*, 1976)	30 years

Perhaps the most important design, certainly the most often cited, is the ECAS General Electric Base Case. The first mass and energy balance schematic of this case showed the potential of flexibility of input fuels, Figure 3.2-1. A slightly revised and later version of this schematic is shown in Figure 3.2-2.

The ECAS Phase I Westinghouse equivalent Base Case is shown in the schematic diagram in Figure 3.2-3 (Base Case 2). The other major configurations studied by Westinghouse included a coal gasifier, shown in Figure 3.2-4, and a char fuel option, shown in Figure 3.2-5.

Another important mass and energy schematic is that developed for the U.S. Department of Energy that is to represent the goal for the first commercial facility, see Figures 3.2-6 and 3.2-7.

EPRI has also sponsored mass and energy schematics, and that closest to the ECAS Base Cases is shown in Figure 3.2-8. Figure 3.2-9 shows a scheme for increasing the stiochiometric air ratio to 120%. This cycle is incorporated into the other EPRI-sponsored schematic in Figure 3.2-10 as an attempt to maximize NO_x and extract it as a fixed nitrogen source for fertilizers.

Aside from these system-wide schematics there are a number of mass and energy balances of particular types of components. For example, perhaps the most important of these are the seed regeneration schematics which include the ECAS schematics, Figure 3.2-11, Tables 3.2-1 and 3.2-2, as well as others, Figure 3.2-12, Tables 3.2-3, 3.2-4 and 3.2-5.

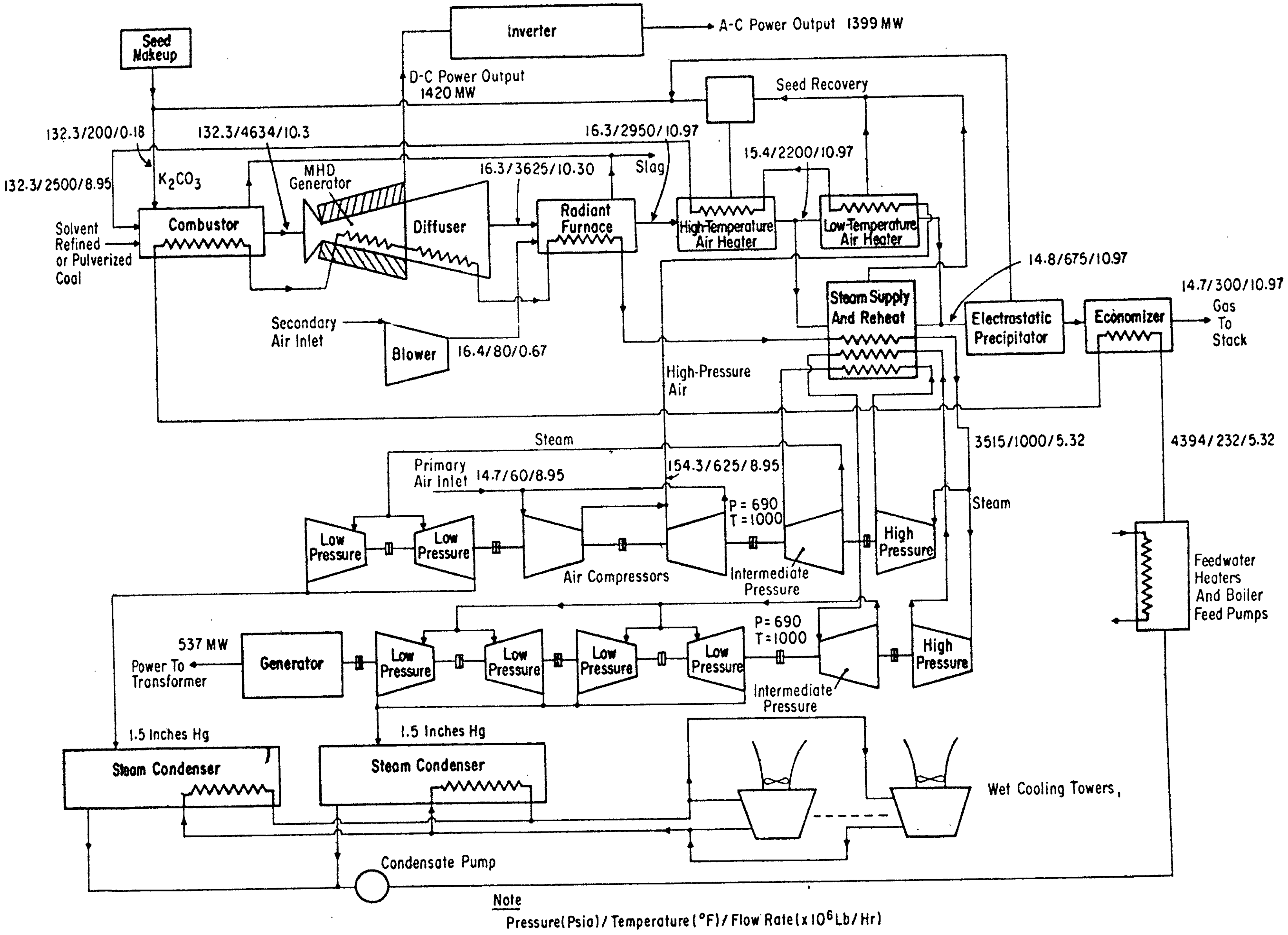
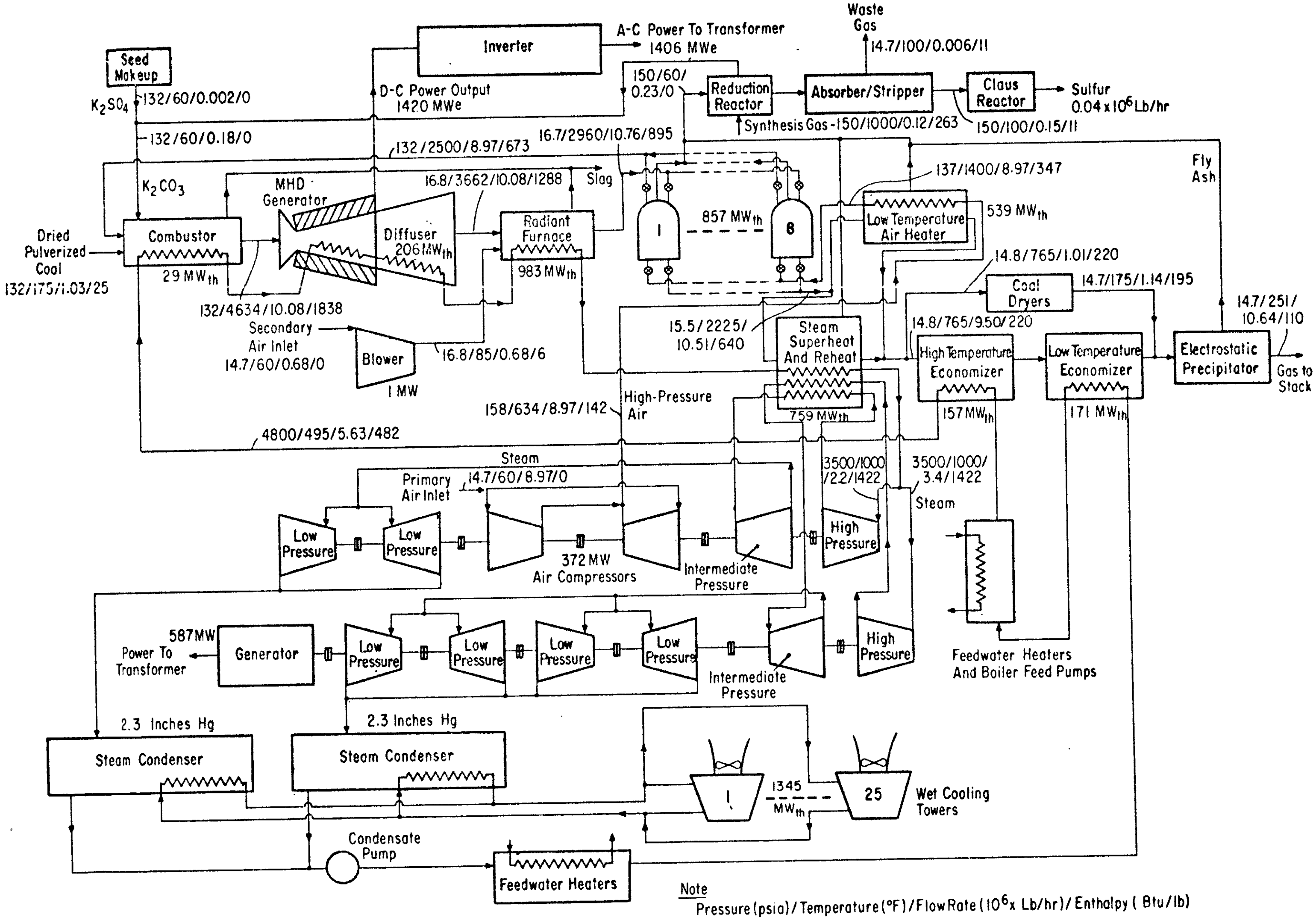
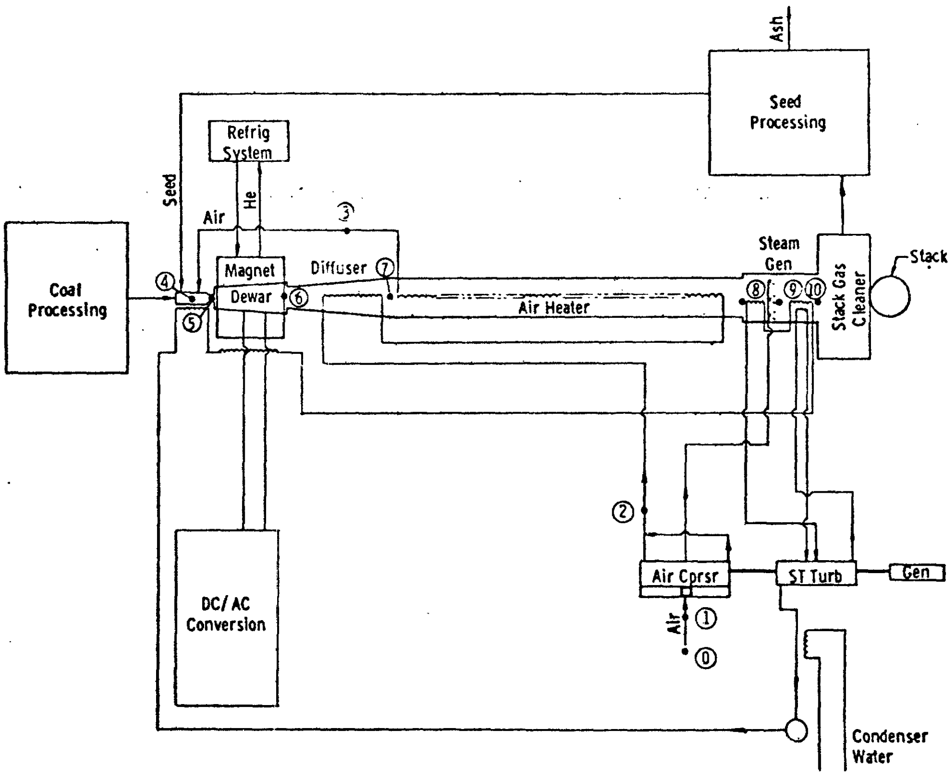


Figure 3.2-1 Open-Cycle MHD for GE ECAS **Base Case** 1 (General Electric, 1976)



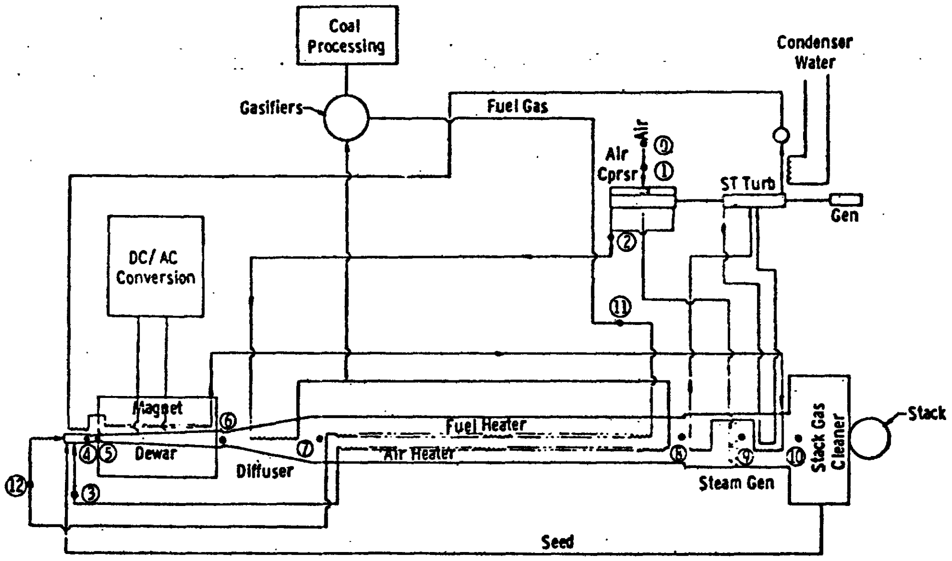
Note
Pressure (psia)/Temperature (°F)/Flow Rate (10^6x Lb/hr)/Enthalpy (Btu/lb)

Figure 3.2-2 Later Schematic Diagram of ECAS Base Case Open Cycle MHD (General Electric, 1976)



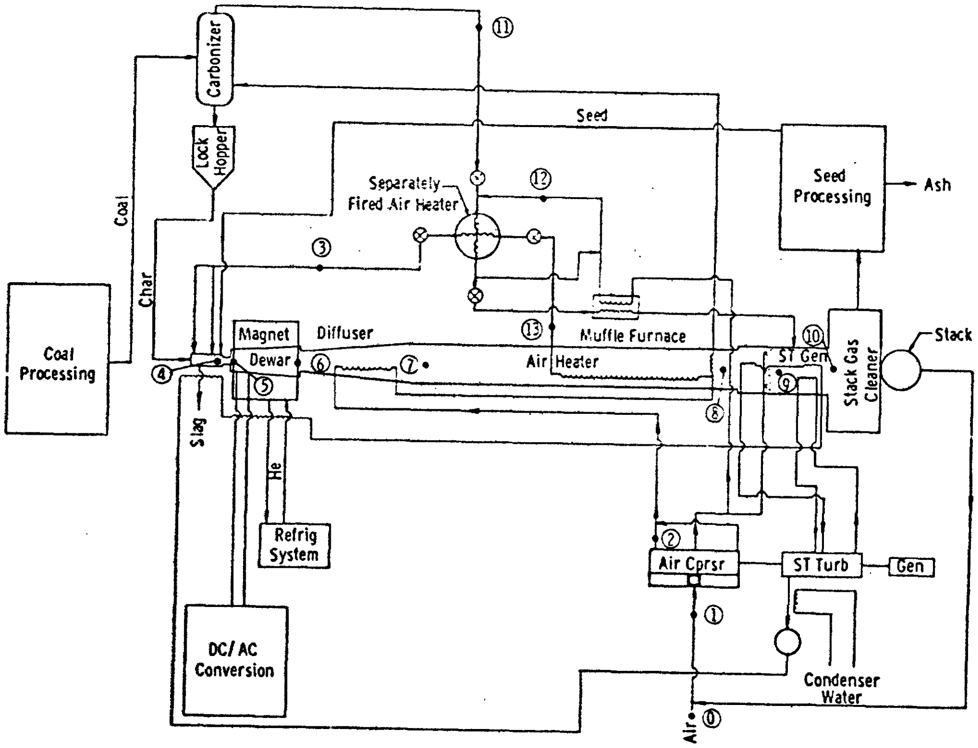
Location	Point No.	Pressure, Psia	Temperature, °F	Flow, lb/s
Ambient	0	14.696	59.0	2768.5
Compressor Inlet	1	14.40	59.0	2768.5
Compressor Outlet	2	95.36	465.2	2768.5
Preheater Outlet	3	92.58	2398.4	2768.5
Combustor Outlet	4	88.18	4414.4	3144.3
MHD Duct Entrance	5	59.18	4185.8	3144.3
MHD Duct Exit	6	13.09	3460.4	3144.3
Diffuser Exit	7	17.00	3644.0	3144.3
Preheater Exit	8	16.52	2538.0	3435.8
Air Quench Chamber Exit	9	15.58	1880.0	3435.8
Steam Generator Exit	10	14.696	305.0	3435.8

Figure 3.2-3 Schematic Diagram and State Points for Open Cycle MHD Westinghouse ECAS Base Case 2 (Westinghouse, 1976)



Location	Point No.	Pressure, Psia	Temperature, °F	Flow, lb/s
Ambient	0	14.696	59.0	1710.2
Compressor Inlet	1	14.40	59.0	1710.2
Compressor Outlet	2	158.94	603.8	1710.2
Air Preheater Outlet	3	154.31	2587.4	1710.2
Combustor Outlet	4	146.96	4400.0	3030.2
MHD Duct Entrance	5	99.02	4119.6	3030.2
MHD Duct Exit	6	13.54	3280.4	3030.2
Diffuser Exit	7	17.00	3446.0	3030.2
Air Preheater Exit	8	16.52	2230.4	3210.2
Air Quench Chamber Exit	9	15.58	1680.0	3210.2
Steam Generator Exit	10	14.696	305.0	3210.2
Fuel Preheater Entrance	11	158.90	1600.0	1282.9
Fuel Preheater Exit	12	154.31	2591.0	1282.9

Figure 3.2-4 Schematic Diagram and State Points for Open Cycle MHD Westinghouse ECAS Base Case 3 (Westinghouse, 1976)



Location	Point No.	Pressure, Psia	Temperature, °F	Flow, lb/s
Ambient	0	14.696	59.0	1976.3
Compressor Inlet	1	14.40	132.1	2934.7
Compressor Outlet	2	95.36	54.69	2934.7
Air Preheater Outlet	3	92.58	2933.5	2934.7
Combustor Outlet	4	88.18	4400.0	3194.8
MHD Duct Entrance	5	58.59	4162.4	3194.8
MHD Duct Exit	6	12.94	3422.6	3194.8
Diffuser Exit	7	17.00	3620.6	3194.8
Air Preheater Exit	8	16.52	2483.0	3194.8
Air Quench Chamber Exit	9	15.58	1880.0	3493.4
Steam Generator Exit	10	14.696	305.0	3493.4
Gapor	11	16.16	800.0	113.0
SFA Combustion Air	12	21.25	2384.0	632.0
Cross-over Air	13	93.5	2384.0	2934.7

Figure 3.2-5 Schematic Diagram and State Points for Open Cycle MHD Westinghouse ECAS Base Case 1 (Hoover, et al., 1976)

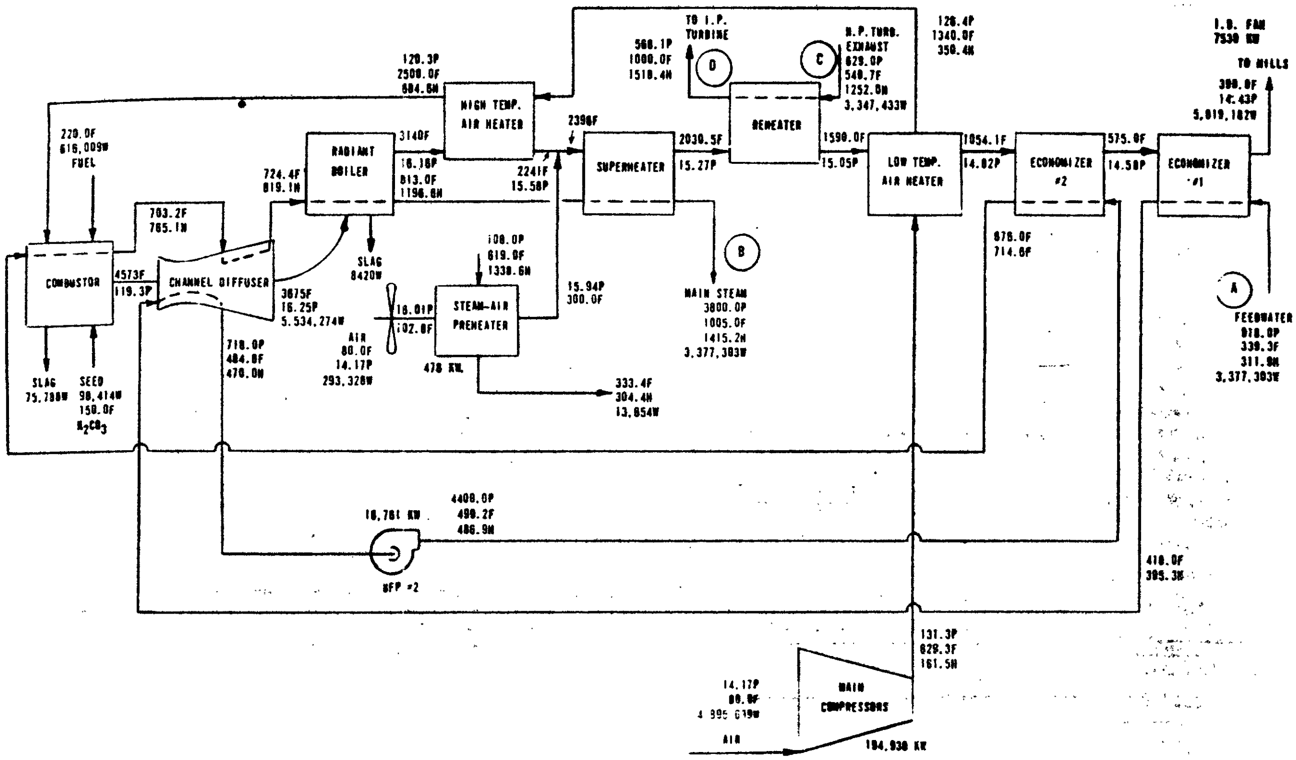


Figure 3.2-6 **Air-Gas Side Balance** of OCMHD (**Jackson**, et al., Oct. 1976)

LEGEND:
H - ENTHALPY - BTU/LB
W - FLOW / LB/HR
P - PRESSURE - PSIA
F - TEMPERATURE - F DEGREES

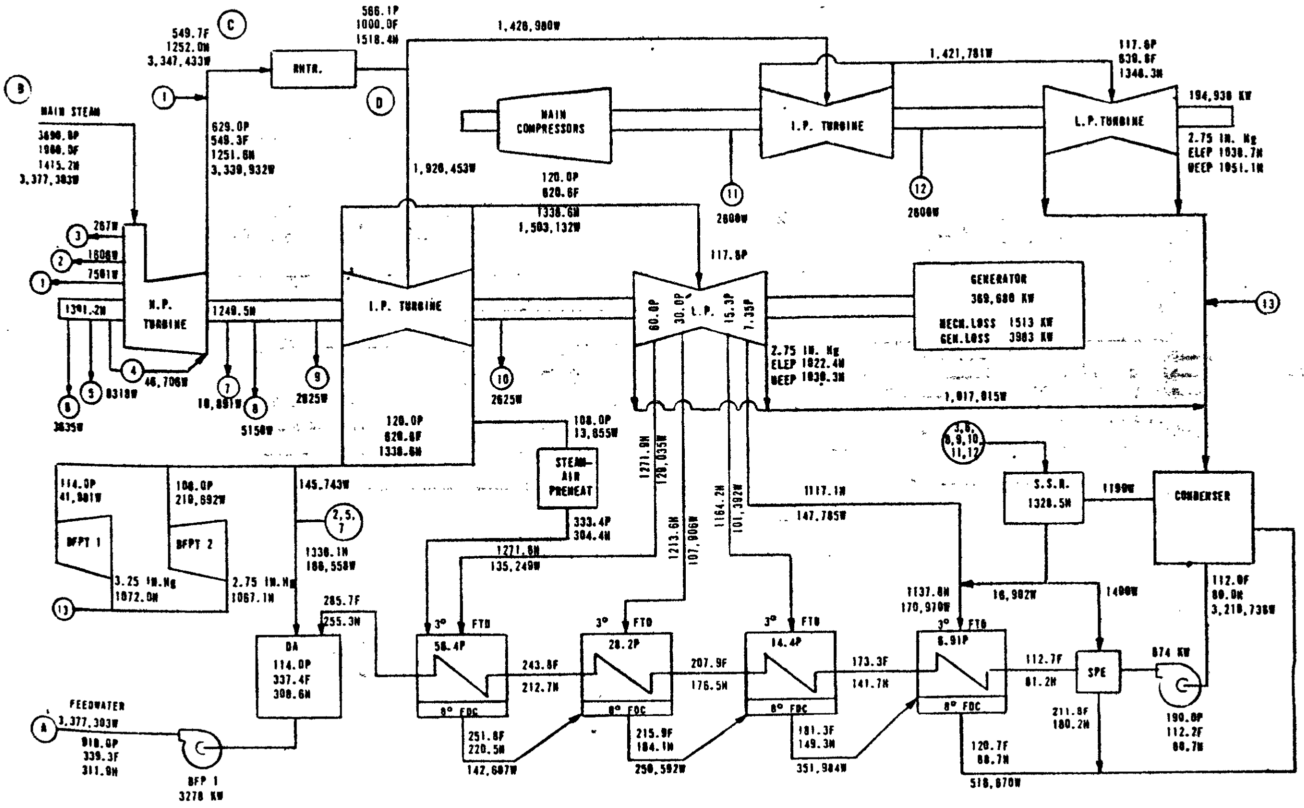


Figure 3.2-7 **Steam Side Balance** of OCMHD (Jackson, et al., Oct. 1976)

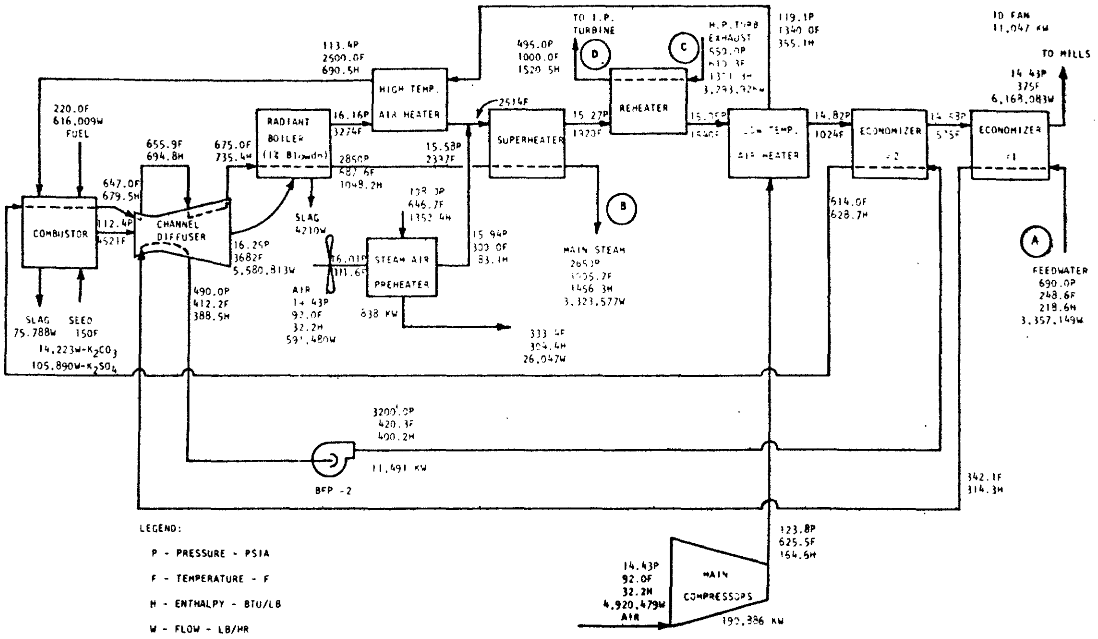


Figure 3.2-8 **Air-Gas Side Flow Diagram-EPRI** Case 2 (Cutting, et al., 1977)

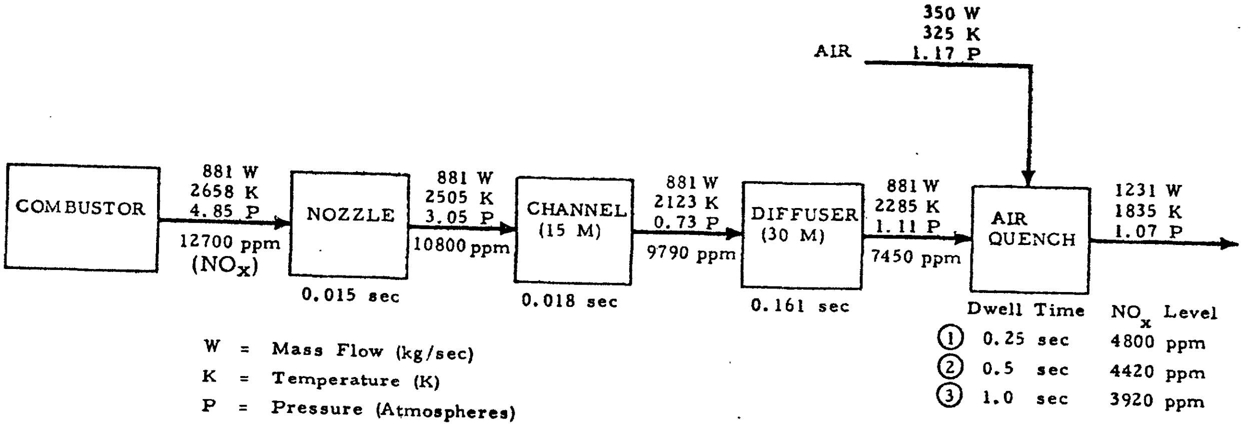


Figure 3.2-9 **Thermodynamic State Points and Flowrates for Topping Cycle-120%** Stoichiometric Air EPRI Case 4 (Cutting, et al., 1977)

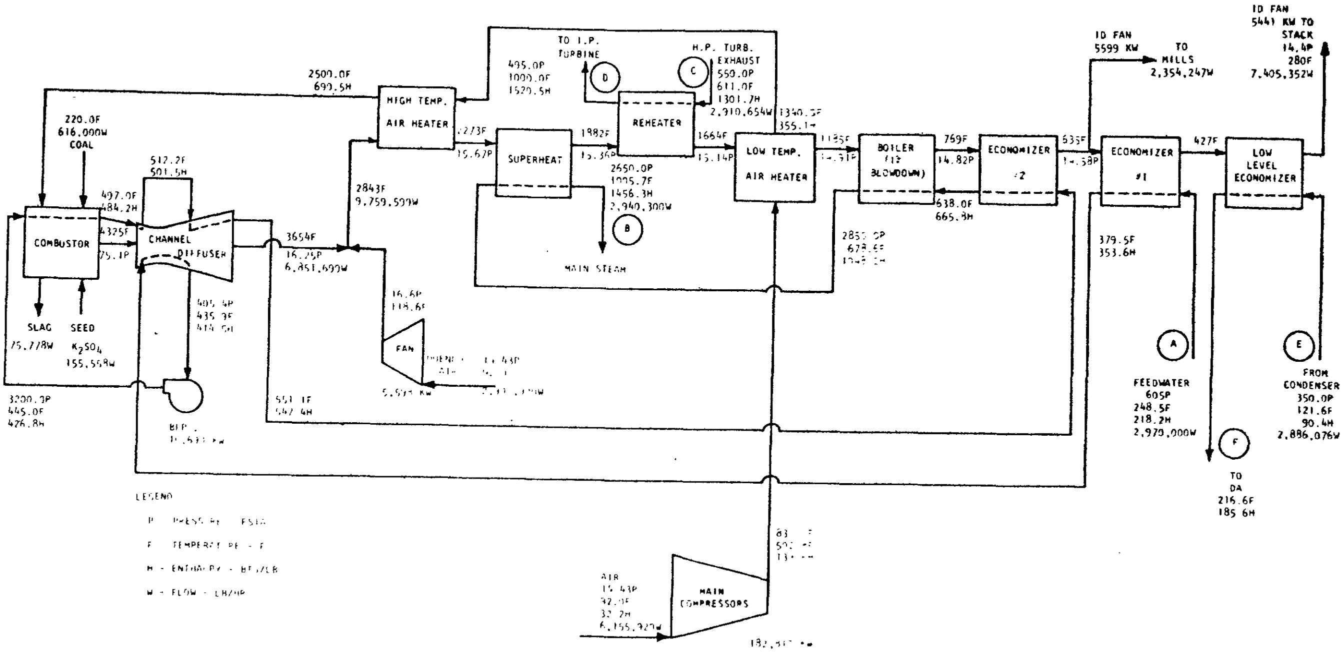


Figure 3.2-10 Air-Gas Side Flow Diagram-EPRI Case 4 (Cutting, et al., 1977)

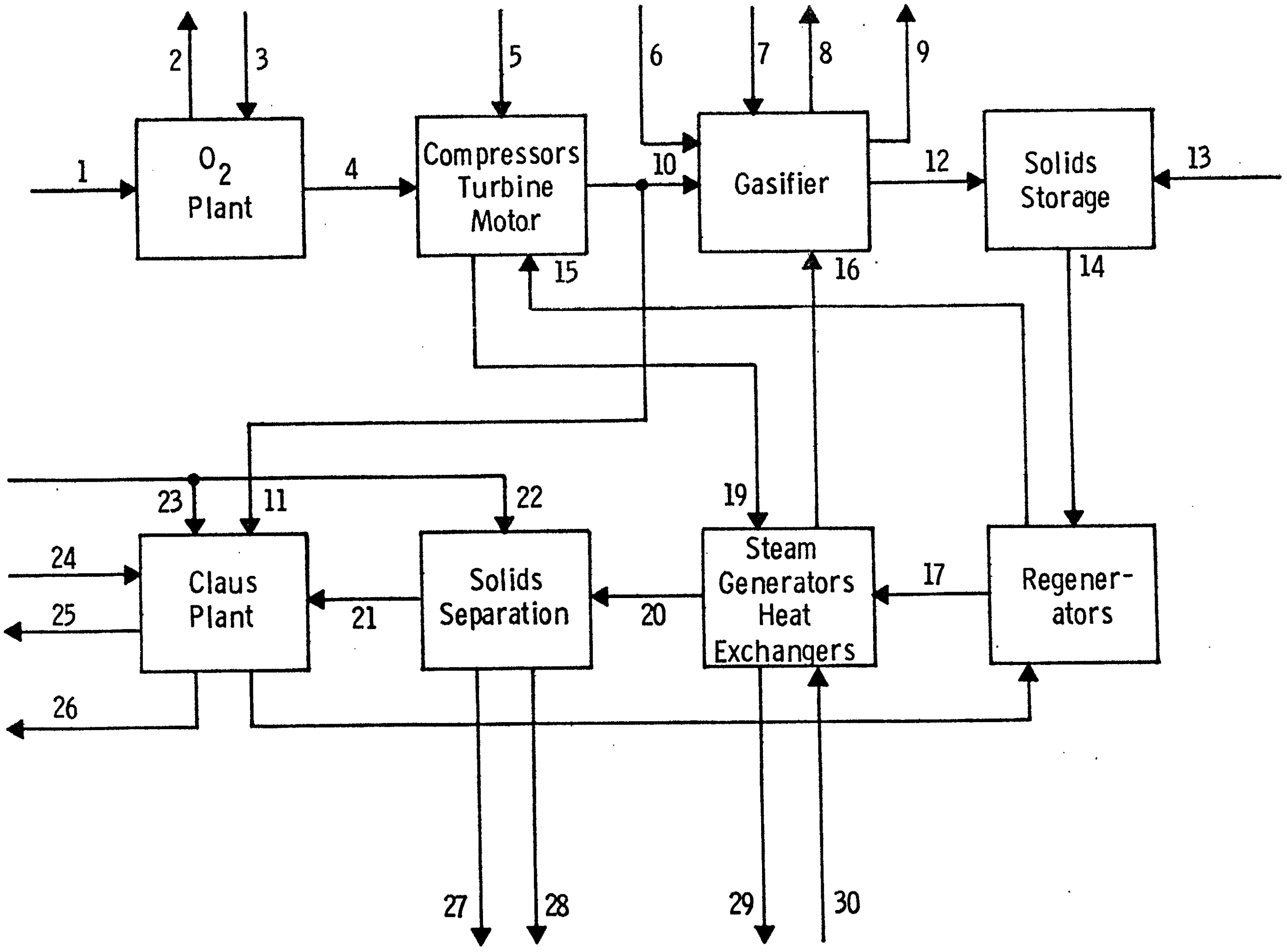


Figure 3.2-11 Simplified Flow Diagram of Seed Regenerative System for **Westinghouse** ECAS **Base Case** 2 (Westinghouse, 1976)

Table 3.2-1 Flow Chart for Seed Regeneration System for Westinghouse ECAS Base Case 2 (Westinghouse, 1976)

Flow Name	Air Feed	N_2 Rejection	Power	O_2	Power	Coal Feed	Power	Ash Reject	Exhaust	O_2	O_2	Process Gas	Seed + Ash	Solids + Gas	Warmed Gas
Flow Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mass Rate, kg/s	73.99	56.75		17.24		21.72		2.09	7.18	14.2	3.04	43.5	36.55	80.05	36.3
Temperature, °K	300	300		300		300		1144	370	669	669	1144	350	960	760
Pressure, kPa	101	101		101		101		1520	101	1722	1722	1520	101	1520	1418
Power, kW			16136		1483		331.65		0.7066						
N_2, Mole Fraction	0.79	1.0		0					0	0	0	0		0	0
H_2	0	0		0					0	0	0	0.2788		0.2788	0.2167
CO	0	0		0					0.1632	0	0	0.3764		0.3764	0.2927
CO_2	0	0		0					0.1048	0	0	0.1464		0.1464	0.3921
H_2O	0	0		0					0	0	0	0.1324		0.1324	0.0128
H_2S	0	0		0					0	0	0	0 .011		0 .011	0
CH_4	0	0		0					0	0	0	0.0551		0.0551	0.0856
SO_2	0	0		0					0.0254	0	0	0		0	0
O_2	0.21	0		1.0					0	1.0	1.0	0		0	0
S, kg/s													0	0	
K_2SO_4													32.71	32.71	
K_2CO_3													0	0	
Ash								2.09					3.84	3.84	
Molecular Weight (Gas)	28.6	28							29.66	32	32	21.3		21.3	27.5

Table 3.2-2 Flow **Chart for Seed Regeneration System for Westinghouse ECAS Base Case** 2 (cont'd)

Flow Name	Steam	Process Gas	Cold Gas	Expanded Gas	Cool Process Gas	Cool Process Gas	Power	Power	Cool Water Make	Evap. Water	Sulfur + Water	K_2CO_3 K_2SO_4	Ash + Seed	Hot Gas to MHD	Steam Water
Flow Number	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Mass Rate, kg/s	11.89	80.05	36.3	36.3	80.05	49.39			8.6	8.6	16.13	22.61	8.05	35.2	11.89
Temperature, °K	478	1040	332	598	541	541			300	373	420	541	541	899	478
Pressure, kPa	1722	1499	1428	607	1469	1444			101	101	1418	1418	1418	607	1722
Power, kW							9.2	221							
N_2, Mole Fraction	0	0	0	0	0	0			0	0	0			0	0
H_2	0	0.1522	0.2167	0.2167	0.1522	0.1522			0	0	0			0.2167	0
CO	0	0.2055	0.2927	0.2927	0.2055	0.2055			0	0	0			0.2927	0
CO_2	0	0.2753	0.3921	0.3921	0.2753	0.2753			0	0	0			0.3921	0
H_2O	1.0	0.2078	0.0128	0.0128	0.2078	0.2078			1.0	1.0	1.0			0.0128	1.0
H_2S	0	0.0990	0	0	0.0990	0.0990			0	0	0			0	0
CH_4	0	0.0601	0.0856	0.0856	0.0601	0.0601			0	0	0			0.0856	0
SO_2	0	0	0	0	0	0			0	0	0			0	0
O_2	0	0	0	0	0	0			0	0	0			0	0
S, kg/s		0									6.01	0	0		
K_2SO_4		4.28									0	3.61	0.673		
K_2CO_3		22.54									0	19.0	3.54		
Ash		3.84									0	0	3.84		
Molecular Weight (Gas)	18	26.3	27.5	27.5	26.3	26.3			18	18	18			27.5	18

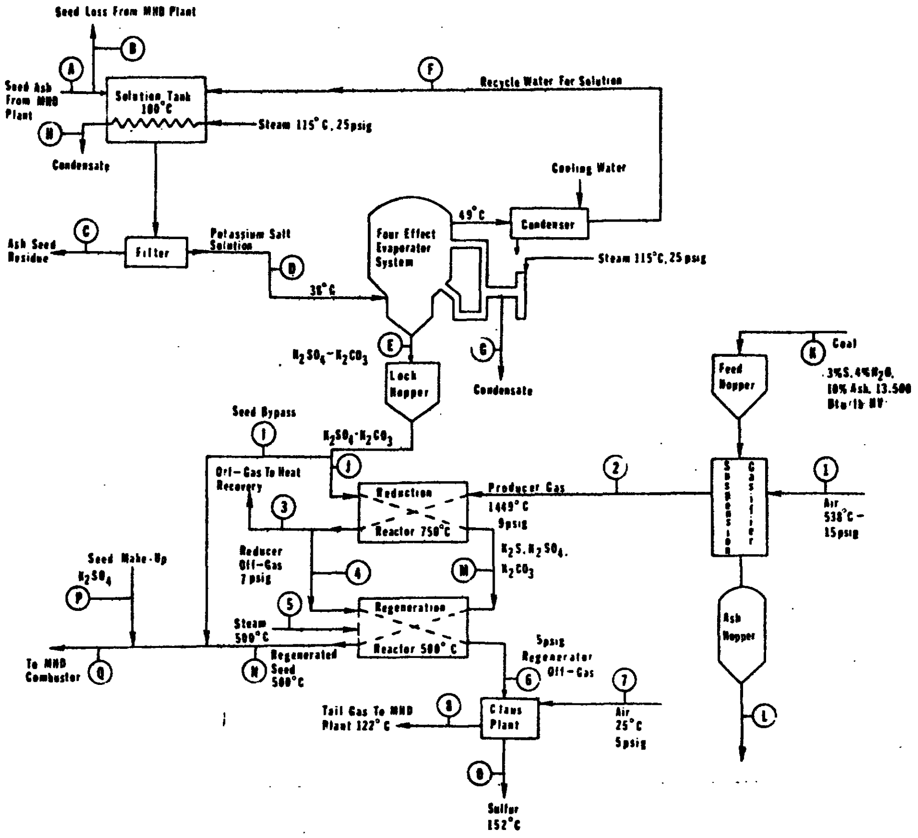


Figure 3.2-12 Desulfurization Scheme for Combined Cycle MHD Power Plant (Bergman, et al., 1977)

Table 3.2-3 Solid and Liquid Streams - Material Balance for Base Case MHD Processing Scheme (Bergman, et al., 1977)

Solid or Liquid Streams

Flow Stream*	Coal**	Ash***	K_2SO_4	Sulfur	K_2S	K_2CO_3	H_2O	Enthalpy**** H
			(lb/hr)					(Btu/hr)
								$\times 10^{-6}$
A		4750	82100			4700		
B			820			50		
C		4700	810			50		
D		50	80460			4600	345080	
E		50	80460			4600		
F							345080	
G							78500	
H							33500	
I		10	12070			700		
J		40	68390			3900		-257.32
K	25370						1015	-29.76
L	1270	2280						-11.19
M		300	1370		42300	3910		-68.27
N		300	1370		1270	55470		-192.90
O				11600				0.87
P			1750					
Q		310	15190		1270	55470		

---

*See Figure 3.2-12

**Coal Analysis (4.95% H, 76.1% C, 1.0% N, 4.95% O, 3.0% S, 10.0% Ash, 4 Kg H_2O/100 Kg dry coal)

***Ash Analysis (28.0% Al_2O_3, 4.4% CaO, 15.0% Fe_2O_3, 1.6% K_2O, 1.1 % MgO, 0.8% Na_2O, 0.5% P_2O_5, 46.5% SiO_2, 1.3% TiO_2)

****At 298 K and 1 atm the enthalpy of all elements in that physical state is 0.

Table 3.2-4 Gaseous Streams - Material Balance for Base Case MHD Seed Processing Scheme (Bergman, et al., 1977)

Flow Stream*		Mole %									Volumetric Flow Rate scfh** X 10^{-6}	Enthalpy H*** X 10^{-6} Btu/hr
No	Name	Ar	CO_2	CO	H_2	H_2O	H_2S	N_2	O_2	X		
1.	Gasifier Air	0.92	0.03	-	-	1.26	-	77.10	20.69	-	1.45	21.91
2.	Producer Gas	0.70	3.06	24.86	8.80	3.67	0.29	58.64	-	0.08	1.92	-5.68
3.	Reducer Off-gas to heat recovery	0.70	24.25	3.67	1.31	11.16	0.29	58.54	-	0.08	1.25	-153.33
4.	Reducer Off-gas to regeneration	0.70	24.25	3.67	1.31	11.16	0.29	58.54	-	0.08	0.66	-80.60
5.	Steam	-	-	-	-	100.00	-	-	-	-	0.087	-23.32
6.	Regenerator Off-gas	0.75	4.34	3.95	1.40	4.34	22.01	63.12	-	0.09	0.62	-16.29
7.	Claus Plant Air	0.92	0.03	-	-	1.26	-	77.10	20.69	-	0.40	-1.48
8.	Claus Plant Tail Gas	0.64	5.46	-	-	18.23	.35	74.95	-	0.40	0.955	-65.57

---

* See Figure 3.2-12

** The molar gas volume is taken to be 359 ft^3 at 273 K and 1 atm.

*** At 298 K and 1 atm the enthalpy of all elements in that physical is 0.

Table 3.2-5 Energy Requirements for Seed Desulfurization in Base Case (Bergman, et al., 1977)

Coal Input (MWt)	98.2
Thermal Input (MWt)	
Air preheat	(6.92)
Steam for regeneration reaction	(0.51)
Total	(7.43)
Thermal Output (MWt)	
Gasifier steam	2.63
Reductor steam	11.79
Regenerator steam	11.44
Claus plant steam	13.77
Reductor gas, sensible heat, and heating value	15.87
Solids sensible heat	3.59
	59.09
Net heat recovered (MWt)	51.60
Electricity produced (40% efficiency, MWe)	20.64
Electrical input for auxiliaries (compressors, pumps, etc., MWe)*	(0.32)
Credit for carbonate production (MWe)	3.00
Net electricity production (MWe)	23.32

Effect on Efficiency

$$\frac{1000 + 23.32}{2000 + 98.2} = \frac{1023.3}{2098.2} = 48.77$$

Loss of Efficiency 50.00 - 48.80 = 1.23 points

---

*Includes seed leaching system energy consumption and assumes steam drives for pumps and gas compressors above 50 HP.

3.3 Energy Efficiency Evaluations

Table 3.3-1 shows the wide spread of estimates of OCMHD efficiencies. Of course some of this variation is due to lack of data and some is due to differences in designs. The energy losses at the points in several specific designs can be computed from the schmeatics in the previous section. This section begins with some general energy loss information and proceeds to the specific energy effects of changes in various design and operating parameters.

In comparison with other advanced energy cycles the Phase I ECAS studies shown how OCMHD's appear now to be competitive, Figures 3.3-1 and 3.3-2. With the axes reversed Figure 3.3-3 shows a slightly different set of results directly from the Westinghouse ECAS report. In the detailed ECAS Phase II studies the energy balance is shown in the flow chart in Figure 3.3-4. Table 3.3-2 displays a slightly more explicit breakdown of combustion losses; Table 3.3-3 shows additional detail on energy use of auxiliary components, and Table 3.3-4 shows a similar loss breakdown for the "reference" commercial facility of the future.

The best way to determine the energy efficiency changes due to particular parameter variations is currently through parametric investigations in the analytic system models. Some of these studies have been done as part of ECAS Phase I, Table 3.3-5. Unfortunately there were not enough of these parameteric studies to allow for a unique solution for the effects of various parametric changes. Statistically stated there are not enough values to ensure that predictive formulae would not capitalize on chance effects in the observed data. There have been some

TABLE 3.3-1

PROJECTED OVERALL OCMHD ENERGY EFFICIENCIES

Reference	Estimate
(Pomeroy, *et al.*, 1978)	48.3% - 49.2%
(Cutting, *et al.*, 1977)	46% - 46.9%
(NASA, 1977)	48.3% - 48.7%
(Penny, Bourgeois, Cain, 1977)	55% - 60%
(Bergman, Bienstock, 1976)	45.6% - 50.14%
(Jackson, *et al.*, 1976)	47%
(NASA, 1976)	46% - 54% low Btu Westinghouse data
(NASA, 1976)	loss of 3% for seed reprocessing associated with high-sulfur coal
(Seikel, Harris, 1976)	41% - 53% (GE Co.)
(Seikel, Harris, 1976)	42% - 50% (WE Co.)
(Seikel, Harris, 1976)	48.3% (GE Co.)
(Westinghouse, 1976)	44% - 49% direct air preheat
(Westinghouse, 1976)	44% - 54%
(General Electric, 1975)	44% - 55%
(General Electric, 1975)	40% - 46% with solvent refined coal
(Pepper, Yu, 1975)	52% thermal
(Powell, Ulmer, 1974)	50% - 55%
(Feldmann, Simons, Bienstock, 1970)	50.8% - 51.9% thermal efficiency
(Hals, Jackson, 1969)	50% - 60%

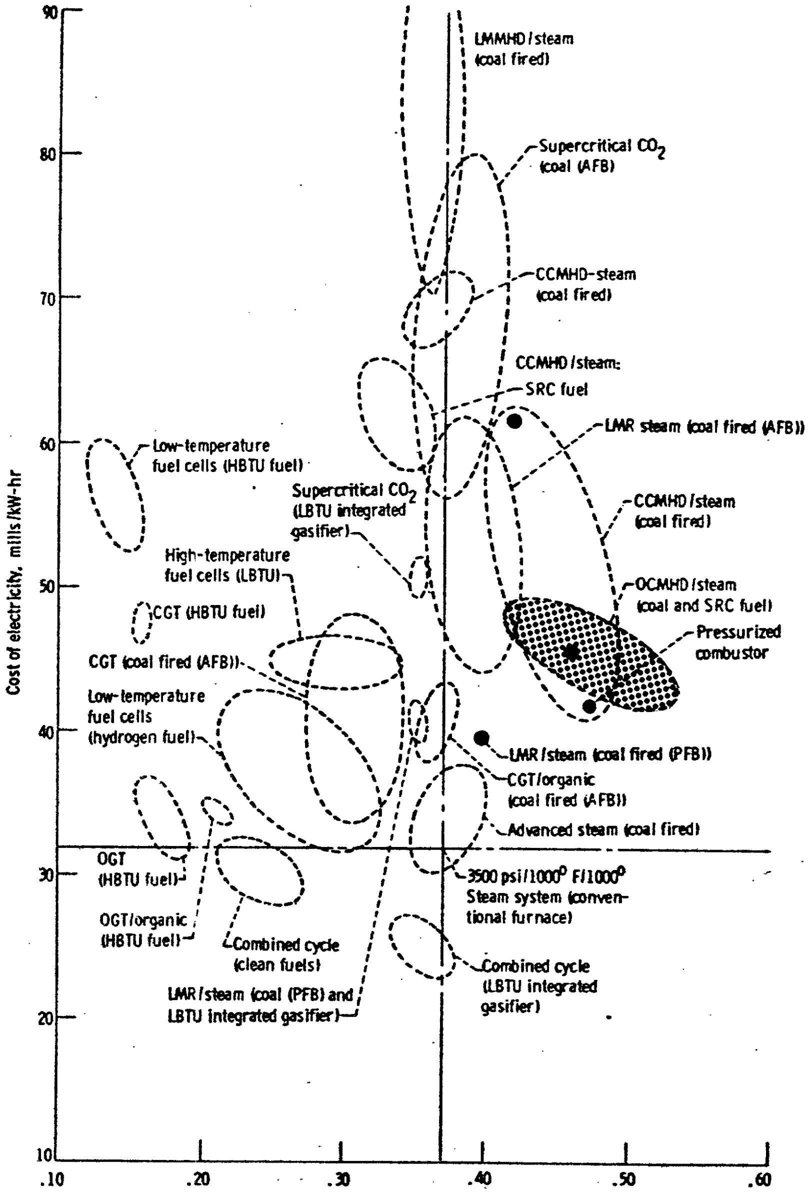


Figure 3.3-1 Effect of Overall Energy Efficiency on Cost of Electricity in General Electric Results with Shaded Area OCMHD (Seikel, Harris, 1976)

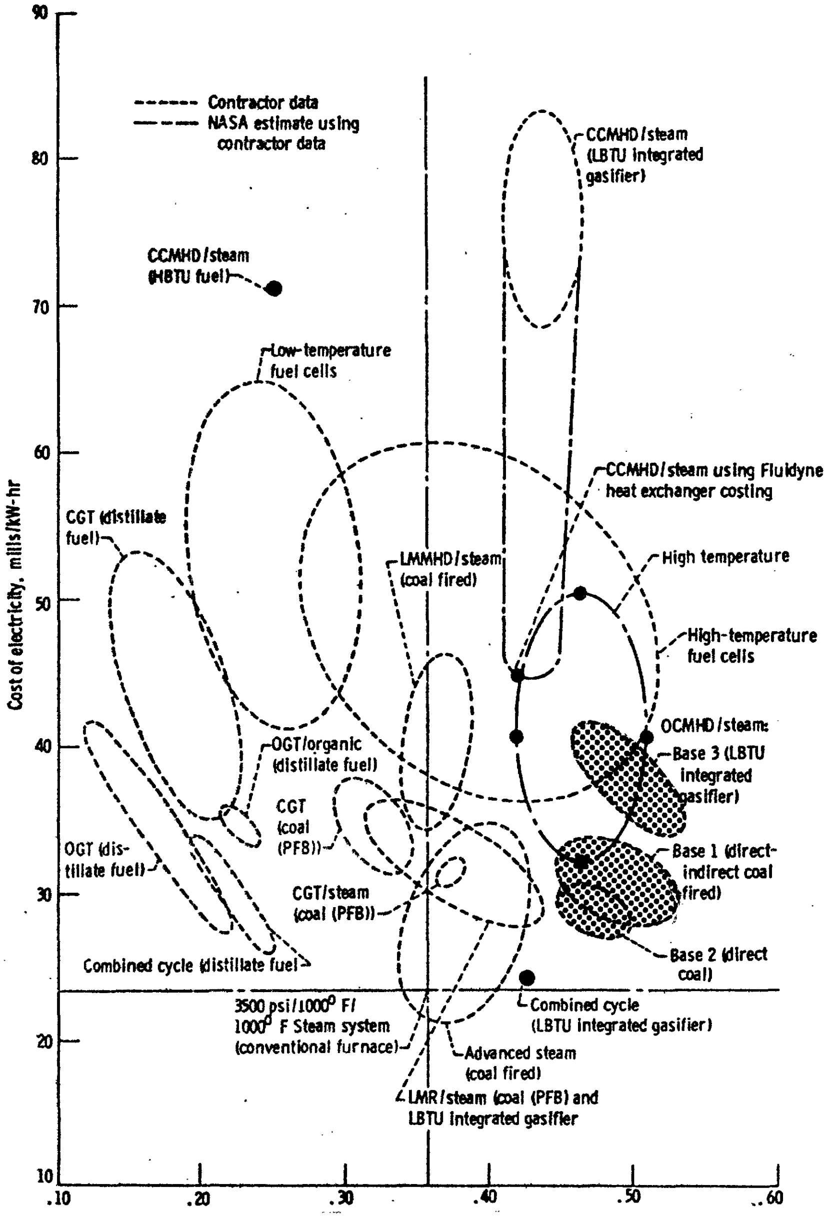
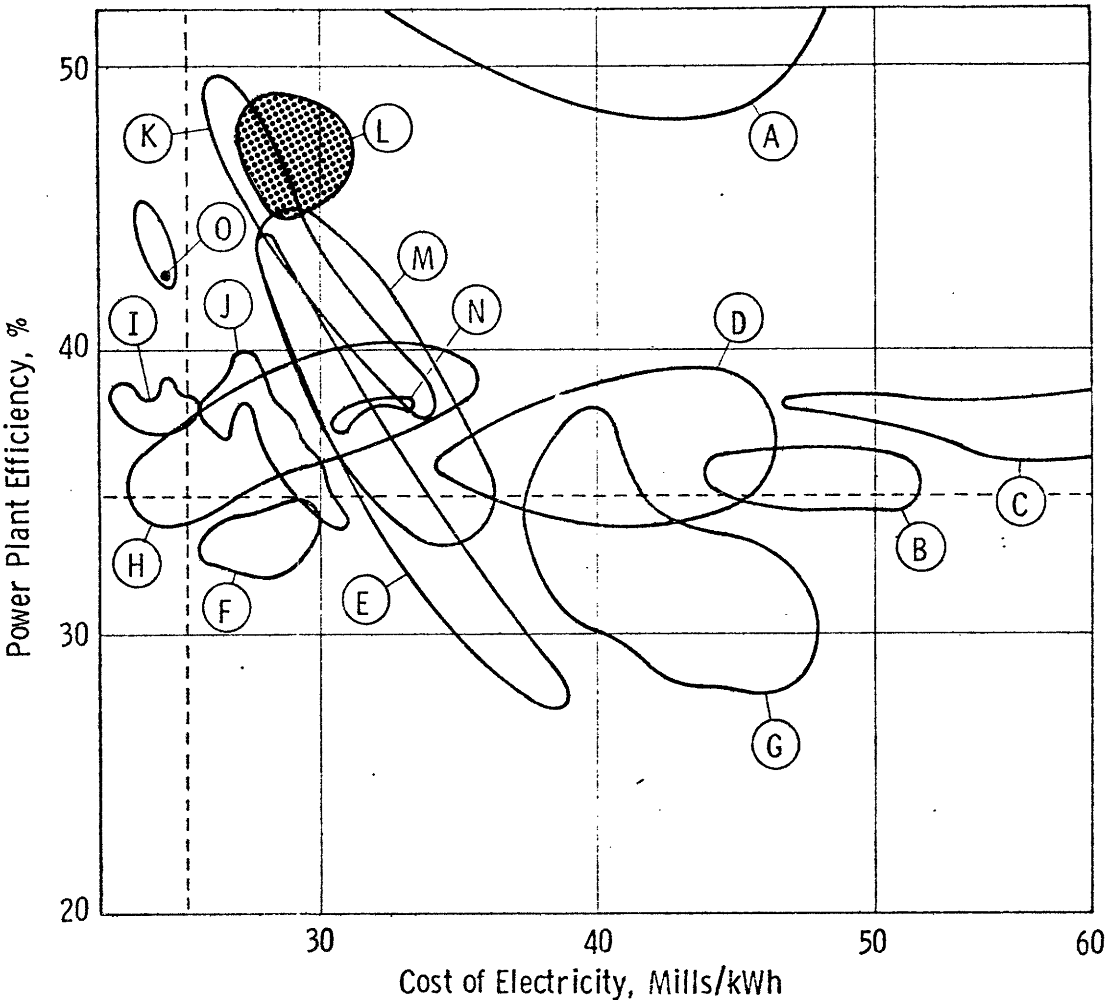


Figure 3.3-2 Effect of Overall Energy Efficiency on Cost of Electricity in Westinghouse Results with Shaded Areas OCMHD (Seikel,Harris, 1976)



A-Fuel Cell Steam Bottoming
    1-Molten-Carbonate
    2-Solid Electrolyte
B-Fuel Cell (Phosphoric Acid)
C-Alkaline Fuel Cells
D-Liquid Metal MHD
E-Recuperated-Open-Cycle Gas Turbine
F-Closed Recuperated Gas Turbine (Coal)
G-Recuperated-Closed-Cycle Gas Turbine
H-Steam (Atmospheric Boiler)
I-Steam (Pressurized Fluidized Bed Boiler)
J-Steam (Pressurized Boiler)
K-Distillate-Burning Combined-Gas Turbine
L-Open-Cycle MHD
M-Metal Vapor Rankine Topping Cycle
N-Combined-Closed-Cycle Gas-Steam Turbine
O-Coal Burning Combined-Cycle-Gas Steam Turbine

Figure 3.3-3 Advanced Energy-Conversion Systems - Range of Results with Shaded Area OCMHD (Beecher, et al. 1976)

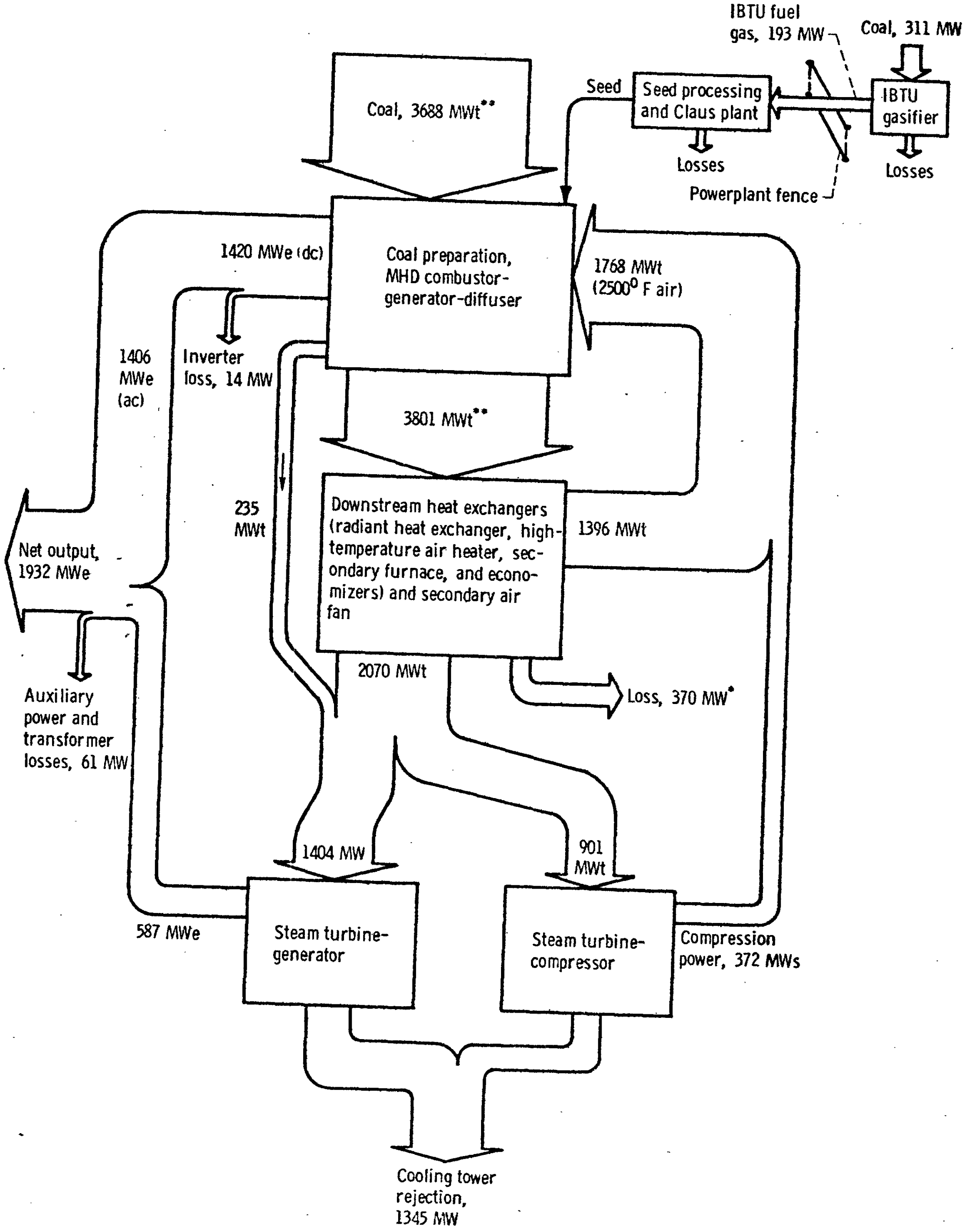


Figure 3.3-4 Simplified Energy Flow Diagram for Phase 2 Conceptual Powerplant - Coal/Open Cycle MHD/ Steam System (NASA, 1977)

Table 3.3-2 Energy Balance for Combustion Flow (Harris, Shah, 1976)

Energy Outputs			
*MHD power output		1420	
*Combustor/channel/diffuser cooling		235	
*Radiant furnace heat transfer		983	
*HTAH heat transfer		857	
*Secondary furnace heat transfer		1298	
*(Economizers		328	
(Coal dryers		8	
Leaving losses		370	
Coal ash (sensible + latent)	22		
K_2SO_4 (sensible + latent)	10		
Combustion gas (sensible)	183		
Combustion gas (latent)	155		
Energy Inputs Other Than Combustion			
Air heating (857 + 539)		1396	
Air compressor power		372	
Coal heating in mills, dryers		8	
Net Energy Output			3723 MWt
Combustion Energy Input			3750 MWt
Fuel HHV @ 10.788 Btu/lb	3688		
Correction for $SO_x \rightarrow K_2SO_4(G)$	17		
Condensation and solidification of K_2SO_4	45		
Excess Energy Input			27 MWt

*Values specified by system advocate

Table 3.3-3 Auxiliary Power Requirements and Electrical Losses for ECAS Open Cycle MHD (Harris, Shah, 1976)

ITEM	ASSUMPTIONS	NO. OF UNITS	MW$_e$ EACH	TOTAL MW$_e$
PUMPS				
CONDENSATE	A/E ESTIMATE	4		1.46
CIRCULATING WATER	PROPORTIONAL TO COOLING TOWER HEAT LOAD	3		4.61
AIR BLOWER	$\eta = 80\%$	1		1.00
COOLING TOWERS	PROPORTIONAL TO HEAT LOAD	25		2.15
COAL HANDLING	¾ OF EQUIPMENT RATING			2.25
COAL PROCESSING	EQUIPMENT RATING			14.00
MHD COMPONENTS	0.75% MHD POWER			10.50
TURBINE AUXILIARIES	0.75% STEAM POWER			6.90
"HOTEL" LOAD	A/E ESTIMATE			6.37
MAKEUP WATER TREATMENT	A/E ESTIMATE			.75
INTAKE STRUCTURE	A/E ESTIMATE			.75
INVERTER LOSSES	1% MHD D-C OUTPUT			14.2
TRANSFORMER LOSSES	0.5% 60 Hz GENERATION			9.96
				74.9

Table 3.3-4 OCMHD System Energy Balance for Eventual Commercial OCMHD (Jackson, et al., 1976)

	KW	KW
GENERATORS		
MHD	634,000	
Steam Turbine	370,408	
Subtotal Generators		1,004,408
MOTORS (CALCULATED)		
Secondary Air Fan	484	
Circulating Water Pump	4,907	
Condensate Pump	1,230	
Boiler Feed Booster Pump	766	
Induced Draft Fan	7,556	
Subtotal Motors		-14,943
PLANT AUXILIARIES (ESTIMATED)		
Main Steam Turbine	295	
Fuel Handling	6,307	
Ash Handling	1,636	
Service Water System	293	
MHD Transformer	12,683	
Steam Turbine Transformer	5,548	
Seed Handling	10,000	
Inverter	6,311	
Cleanup System	13,671	
Magnet	1,000	
Miscellaneous	1,936	
Subtotal Auxiliaries		-59,680
TOTAL PLANT OUTPUT (NET)		929,785
COAL BURNER		
LB/HR	616,009	
HHV	11,081	
BTU/SEC	1,896,111	
KW_{th}	2,000,000	
STATION HEAT RATE (BTU/KWH) (BASED ON HHV)		7341
STATION EFFICIENCY (%)		46.50

Table 3.3-5 Parametric Variations for General Electric ECAS Task I Study Open Cycle MHD (Corman, et al., 1976)

Parameters	Case 1*	2	3	4	5	6	7	8**	9	10	11	12	13	14	15
	Common Elements: Direct Coal Combustion, Avco Combustors, and Refractory S														
Power Output (MWe)	1895	1180	599	1870	1867	1888	1888	1426	1991	1994	2017	2073	1738	1929	1799
Combustion															
Coal	Ill. #6	→	→	Mont	N. D.	Ill. #6	→	→	→	→	→	→	→	→	→
Oxidizer	Air	→	→	→	→	→	→	→	Air/O_2	Air	→	→	→	→	→
Combustor slag rejection (percent)	90	→	→	→	→	80	0	90	→	→	→	→	→	→	→
Preheater															
Firing	Direct	→	→	→	→	→	→	→	→	Indirect	Direct	→	→	→	→
Oxidizer temperature (°F)	2500	→	→	→	→	→	→	→	1500	3100	→	→	2000	2500	→
MHD Generator															
Type	Faraday	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Inlet pressure (atm)	9	8.9	8.7	7	6.5	9	→	7	10.2	11.5	13.0	16	6	8.7	9
Average magnetic field (T)	5	→	→	→	→	→	→	→	→	→	→	6	5	→	→
Potassium seed (percent)	1.0	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Electrical load parameter	0.8	→	→	→	→	→	→	→	→	→	→	→	→	0.85	0.7
Heat Exchangers															
Gas (Δp/p)	0.15	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Air (Δp/p)	0.10	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Steam Bottoming Cycle															
Turbine inlet temperature (°F)	1000/1000	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Turbine inlet pressure (psi)	3500	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Maximum feedwater temperature (°F)	232	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Air Bottoming Cycle															
Turbine inlet temperature (°F)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pressure ratio	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Heat Rejection (in. Hg)	WCT 1.5	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Actual Powerplant Output (MWe)	1895	1180	599	1870	1867	1888	1888	1426	1991	1994	2017	2073	1738	1929	1799
Thermodynamic Efficiency (percent)	52.8	52.0	52.3	49.6	48.4	52.7	52.7	51.6	50.0	55.5	56.1	57.7	48.6	53.7	50.2
Powerplant Efficiency (percent)	49.2	48.5	48.7	47.9	46.5	49.1	49.1	47.2	46.9	51.8	52.4	53.9	45.1	50.1	46.8
Overall Energy Efficiency (percent)	48.3	47.6	47.8	47.8	46.3	48.1	48.1	46.1	46.1	50.8	51.4	52.8	44.3	49.2	45.9
Coal Consumption (lb/kWh)	0.65	0.67	0.66	0.80	1.07	0.66	0.66	0.69	0.69	0.62	0.62	0.60	0.71	0.64	0.69
Plant Capital Cost ($ million)	2090	1239	715	2060	2107	2092	2091	2018	2016	2164	2152	2173	2052	2116	2059
Plant Capital Cost ($/kWe)	1102	1049	1193	1101	1128	1108	1107	1415	1012	1085	1067	1048	1181	1096	1144
Cost of Electricity, Capacity Factor = 0.65															
Capital (mills/kWh)	34.9	33.2	37.7	34.8	35.7	35.0	35.0	44.7	32.0	34.3	33.7	33.1	37.3	34.7	36.2
Fuel (mills/kWh)	6.2	6.3	6.3	6.1	6.3	6.3	6.3	6.6	8.8	5.9	5.9	5.7	6.8	6.1	6.6
Maintenance and operating (mills/kWh)	2.8	2.9	3.2	2.9	2.9	2.8	2.8	3.6	2.3	2.9	2.7	2.6	3.0	2.7	2.9
Total (mills/kWh)	43.9	42.4	47.3	43.8	44.9	44.1	44.1	55.0	43.1	43.1	42.3	41.4	47.1	43.5	45.6
Sensitivity															
Capacity factor = 0.50 (total mills/kWh)	55.1	53.2	59.6	55.2	56.5	55.4	55.4	69.5	53.4	54.2	53.2	52.1	59.2	54.7	57.4
Capacity factor = 0.80 (total mills/kWh)	36.8	35.6	39.6	36.8	37.7	37.0	37.0	45.9	36.6	36.1	35.4	34.7	39.6	36.5	38.3
Capital Δ = 20 percent (Δ mills/kWh)	7.0	6.6	7.5	7.0	7.1	7.0	7.0	8.9	6.4	6.9	6.7	6.6	7.5	6.9	7.2
Fuel Δ = 20 percent (Δ mills/kWh)	1.2	1.3	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.1	1.4	1.2	1.3
Estimated Time for Construction (years)	7	6	6	7	7	7	7	7	7	7	7	7	7	7	7
Estimated Date of 1st Commercial Service (year)	1997	1997	1997	1997	1997	1997	1997	1997	1993	1993	1999	1999	1995	1997	1997

*Base case 1.
**Base case 1 configuration, reduced power output.
† Base case 2.

DCT = Dry cooling tower
HT = High temperature
Ill. = Illinois

Mont = Montana
N. D. = North Dakota
WCT = Wet cooling tower

Table 3.3-5 (cont'd)

Parameters	orage HT Air Preheater								Common Elements: SRC Fuel, Avco Combustor, and Refractory Storage HT Air Preheater						
	16	17	18	19	20	21	22	23	24+	25	26	27	28	29	30
Power Output (MWe)	1701	1895	1895	1883	1901	1870	1999	1889	1932	1754	2005	1931	1937	1942	1919
Combustion															
Coal	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Oxidizer	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Combustor slag rejection (percent)	→	→	→	→	→	→	→	→	0 →	→	→	→	→	→	→
Preheater															
Firing	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Oxidizer temperature (°F)	→	→	→	→	→	→	→	→	3100	2500	3600	3100 →	→	→	→
MHD Generator															
Type	→	→	→	Diagonal Faraday		→	→	→	Faraday →	→	→	→	→	→	→
Inlet pressure (atm)	→	→	→	→	→	→	→	→	15	9	20	15 →	→	→	→
Average magnetic field (T)	→	6	7	5 →	→	→	→	→	6 →	→	→	5	7	6 →	→
Potassium seed (percent)	→	→	→	→	0.5	1.5	1.0 →	→	→	→	→	→	→	0.5	1.5
Electrical load parameter	0.6	0.8 →	→	→	→	→	→	→	→	→	→	→	→	→	→
Heat Exchangers															
Gas (Δp/p)	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Air (Δp/p)	→	→	→	→	→	→	→	→	→	→	→	→	→	→	→
Steam Bottoming Cycle															
Turbine inlet temperature (°F)	→	→	→	→	→	→	--	1000/1000 →	→	→	→	→	→	→	→
Turbine inlet pressure (psi)	→	→	→	→	→	→	--	3500 →	→	→	→	→	→	→	→
Maximum feedwater temperature (°F)	→	→	→	→	→	→	--	232 →	→	→	→	→	→	→	→
Air Bottoming Cycle															
Turbine inlet temperature (°F)	--	--	--	--	--	--	2400	--	--	--	--	--	--	--	--
Pressure ratio	--	--	--	--	--	--	10	--	--	--	--	--	--	--	--
Heat Rejection (in. Hg)	→	→	→	→	→	→	→	DCT 1.8	WCT 1.5 →	→	→	→	→	→	→
Actual Powerplant Output (MWe)	1701	1895	1895	1883	1901	1870	1999	1889	1932	1754	2005	1931	1937	1942	1919
Thermodynamic Efficiency (percent)	47.6	52.8	52.8	52.5	53.0	52.1	55.5	52.8	58.2	53.0	60.4	58.2	58.4	58.6	57.9
Powerplant Efficiency (percent)	44.2	49.2	49.2	48.9	50.4	47.6	51.9	49.1	56.8	51.6	58.9	56.8	56.9	57.1	56.4
Overall Energy Efficiency (percent)	43.4	48.3	48.3	48.0	49.9	46.3	50.9	48.1	44.3	40.2	46.0	44.3	44.4	44.5	44.0
Coal Consumption (lb/kWh)	0.73	0.65	0.65	0.66	0.63	0.68	0.62	0.66	0.71	0.79	0.69	0.71	0.71	0.71	0.72
Plant Capital Cost ($ million)	2036	2028	2024	2089	2105	2089	2304	2153	1866	1783	1883	1870	1852	1873	1859
Plant Capital Cost ($/kWe)	1197	1069	1067	1109	1107	1117	1152	1140	965	1016	939	968	956	964	968
Cost of Electricity, Capacity Factor = 0.65															
Capital (mills/kWh)	37.8	33.8	33.8	35.1	35.0	35.3	36.4	36.0	30.5	32.1	29.7	30.6	30.2	30.5	30.6
Fuel (mills/kWh)	7.0	6.2	6.2	6.3	5.9	6.6	5.9	6.3	10.8	11.9	10.4	10.8	10.8	10.8	10.9
Maintenance and operating (mills/kWh)	3.1	2.8	2.8	2.8	2.7	2.8	3.2	2.8	2.8	3.0	3.0	2.8	2.8	2.8	2.8
Total (mills/kWh)	47.9	42.8	42.7	44.1	43.7	44.7	45.6	45.1	44.1	47.0	43.1	44.2	43.8	44.0	44.3
Sensitivity															
Capacity factor = 0.50 (total mills/kWh)	60.2	53.8	53.7	55.5	55.0	56.1	57.5	56.7	54.1	57.6	52.9	54.3	53.7	54.0	54.4
Capacity factor = 0.80 (total mills/kWh)	40.2	36.0	35.9	37.0	36.6	37.6	38.1	37.8	37.9	40.4	37.0	38.0	37.6	37.8	38.1
Capital Δ = 20 percent (Δ mills/kWh)	7.6	6.8	6.8	7.0	7.0	7.1	7.3	7.2	6.1	6.4	5.9	6.1	6.0	6.1	6.1
Fuel Δ = 20 percent (Δ mills/kWh)	1.4	1.2	1.2	1.3	1.2	1.3	1.2	1.3	2.2	2.4	2.1	2.2	2.2	2.2	2.2
Estimated Time for Construction (years)	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Estimated Date of 1st Commercial Service (year)	1997	1997	1997	1997	1997	1997	1999	1997	1999	1995	2003	1999	1999	1999	1999

additional investigations of efficiency changes due to variations in one parameter, the moisture content of the coal, Tables 3.3-6, 3.3-7 and 3.3-8. Attempts to model the effects of parameter changes have been made for sulfur content of coal, Figure 3.3-5, and for channel wall temperature and pressures, Figures 3.3-6 and 3.3-7.

Some crude initial models of OCMHD efficiencies are shown in Figures 3.3-8 and 3.3-9.

Table 3.3-6 Energy Balance for 2000 MWt MHD Power Plant Operating on Eastern and Western Coal with Thermal Drying (Bergman, Bienstock, 1976)

	Pittsburgh Seam	**Rosebud Seam**		
	2	2	10	27.4
Moisture Level (wt. H_2O)x100/(wt. dry coal)				
Gross MHD Channel Power, MWe	634.54	601.12	581.96	532.15
Gross Steam Plant Power, MWe	583.31	593.50	592.80	595.25
Compressor Power, MWe	171.17	172.23	172.23	172.23
Plant Auxiliaries and Electrical Losses, MWe	43.82	43.60	43.19	42.32
Net Power, MWe	1002.86	978.79	959.34	912.85
Drying Energy, MWt 1/	0	93.0	66.1	0
Efficiency, %	50.14	46.74	46.43	45.64

1/ Drying energy is supplied by combustion of an auxillary fuel in the dryer.

Table 3.3-7 Energy Balance for 2000 MWt MHD Power Plant Operating on Eastern and Western Coal with Steam Drying (Bergman, Bienstock, 1976)

	Pittsburgh Seam	**Rosebud Seam**		
Moisture (wt H_2O) x 100/ (wt dry coal)	2	2	10	27.4
Gross MHD Channel Power, MWe	634.54	601.12	581.96	532.15
Gross Steam Plant Power, MWe	583.31	585.47	587.10	595.25
Compressor Power, MWe	171.17	172.23	172.23	172.23
Plant Auxiliaries and Electrical Losses, MWe	43.82	43.26	42.94	42.32
Net Power, MWe	1002.86	971.10	953.89	912.85
Drying Energy, 1/ MWt	0	33.8	24.0	0
Efficiency, %	50.14	48.56	47.69	45.64

1/ Drying energy comes from waste steam deposited in steam bottoming plant from MHD topping cycle.

Table 3.3-8 Energy Efficiency Effects of Various Systems Parameters (Annen, Eustis, 1977)

	Illinois #6 Coal						Montana Rosebud Coal					
	Separate Flow Air Turbine		Separate Flow Gas Turbine		Single Flow Gas Turbine		Separate Flow Air Turbine		Separate Flow Gas Turbine		Single Flow Gas Turbine	
Air Preheat Temp.	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K	2000°K	1800°K
Net Power from MHD cycle (MHD PWR-compressor power), MW	636.7	544.5	599.8	513.8	707.9	599.6	648.3	554.7	628.8	541.9	734.0	619.1
Net Power from Air/Gas Turbine, MW	269.9	319.6	297.7	343.4			271.6	321.6	284.5	335.2		
Net Power from Bottoming Cycle, MW	130.2	143.6	134.1	142.8	327.8	383.0	119.2	133.3	116.8	128.8	313.5	368.7
Total Power, MW	1036.8	1007.7	1031.6	1000.0	1035.7	982.6	1039.1	1009.6	1030.1	1005.9	1047.5	987.8
Thermal Efficiency (based on lower heating value) %	51.8	50.4	51.6	50.0	51.8	49.1	52.0	50.5	51.5	50.3	52.4	49.4
Bottoming Cycle and Intercooler Heat Rejection (proportional to cooling water requirement) MW	384.4	424.0	400.6	424.9	540.1	631.3	352.0	391.3	366.3	397.7	516.7	607.7
MHD Mass Flow Rate kg/sec	763		665		806		772		692		826.6	
Air/Gas Turbine Mass Flow Rate kg/sec	1479	1751	830	1080			1488	1762	838	1111		
MHD Combustor Flame Temp. °K	2932	2841	2963	2870	2794	2689	2934	2843	2963	2871	2805	2700
MHD Duct Length	18.2	15.2	20.1	16.7	13.4	10.3	18.8	15.4	20.2	17.2	14.5	10.7

(Thermal Input = 2000 MW)

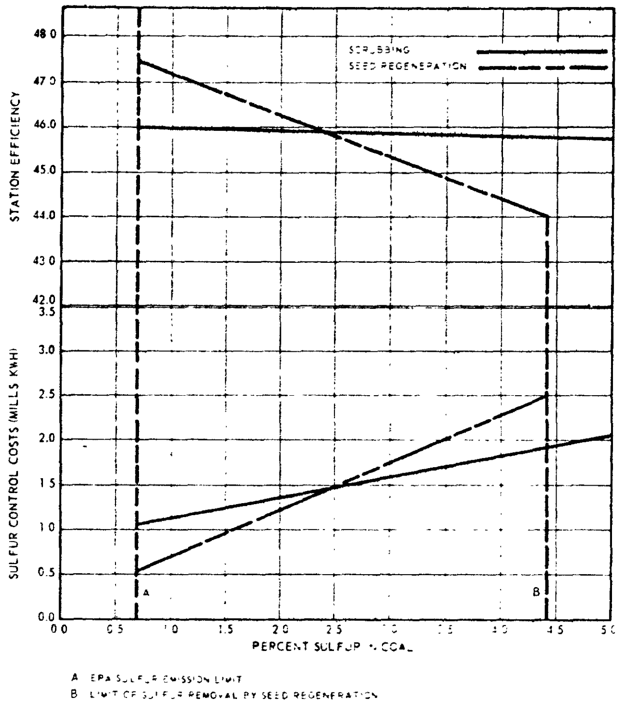


Figure 3.3-5 Baseline **Plant Station** Efficiency and Sulfur Control Costs **vs. Coal** Sulfur Content (Jackson, et al., 1976)

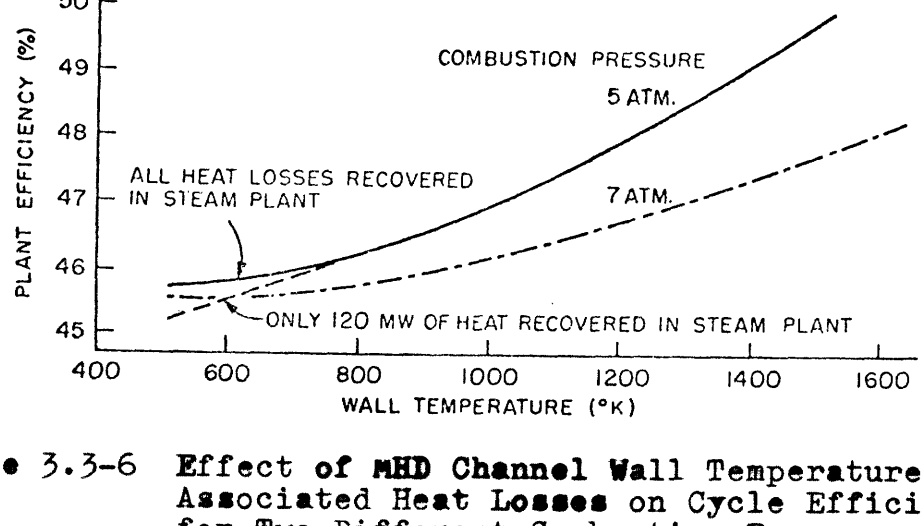


Figure 3.3-6 **Effect of MHD Channel Wall** Temperature and Associated **Heat Losses** on Cycle Efficiency for Two Different Combustion **Pressures** (REA, 1975)

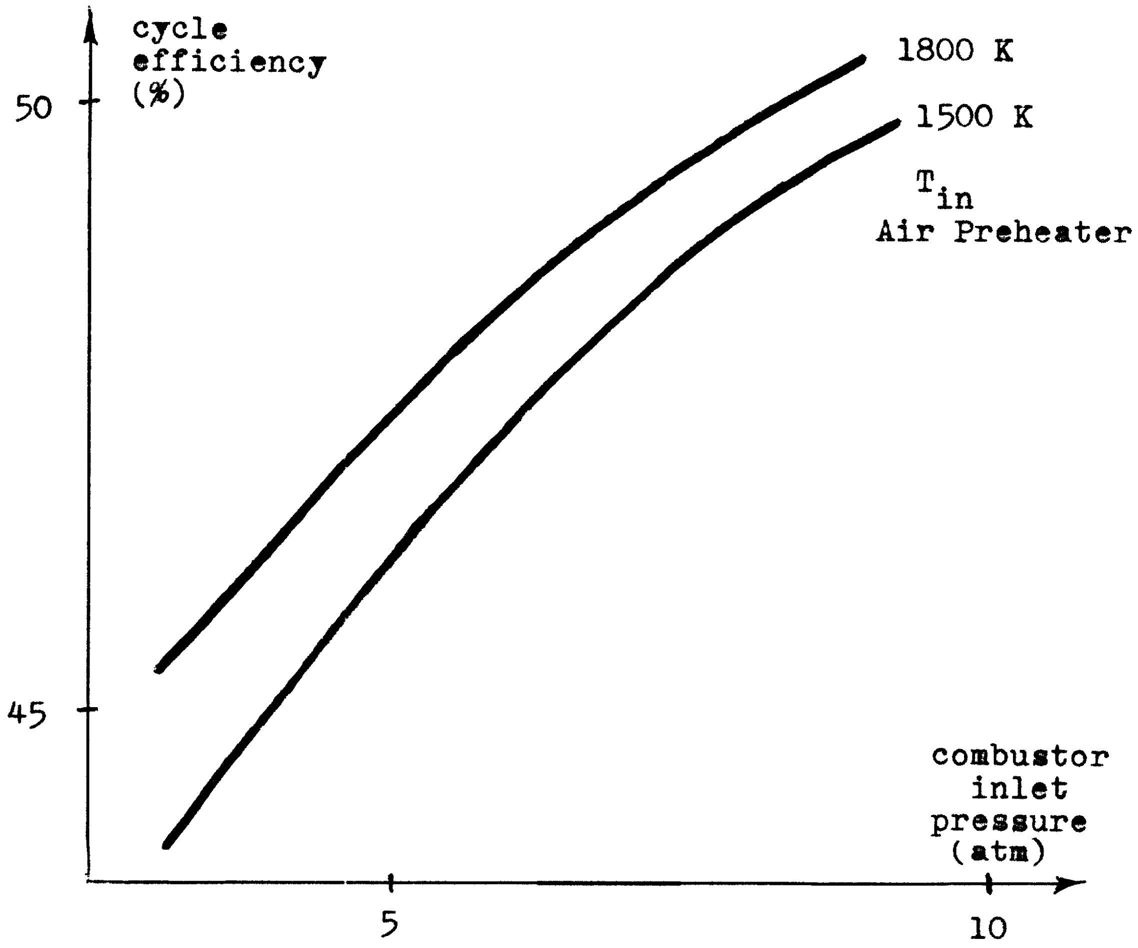


Figure 3.3-7 Open Cycle MHD Efficiency Variation with Changes in Combustor Pressure(Amend,1975)

Model of Overall Energy Efficiency of OCMHD:

$$\begin{aligned} E = {} & .415 - 1.392C + 3.977A - .00056R - .004F + .0229T - .0115G \\ & + 1.535P - 10.98M - 1.842S + 23.13L + 1.87B + .0122W \\ & + .00615W\ M - .00216W\ P - .00001W\ T + .218M\ P \\ & - .000836M\ T + .00057P\ T - 1.035(C-2.2)^2 \end{aligned}$$

E = Overall energy efficiency of OCMHD design, in percent
C = Coal type: Ill #6=1, Montana= 2, N.D.=3, SRC=4
A = Combustion oxidizer: air=1, air/O2=2
R = Combustor slag rejection in percent
F = Preheater firing: direct=1, indirect=2
T = Temperature in ^{o}F of preheated air
G = Generator type: Faraday=1, diagonal Faraday=2
P = Generator inlet pressure in atmospheres
M = Average magnetic field strength in Teslas
S = Potassium seeding in percent
L = Electrical load parameter,as fraction
B = Bottom cycle type: steam=1, air=2
W = power output of OCMHD, in megawatts

Fit to 39 parametric designs with arithmetic standard deviation equal to 0.28%
Correlation of actual to predicted values is R^2=.985

Figure 3.3-8 Simplified model fit to the energy efficiency result from GE ECAS Task 1 (Corman, et al., 1976).

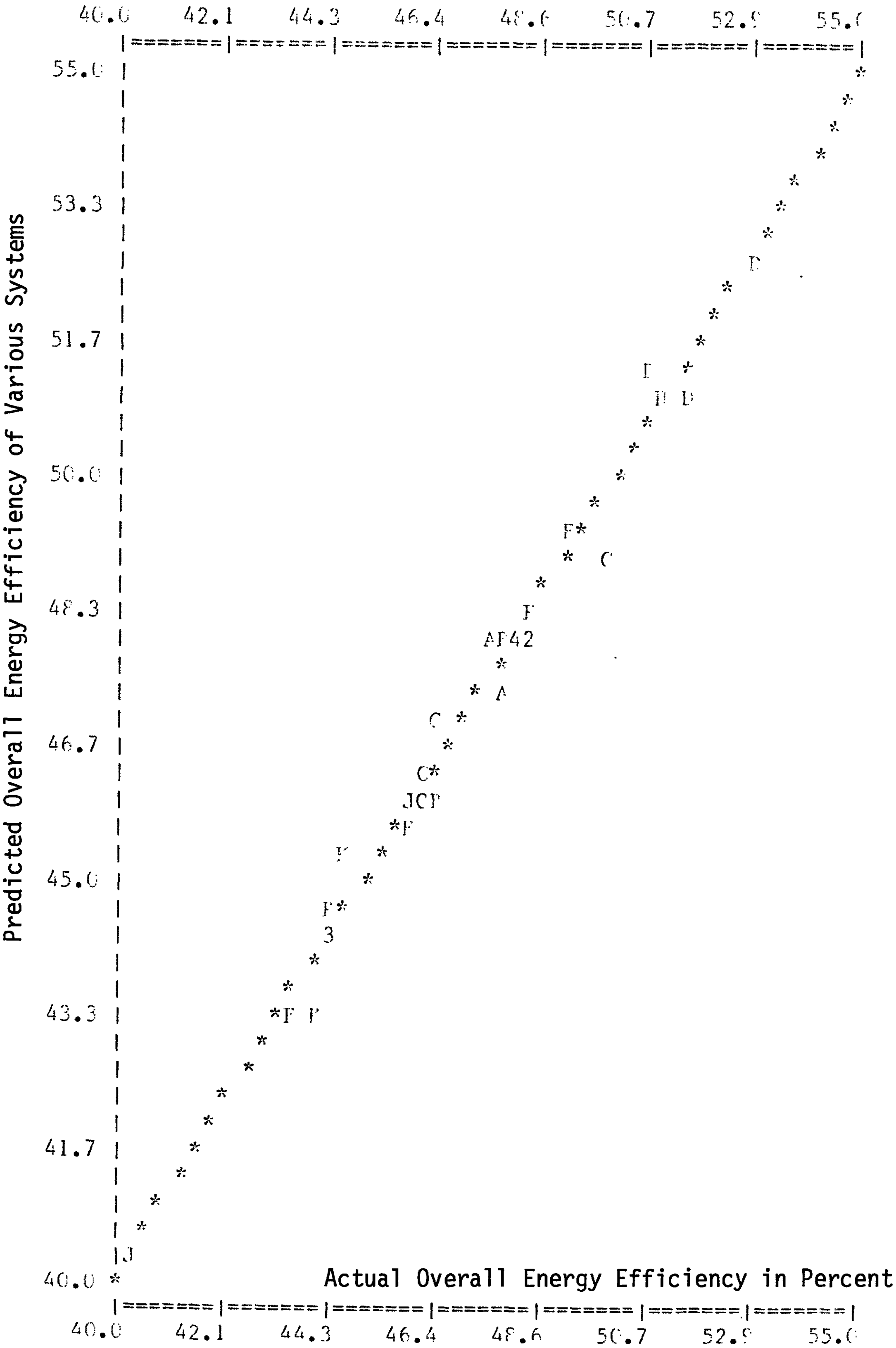


Figure 3.3-9 Scatterplot of predicted efficiencies versus those analytically derived in GE ECAS Task 1, different letters refer to different types of system configurations.

4. Environmental Assessment

The primary impetus for developing open cycle MHD power plants is the economic attractiveness. Some of this economic potential is due to the very high efficiencies of these cycles and part is due to the lack of need for scrubbers. Investigations to date indicate that there are other environmental gains possible, but data are still lacking on many key points. In particular only a few of the potential air pollution emissions have been studied whereas the list of possible pollutants from fossil-fuel facilities includes more than 602 inorganic pollutants and 491 organics. Liquid emissions are expected to be total suspended solids, oil, grease, copper, iron, other heavy metals, and thermal discharges (Penny, *et al.*, 1977). Solids will be dominated by furnace wastes, other collected solids, and sulfur. The following sections deal in more detail with the particular emissions that have been studied to date.

4.1 Air Emissions

When they come on line OCMHD power plants will have to meet either the EPA New Sources Performance Standards or updated (probably stricter) standards for air pollution from stationary coal-fired power plants, presented in Table 4.1-1. The following sections deal specifically with these emissions, and a summary of these and other environmental and economic data can be found in Appendix A.

4.1.1 Sulfur Oxides

Some projections of OCMHD sulfur oxide emissions are shown in Table 4.1.1-1. The ash holds about 2.4% of the sulfur, and high combustion efficiencies reduce sulfur emissions, see Figure 4.1.1-1, but the

TABLE 4.1-1

ENVIRONMENTAL EMISSION STANDARDS FOR SOLID-FUELED SOURCES

Pollutant	Standard (lb/MBtu)	Possible Future Standard (EPRI-predicted) (lb/MBtu)
SO_x	1.20 (as SO_2)	0.60 to 0.30 (as SO_2)
NO_x	0.70 (as NO_2)	0.40 to 0.13 (as NO_2)
Total Particulates	0.10	0.10 to 0.05
Fine Particulates (less than 3 microns)	none	0.10 to 0.02

TABLE 4.1.1.-1

ESTIMATES OF SULFUR OXIDE EMISSIONS FROM OCMHD

Reference	lb/10^6 Btu input	lb/kWh output
(General Electric, 1976) base case	1.2	.008
(General Electric, 1976) SRC	0.8	.0062
(Jackson, et al., 1976) reference	less than 1.2	-
(Shaw, Cain, 1977)	0.77 g/kWht	1.6 g/kWhe
(Penny, et al., 1977)	-	5 ppm
(Hals, Jackson, 1977) fertilizer recovery system	-	100 ppm
(Harris, Shah, 1976)	0.5	.0034
(REA, 1976)	0.045	-

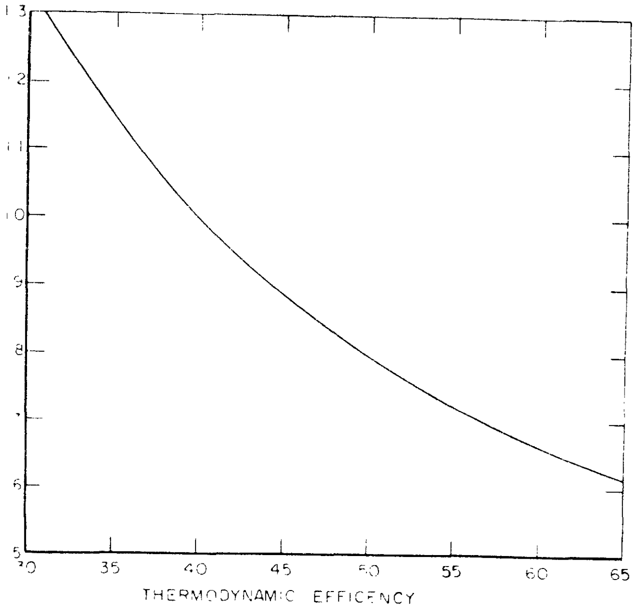


Figure 4.1.1-1 SO_2 Emissions as a Function of Power Plant Efficiency (Bienstock, et al., 1971)

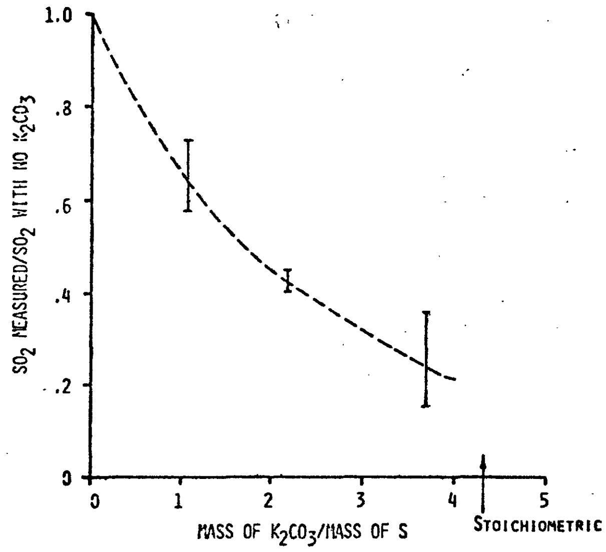


Figure 4.1.1-2 Sulfur Removal by Potassium Carbonate Addition (Dicks, et al., 1977)

overwhelmingly dominant influence on the level of these emissions is the amount of seed material used. As can be seen from Table 4.1.1-2 or from Figure 4.1.1-2 the concentration of SO_2 in the emissions can be lowered to almost any desired value, see Figure 4.1.1-3. This is a very impressive advantage of MHD cycles, however, there are fairly substantial economic and energy-efficiency penalties for high removal percentages. An interesting trade-off then presents itself requiring a choice among low-sulfur coal, beneficiated coal, high seeding levels, and post-combustion sulfur oxide removal. Expectations for commercial-sized facilities (Jackson, et al., 1976) show that the seed recovery method of sulfur oxide control is likely to be the most cost effective technique, 0.5% efficiency penalty versus 1.5% and 3.0% for flue gas desulfurization and coal cleaning (Jackson, et al., 1976), and 1.5% for nitrogen maximization (Cutting, et al., 1977).

Table 4.1.1-2 Removal of Sulfur Oxides in MHD Power Generation with K_2CO_3 as Seed (Bienstock, et al., 1971)

Wgt % of sulfur in coal: 2.2
105% of stoichiometric oxygen
$N_2/O_2 = 2$

Seed concentration				
g moles K_2CO_3 / kg coal	lb K_2CO_3 / 100 lb coal	SO_2 in combustion gas, ppm	SO_2 removal, %	$\frac{\text{Actual } SO_2 \text{ removal}}{\text{stoichiometric removal}^a} \times 100$
0	0	2735	-	-
0.37	5	1608	41.2	~~78~~ 94
0.72	10	102	96.3	~~87~~ 95
0.90	12.5	35	98.7	~~73~~ 82
1.02		5	99.8	65

[a] Based on formation of K_2SO_4.

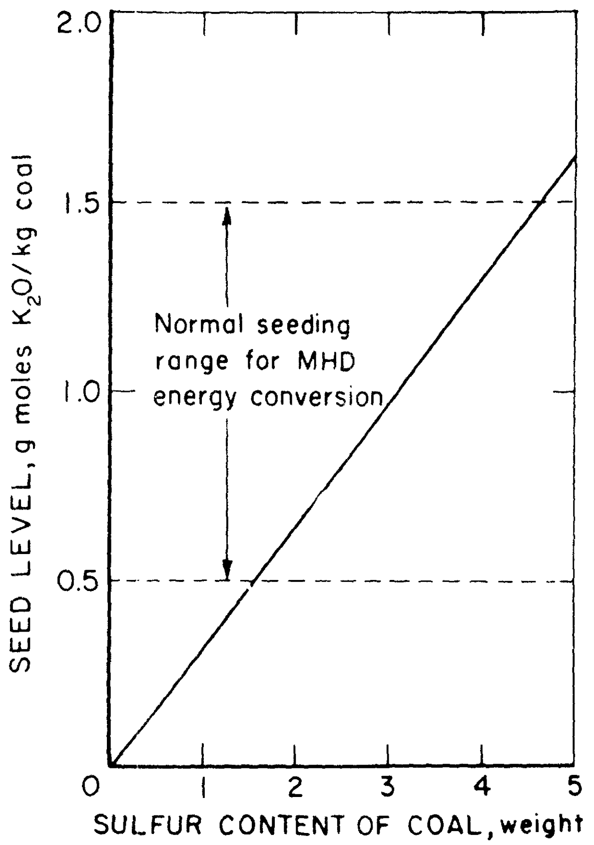


Figure 4.1.1-3 MHD Plasma Seeding Levels for Completely Eliminating Sulfur From Coal (Bienstock, et al., 1974)

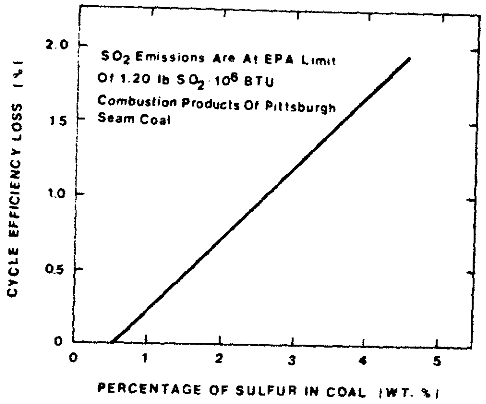


Figure 4.1.1-4 Effect of Sulfur Content on Cycle Efficiency Loss (Bergman, et al., 1977)

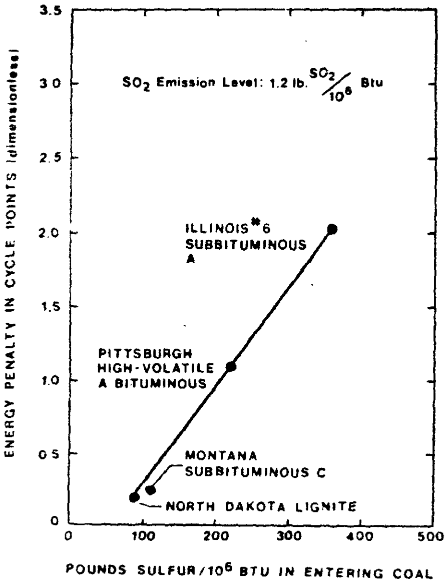


Figure 4.1.1-5 Energy Consumed in Seed Regeneration vs. Type of Coal Employed (Bergman, et al., 1977)

Once the seeding technique has been selected there are several factors that affect the economics of the process:

(1) the seed material used, almost certainly potassium carbonate, but possibly cesium carbonate or a mixture;

(2) the sulfur content of the coal, Figures 4.1.1-4 and 4.1.1.-5, and degree of control desired will affect the amount of potassium sulfate that must be regenerated, see Table 4.1.1-3;

(3) lesser control translates into lesser requirements for reducing gas and thus less equipment; and

(4) threshold standard, Figure 4.1.1-6.

From the initial sulfur in the coal to the sulfur that would come from a Claus plant, the principal reactions are:

$$S + O_2 = SO_2$$

$$2SO_2 + 2K_2CO_3 + O_2 = 2K_2SO_4 + 2CO_2$$

$$K_2SO_4 + 2(CO + H_2) = K_2S + 2(CO_2 + H_2O)$$

$$K_2S + CO_2 + H_2O = K_2CO_3 + H_2S$$

$$2H_2S + 3O_2 = 2SO_2 + 2H_2O$$

$$2H_2S + SO_2 = 3S + H_2O.$$

A previously mentioned alternative to the seeding procedure is the post-combustion removal option. In the particular design where NO is maximized to be drawn off as a fixed nitrogen source for fertilizers the nitrogen oxides convert the SO_2 to SO_3 which is easily removed as sulfuric acid (Hals, Jackson, 1969). Concentrations as low as 100 ppm are apparently possible with this operating configuration, described a little further in the following section.

Table 4.1.1-3 Required Percent of K_2SO_4 to Sulfur-free Potassium Compounds (Jackson, et al., 1976)

Coal	Wt. % Sulfur	Conversion %
Pennsylvania (Pittsburgh)	1.6	16
West. Kentucky	3.3	52
Illinois #6	3.3	57-71
Montana (Rosebud)	0.85	8-12

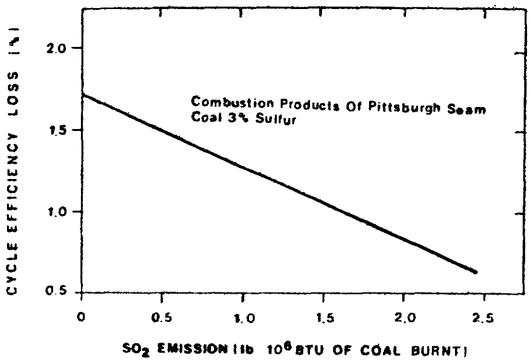


Figure 4.1.1-6 Change of Cycle Efficiency Loss with SO_2 Emmissions Level (Bergman, et al., 1977)

As has been stated before, the best method currently available for computing SO_x or other emissions from MHD's is the composite analytic models. One such model is the GPES system of the MIT Energy Laboratory which can be used to construct hypothetical systems, see Figure 4.1.1-7. Sample results are shown in Figure 4.1.1-8. There are several other such analytic models including those of Argonne National Labs, see Table 4.1.1-4. A crude parametric model of OCMHD emissions is shown in Figure 4.1.1-9.

4.1.2 Nitrogen Oxides

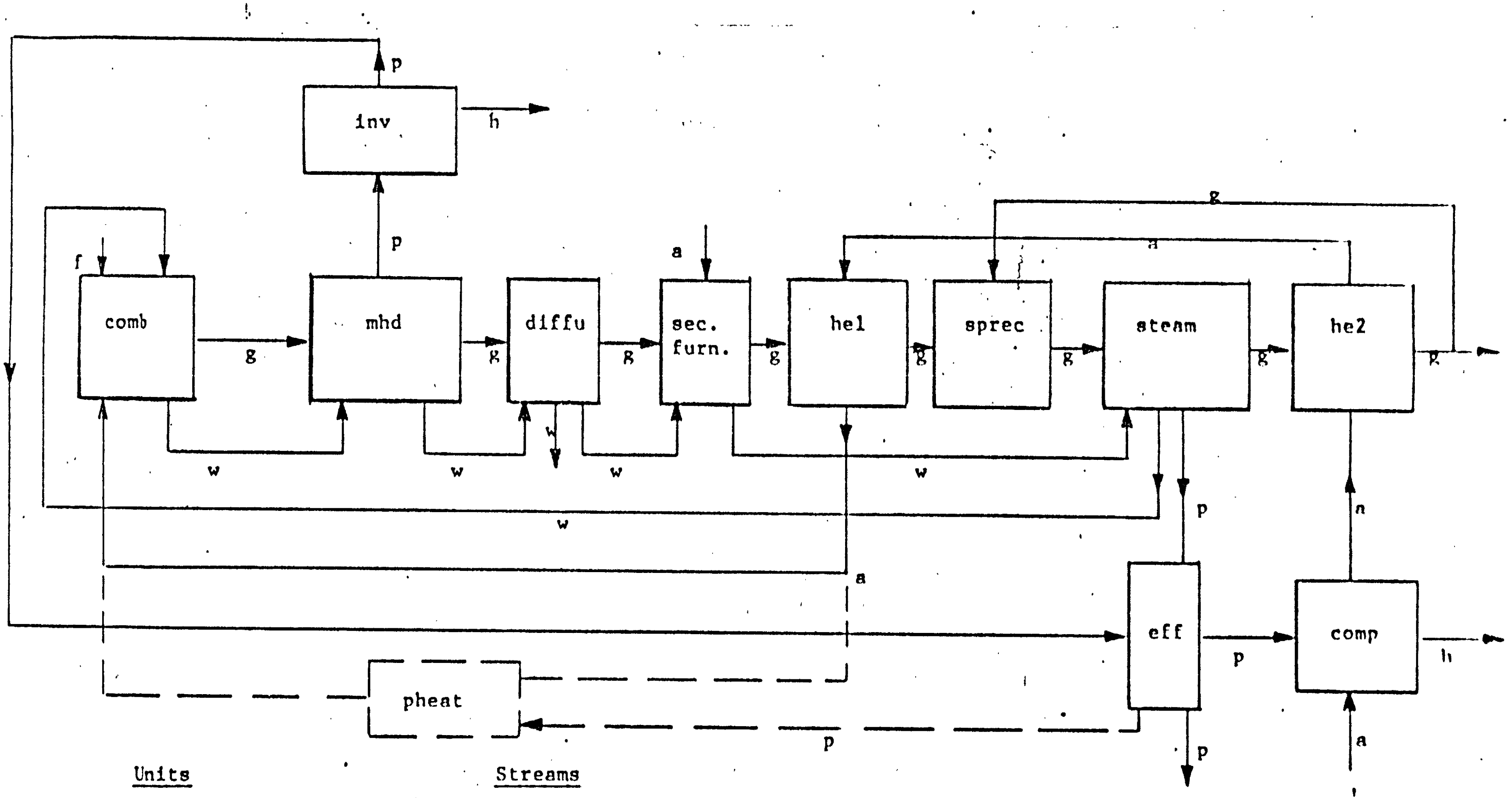
As can be seen in Table 4.1.2-1 there is a considerable variation in the estimated NO_x emissions from OCMHD. In the combustion of fossil fuels the process of nitric oxide formation is a function of temperature, see Figures 4.1.2-1 and 4.1.2-2. With the extremely high temperatures in OCMHD it might be possible to produce levels of NO_x emissions at almost 10 times those for conventional gas- and oil-fired plants, almost 10 times the current standard or 6.6 lbs $NO_2/10^6$ Btu (Beinstock, Demski, Demeter, 1971). Fortunately there are relatively easy methods of substantially reducing these NO_x emissions, namely:

(1) using two-stage combustion,

(2) maximizing NO_x production then scrubbing it out as a valuable fixed nitrogen source for fertilizers, or

(3) using pure oxygen instead of air for the combustion oxidant.

The first of these control options, two-stage combustion, not only reduces NO_x emissions but also can increase the power density by 10 to 20% by operating at 90% of stiochiometric air (Beinstock, Demski, Demeter, 1971). The measured NO_x values in a staged combustion simulation are shown in Table 4.1.2-2. Although it is not the intent of this review to deal explicitly with the various (6 to 60 reaction



Units

comb - combustor
comp - compressor
diffu - diffuser
eff - efficiency
he1,he2 - heat exchangers
inv - inverter
mhd - mhd-generator
pheat - pre-heater
sprec - seed-precipitator
sec.furn. - secondary furnace

Streams

a - air
f - fuel
g - combustion gas
h - heat
p - power
w - water

Figure 4.1.1-7 GPES Configuration **for Open** Cycle MHD Analytic Investigations

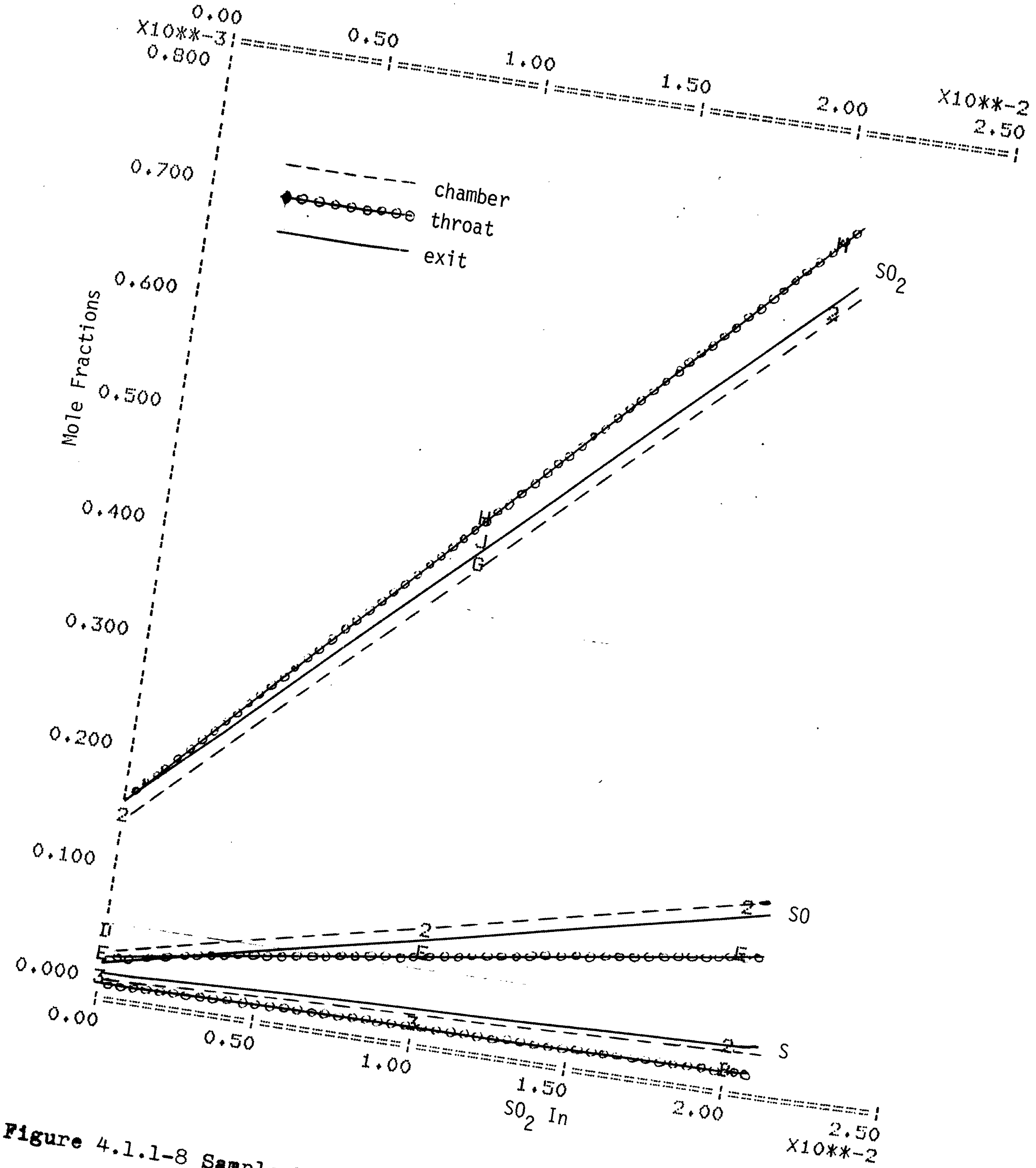


Figure 4.1.1-8 **Sample Mole Fractions of Sulfur Compounds at Different Portions in MHD Cycle as Computed by GPES System**

Table 4.1.1-4 Comparison of Equilibrium Conditions **Between** Computer Codes (Chung, Smith, 1977)

Parameter	Present Code		NASA Code
c_{pg}, average	.31	.33	Computed internally for each specie
Pressure, atm	4	4	4
Gas Temp., °R	4704	4598	4568
Average Molecular Wt.	29.5	29.6	29.5
Mass Fractions			
O_2	.020	.017	.012
CO	.035	.030	.028
CO_2	.2028	.2116	.2125
N_2	.692	.692	.674
NO	.0044	.0044	.0058
SO_2	.0021	.0021	.0020
H_2	.00021	.00021	.00018
H_2O	.0424	.0427	.0495
Ar	-	-	.011

Preheat temp., 1300°R

Stoichiometric Ratio, 1.0

Higher Heating Value, 11946 Btu/lb

Coal, Montana Rosebud with ash removed

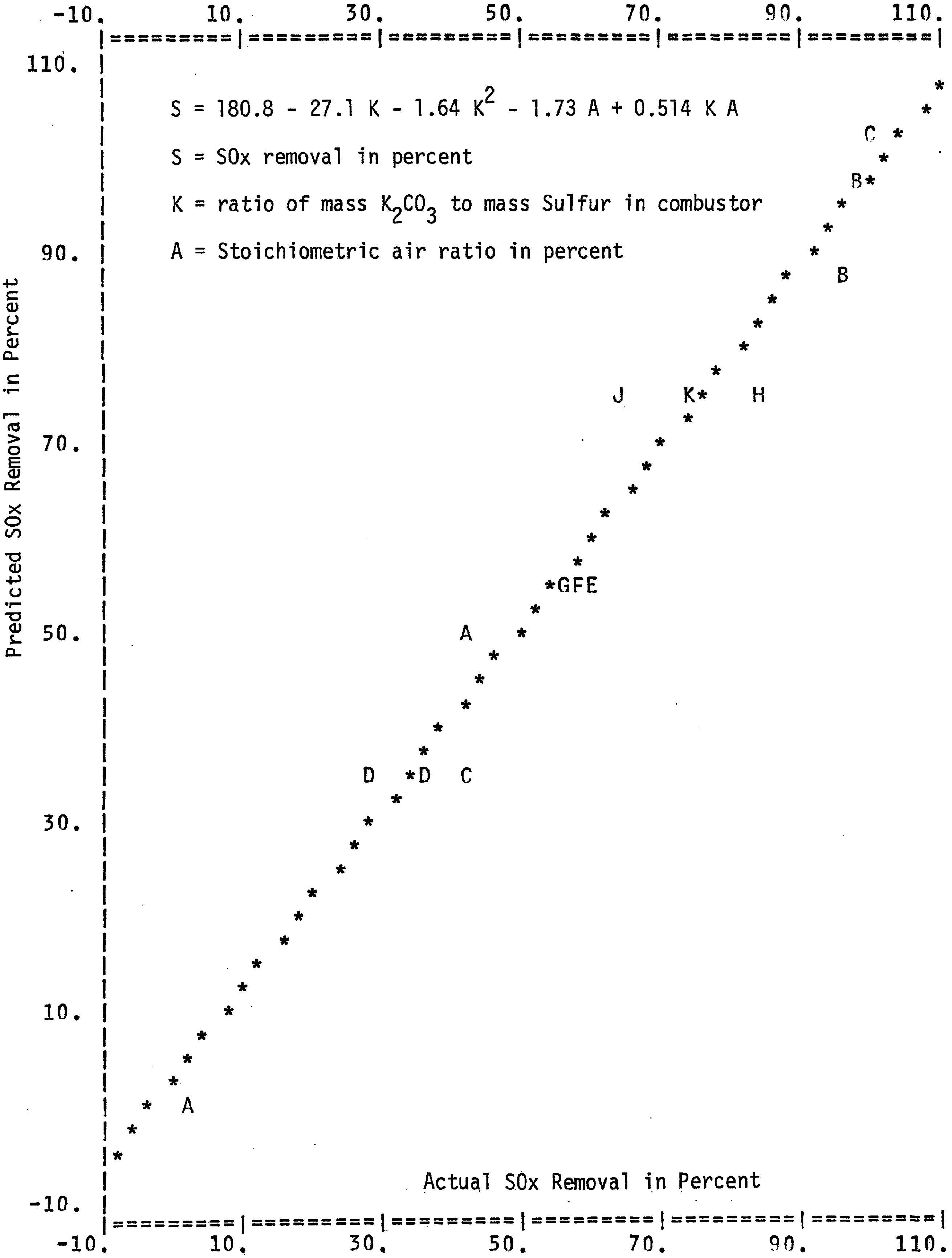


Figure 4.1.1-9 Very crude model of SOx removal based upon data from (Dicks,et al.,1977) and (Bienstock, et al.,1971).

TABLE 4.1.2-1

ESTIMATED NO_x EMISSIONS FOR OCMHD

Reference	lb/106 Btu input	ug/J	lb/kWh output	ppm
(General Electric, 1976) base case	0.3	0.129	.002	248
(General Electric, 1976) SRC	0.3	-	.0023	-
(Jackson, et al., Oct. 1976) Reference	less than 0.7	-	-	-
(Shaw, 1978)	0.71	0.304	-	585
(Folsom, 1978) Old EER set	0.72	0.309	-	595
(Folsom, 1978) New EER set	0.685	0.295	-	566
(Mori, Taira, 1972)	-	-	-	243
(Mori, Taira, 1973)	-	-	-	50
(Pepper, Eustis, Kruger, 1972)	-	-	-	283
(Penny, Bourgeois, Cain, 1977)	-	-	-	135-300
(Bienstock, et al., 1973)	-	-	-	150
(Hals, Lewis, 1972)	-	-	-	160-260
(REA, 1976)	-	-	-	155
(Shaw, Cain, 1977)	1.10g/kWht			2.3g/KWhe

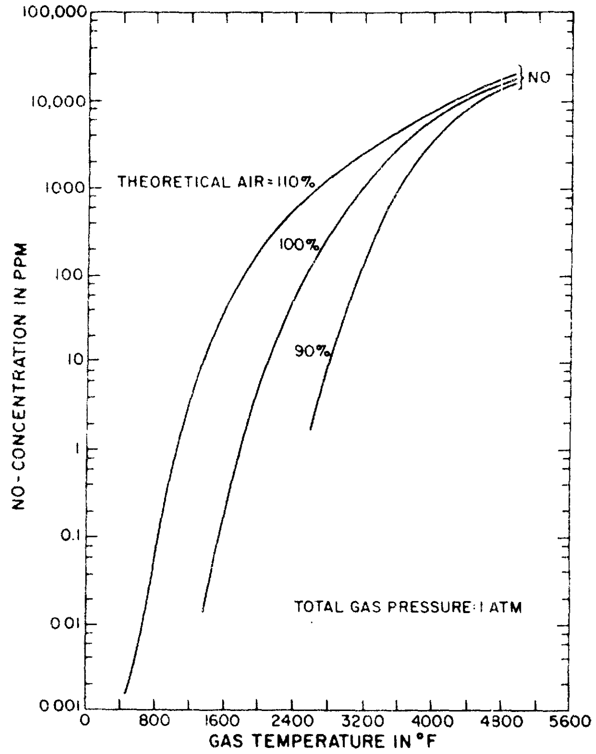


Figure 4.1.2-1 NO-Equilibrium **Concentrations** in Combustion **Gases** (Hals, Lewis, 1972)

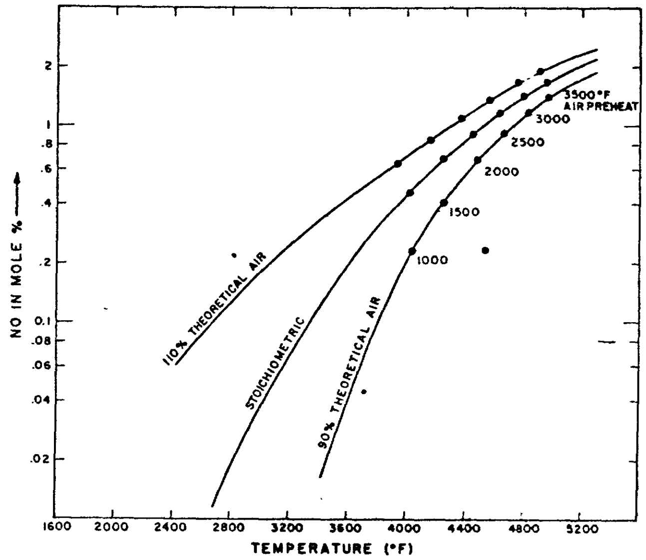


Figure 4.1.2-2 **The Variation** in Nitric Oxide (NO) **Equilibrium** Concentrations for Combustion Products From Coal with Air for Different Preheat Temperatures and Fuel-air Ratios (Hals, Jackson, 1969)

Table 4.1.2-2 NO$_x$ Formation in 2-Stage Combustion (Bienstock, et al., 1973)

First Stage			Second Stage							
Sampling at 3500-3600 °F			Gas entrance temperature, °F				Effluent concentration			
% Stoichiometric oxygen	NO$_x$, ppm	CO vol-%	2000	2150	2450	2850	% Stoichiometric	NO$_x$, ppm	$\frac{\text{lb NO}_2}{10^6\text{ Btu}}$	CO vol-%
110	4400	1.14					110	4086	3.13	0
102	2695	2.17					102	2612	2.00	0.1
101	2650	2.27					101	2225	1.70	0.4
95	880	4.30	x				106	150	0.12	0
94	782	6.61		x			103	351	0.27	0
94	727	6.90			x		105	550	0.40	0
92	543	8.11			x		107	575	0.43	0
92	496	7.53				x	107	885	0.66	0
91	496	9.95				x	104	885	0.64	0
88	356	10.40				x	104	814	0.59	0

equation) analytic models, some of this discussion is really in order to explain extrapolation of the results in Table 4.1.2-2 to large facilities. Comparisons of analytic models is therefore made at a couple of key points in their simulations.

Using principles of thermodynamic chemical equilibria and postulated kinetic mechanisms the principal concern of analytic models of NO_x emissions is the temperature-time-composition environments of the process. The tremendous amount of nitric oxide formed during combustion slowly decomposes to its elements. At some point in this process the mix is frozen and remains unchanged, and analytic models of the time-temperature history are aimed at estimating that freeze point.

In addition to a considerable amount of work at MIT there have been analytic models developed and used by:

(1) NASA-Lewis TRAN-72 (Patel, _et al_., 1976)
(2) US Bureau of Mines (Bienstock, _et al_., 1973)
(3) Avco (Hals, Lewis, 1972)
(4) Stanford (Pepper, Eustis, Kruger, 1972)
(5) Tokyo Institute of Technology (Mori, Taira, 1972)
(6) STD (Patel, _et al_., 1976)
(7) Exxon (Shaw, 1978)
(8) EER (Folsom, 1978)
(9) Argonne (Chung, Smith, 1977)

Comparisons of these models can first be made for the temperature-time profiles of their simulations, see Figures 4.1.2-3 through 4.1.2-7. Exact specification of the cooling rate is essential because high

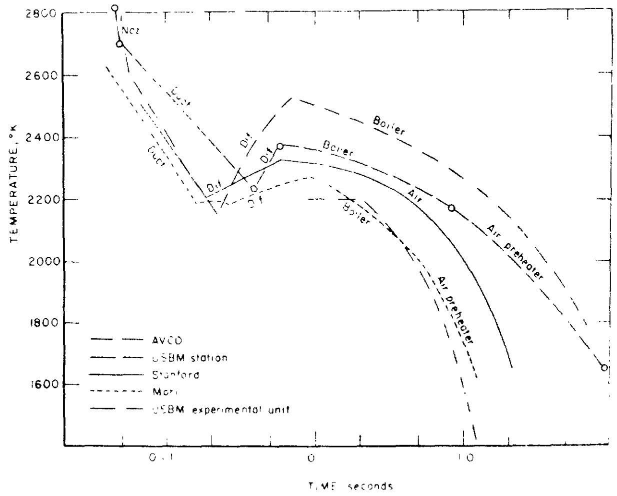


Figure 4.1.2-3 **Temperature** Profile**s** in MHD Plant**s** (Bienstock, et **al.**, 1973)

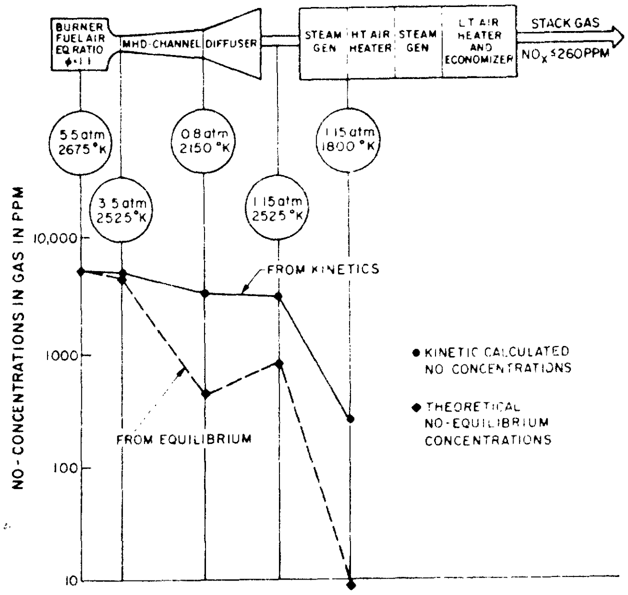


Figure 4.1.2-4 **MHD-Steam** Power Plant with Two **Stage** Combustion**s** for Control of Nitrogen Oxide**s**. 200°F **assumed** Air Preheat Temperature (**Hals**, **Lewis**, 1972)

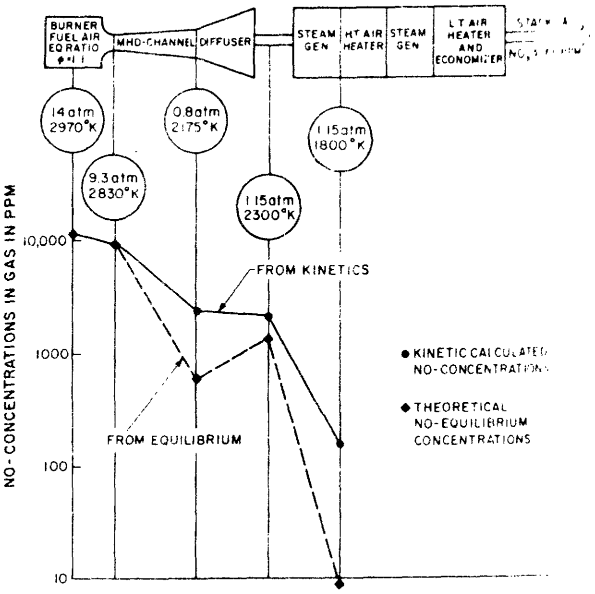


Figure 4.1.2-5 **MHD-Steam** Power Plant with **Two Stage** Combustion**s** for Control of Nitrogen Oxide**s**. 300°**F** Assumed Air Preheat **Tem**perature (**Hals**, **Lewis**, 1972)

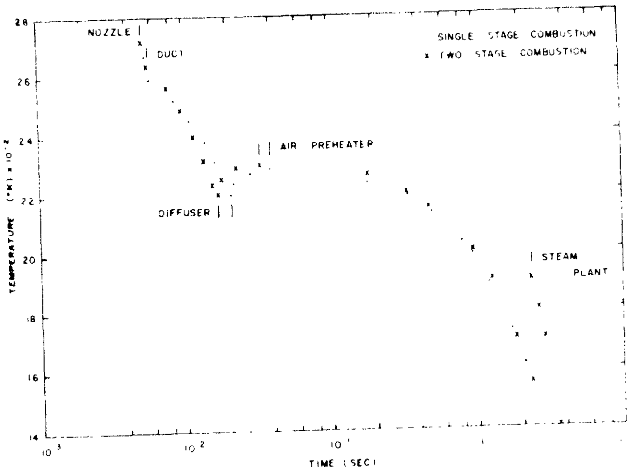


Figure 4.1.2-6 **Temperature**-Time **History** in OCMHD (Pepper, **Eustis**, Kruger, 1972)

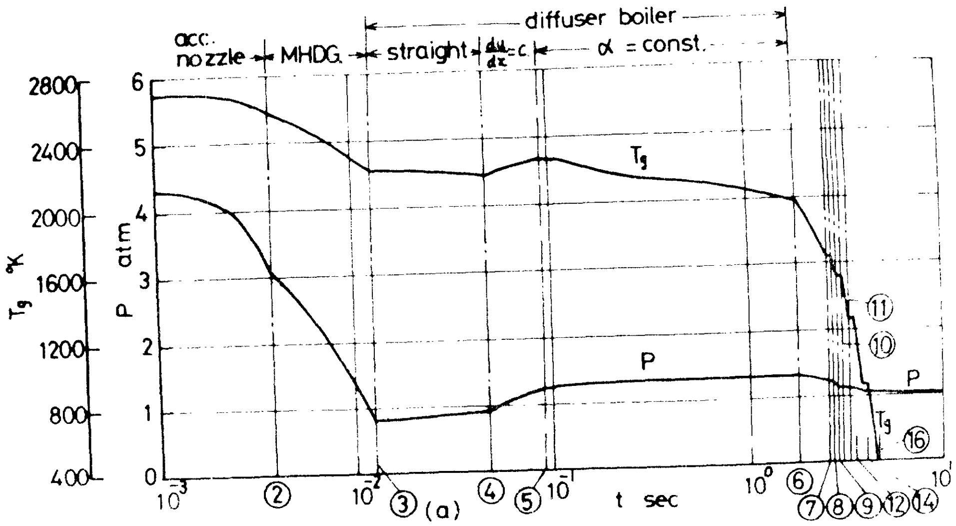


Figure 4.1.2-7 **Analytic Results** for **Temperature-Time History** (Mori, Taira, 1973)

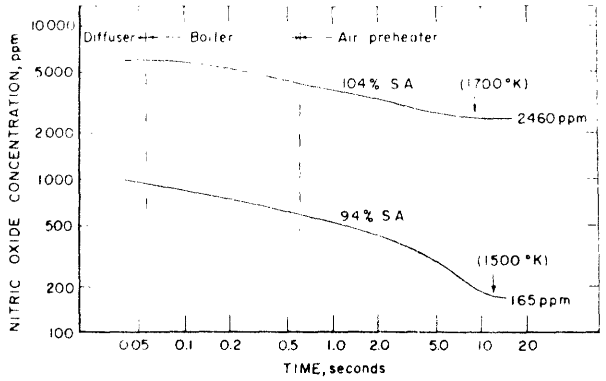


Figure 4.1.2-8 **NO$_x$ Levels in** MHD Plant (**Bienstock, et al.**, 1973)

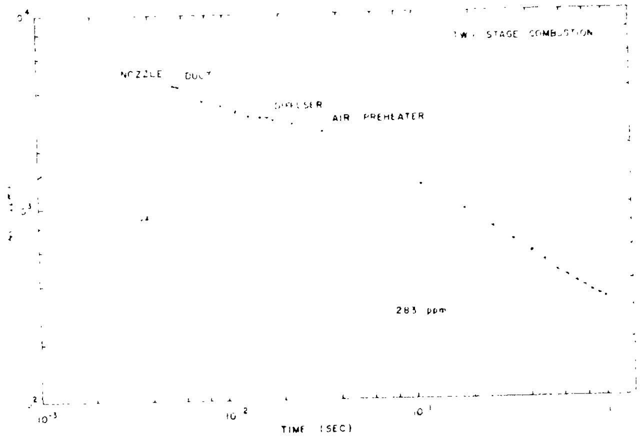


Figure 4.1.2-9 **NO-Time** History in OCMHD (**Pepper, Eustis,** Kruger, 1972)

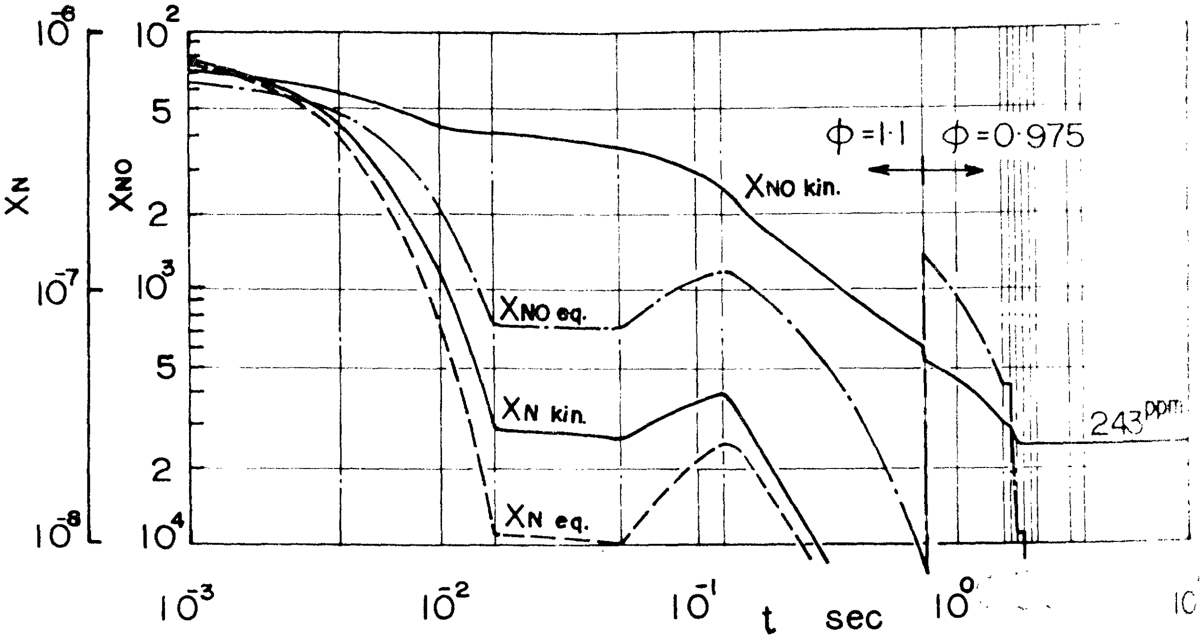


Figure 4.1.2-10 **Analytical Results for the Optimized Power Plant,** (Mori, Taira, 1973) cooling rates cause decomposition to stop, or freeze, at high NO_x concentrations. Translation of these temperature profiles into NO_x histories, including the end frozen flow point are shown in Figures 4.1.2-8 through 4.1.2-11. Gas resident times at high temperatures and substiochiometric air, SA, conditions can be seen to be very important see Figures 4.1.2-12 through 4.1.2-15. Other important factors for NO_x control are method, position, temperature, and pressure of secondary air injection, with some illuminating sensitivity analysis on this subject shown in Table 4.1.2-3.

The second NO_x control scheme is now taken up, namely, that of maximizing NO_x formation and then scrubbing it out as a saleable fertilizer additive (Hoover, et al., 1976), (Cutting, et al., 1977), see Figure 4.1.2-16. It has been determined that NO_x emissions could be as high as 4800 ppm and that a Mitsui wet process could be best for its recovery. The process has been concluded (Cutting, et al., 1977) to be not competitive, losing four points in efficiency with 10% higher capital investment and cost of electricity. The third NO_x control scheme, use of pure oxygen, also is at a substantial cost disadvantage (Hals, Lewis, 1972).

A crude parametric model of NO_x from the staged OCMHD process is developed in Figure 4.1.2-17.

4.1.3 Trace Metals

There are no experimental studies of trace metals from MHD facilities. Some very crude analytic work would be very useful. There is speculation (Harris, Shah, 1976) that all trace elements will vaporize

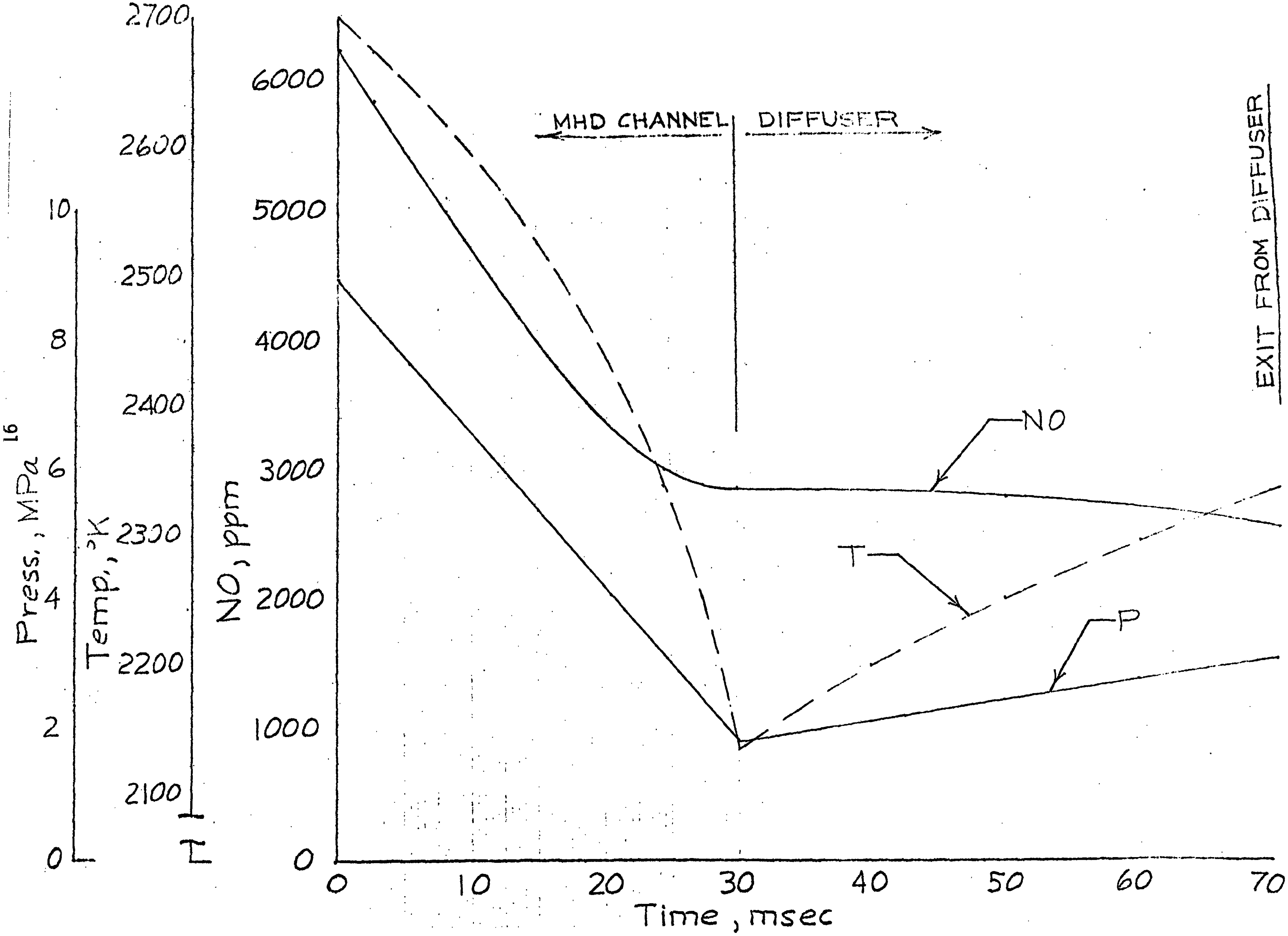
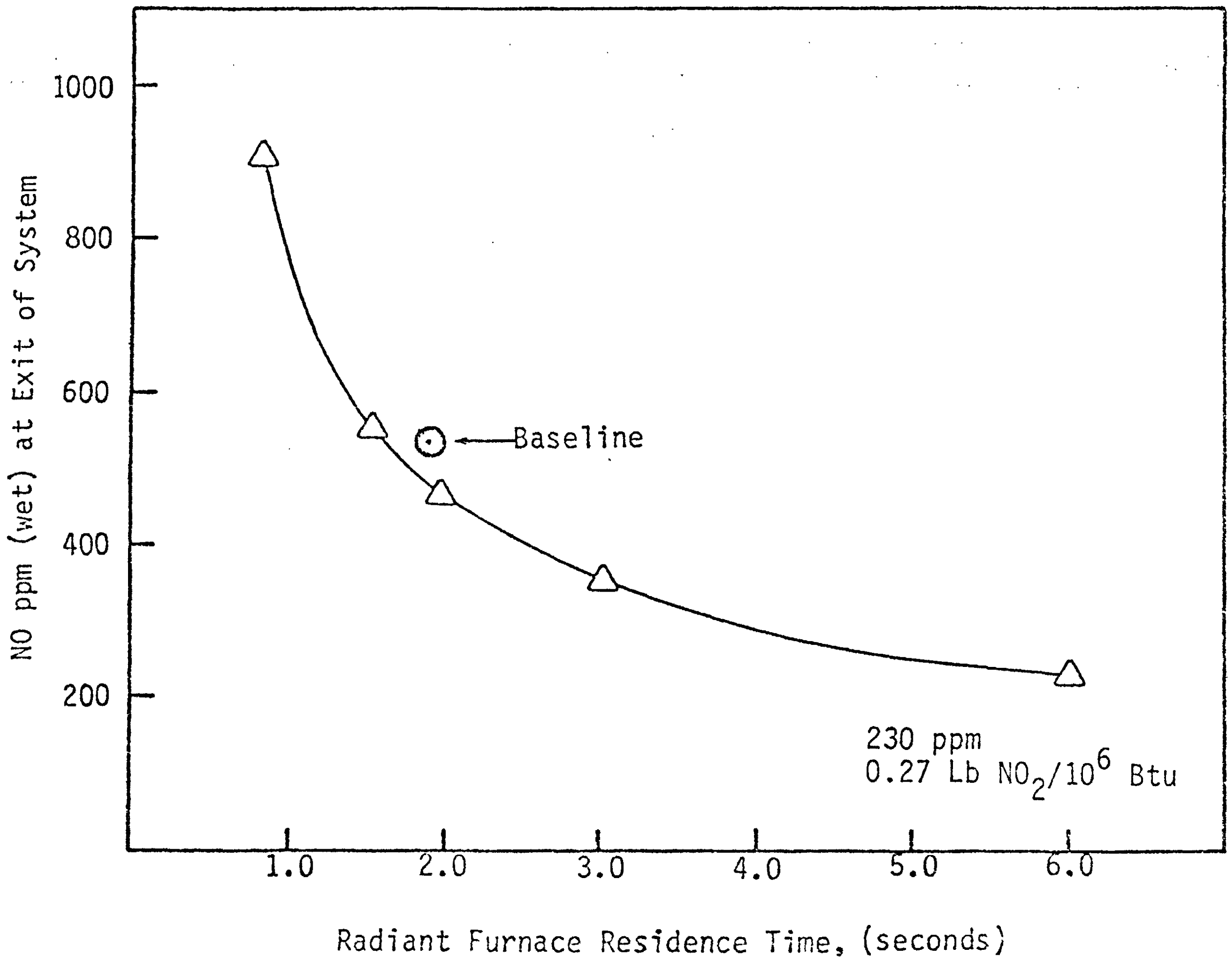


Figure 4.1.2-11 Property Variation Through Isentropic Channel - Diffuser from Other Research on this Exxon - EPA Contract



Radiant Furnace Exit Temperature = 1880°K   Exit Plenum Residence Time = 221 MSEC

Figure 4.1.2-12 **Open Cycle MHD Emission** Control Option **Radiant Furnace Modification** (**Folsom**, 1978)

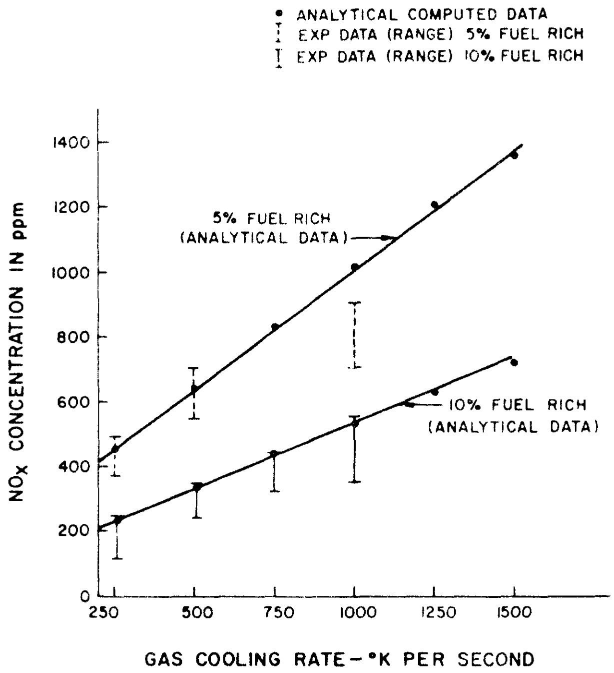


Figure 4.1.2-13 **Final** NO_x-concentrations in **MHD Exhaust** Gas According to Experimental and Analytical Data (Hals, Lewis, 1972)

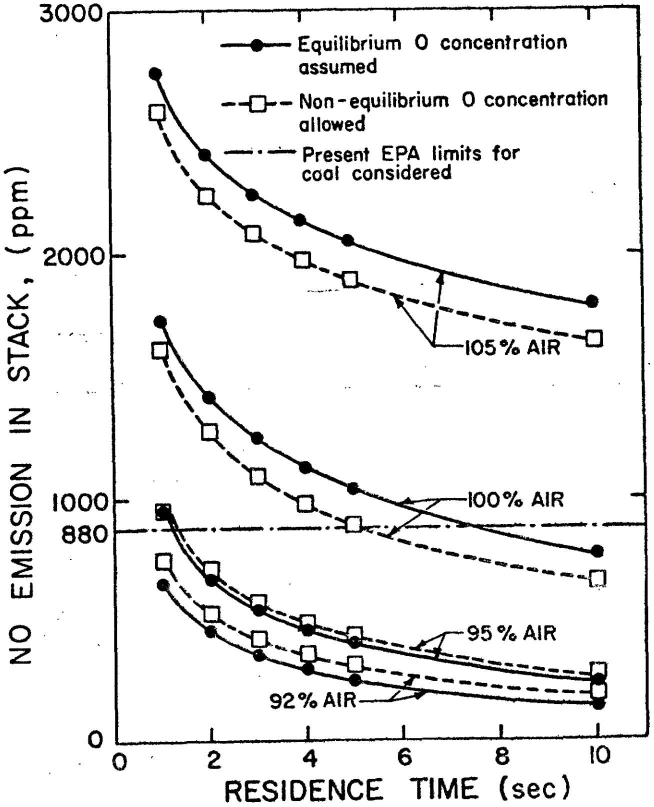


Figure 4.1.2-14 **NO Emissions** in an MHD Power **Plant as a** Function of Residence **Time for the** Radiant Boiler and Air **Preheater** Each (Jackson, et al., 1976)

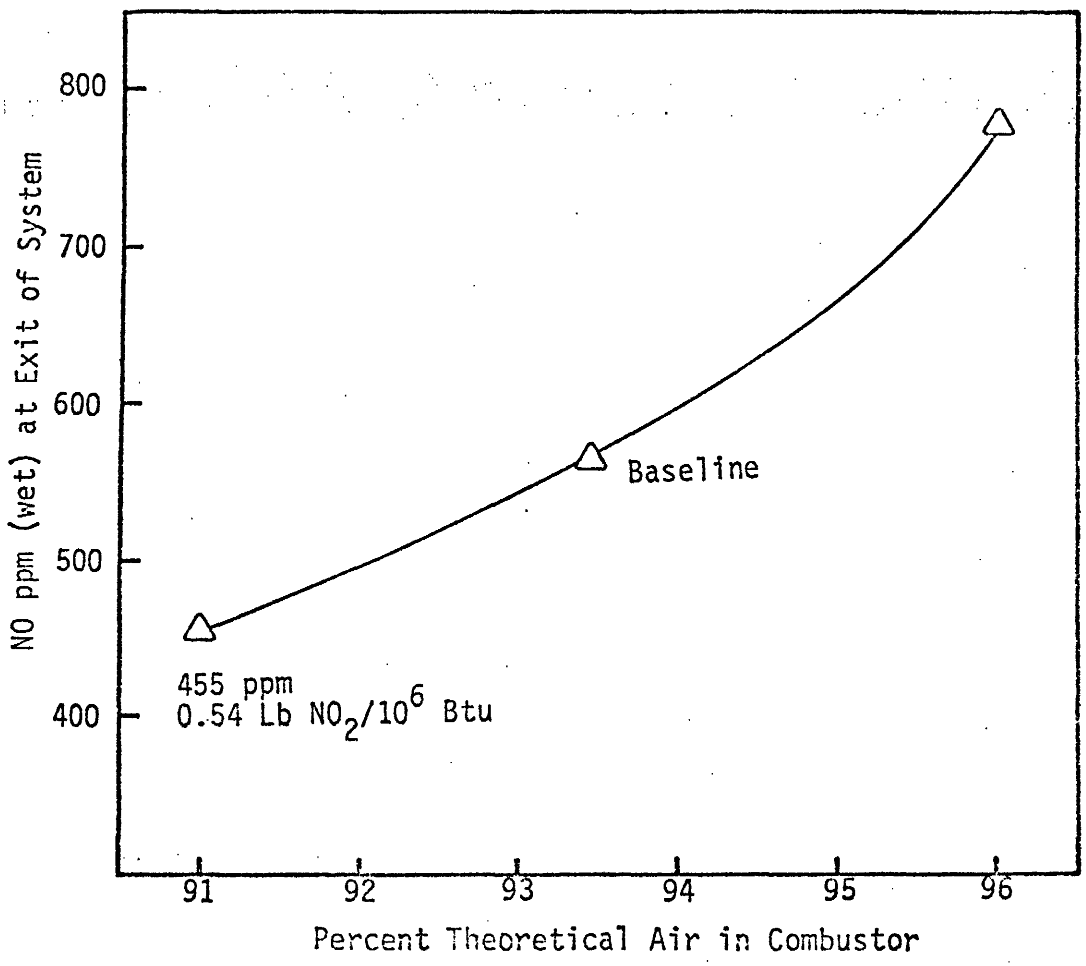


Figure 4.1.2-15 Open Cycle MHD Emission Control Option Stoichiometry Variation (Folsom, 1978)

Table 4.1.2-3 Open Cycle MHD Sensitivity of NO_x Emissions Estimates (Folsom, 1978)

SYSTEM MODIFICATION	NO CONCENTRATION AT END OF EXIT PLENUM (PPM)	PERCENT CHANGE FROM BASELINE
Baseline Configuration	566	0
MHD Channel Residence Time Reduced by Factor of Two	572 *	+ 1.06
Diffuser Residence Time Reduced by Factor of Two	568 *	+ 0.35
Linear MHD Channel Pressure Profile	566	0
Frozen Chemistry in Nozzle		
Combustor NO Concentration Reduced to Zero	565 *	- 0.18
Linear Temperature Profile in Radiant Furnace	590	+ 4.24
Radiant Furance Residence Time Increased by 0.5 sec.	516	- 8.83
Secondary Air Injection in Exit Plenum Delayed 0.5 sec.	417	-26.3
First Order Approximation of Radiant Furnace Three Dimensional Temperature Profile	677 *	+19.6

* NEW RESULT

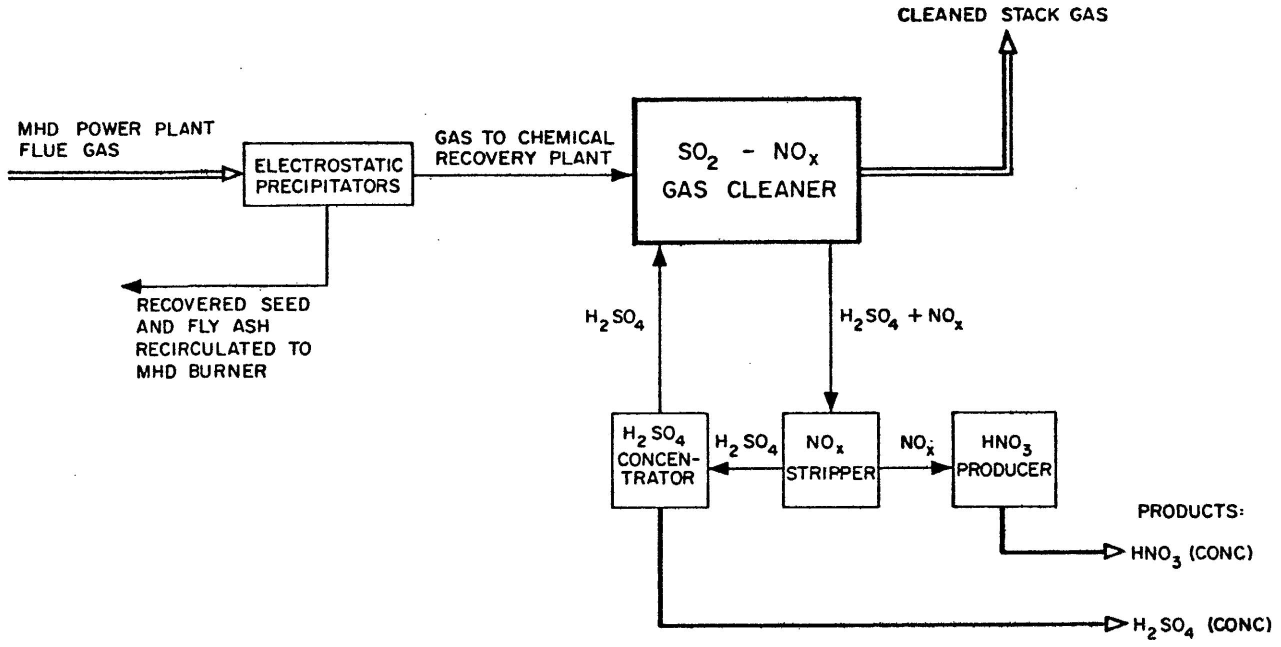


Figure 4.1.2-16 Fixed Nitrogen and Sulfur Recovery Process for Fossil Fueled MHD Power Plants (Hals, Jackson, 1969)

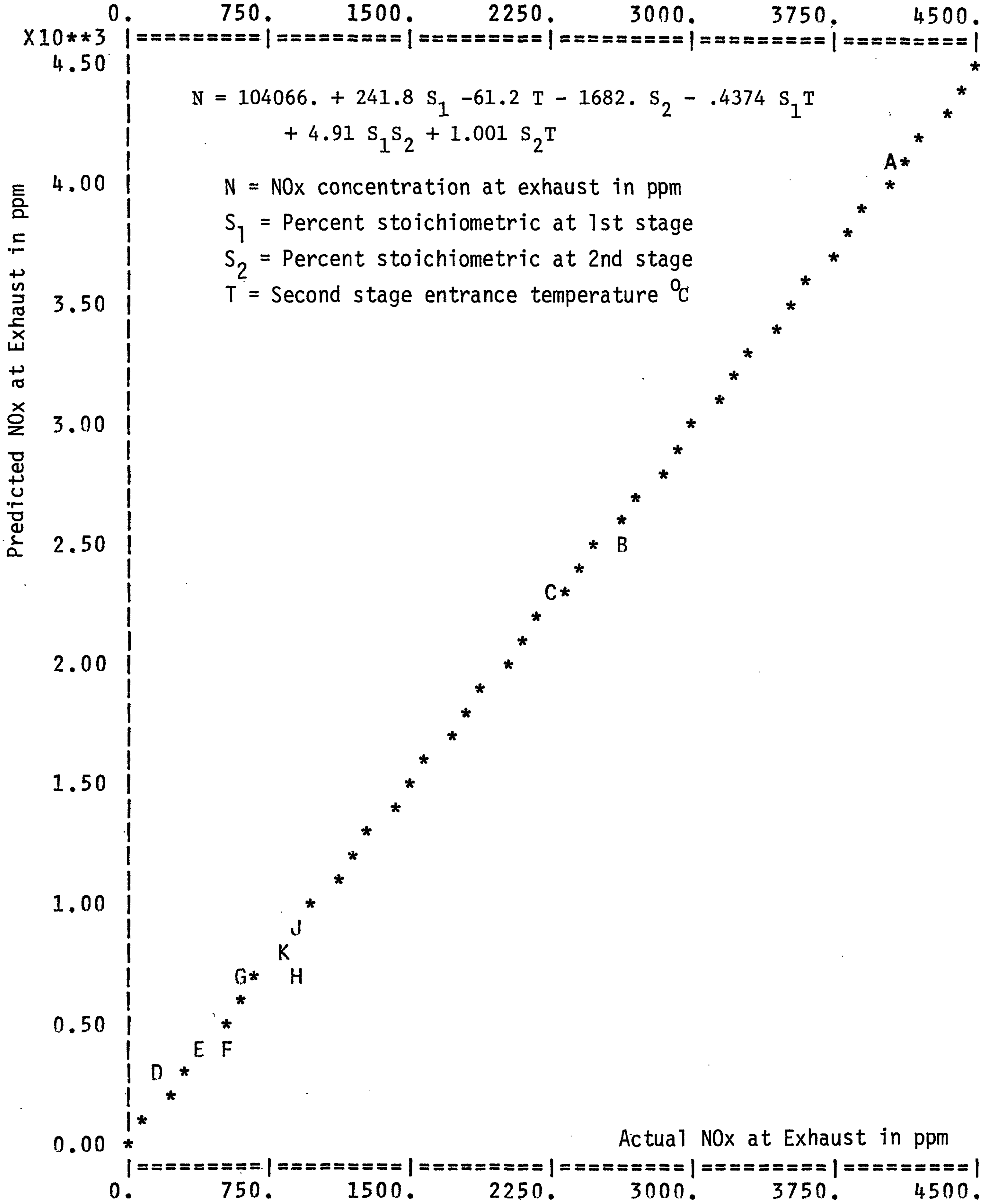


Figure 4.1.2-17 Very crude model of NOx exhaust from two-stage combustor based upon (Bienstock,et al.,1973) data.

in the combustor and form sulfates, oxides, chlorides, and fluorides and should be collected with the K_2SO_4. (Adding to this the inevitable corrosion products of the facility materials, and some refining of the seed material thus appears necessary.) In (Harris, Shah, 1976) they reason that 1% of these elements will appear in the stack gas. Considering particle size distributions, adhesions, and actions of vapors it could be that the eventual levels will be somewhere between the conventional coal combustor levels and these optimistic 99% removal levels, see Table 4.1.3-1. If any of the numbers in these fairly broad ranges are causes of concern then research ought to be directed at those sensitive areas.

4.1.4 Particulates

Estimates of particulate emissions from full-sized OCMHD are shown in Table 4.1.4-1. There are several reasons why particulates may not present a problem for OCMHD's:

(1) to be economically viable 99.5% of seed and ash particles must be captured, see Figure 4.1.4-1;

(2) mechanical cyclones, Venturi scrubbers, baghouse filters, electrostatic precipitators and other collection devices are available technologies;

(3) some pre-generation, hot-side precipitators may be necessary to avoid slag buildups and this would further reduce particulate emissions;

(4) combustion parameters that reject most of the ash as slag will pay great dividends in seed recovery, see Figure 4.1.4-2.

The materials that reach the precipitators consist of approximately 10% of the total coal ash and 50% of the K_2SO_4 formed in the flow (Harris, Shah, 1976).

TABLE 4.1.3-1

ESTIMATED TRACE METAL REMOVAL PERCENTAGES IN OCMHD

Element	Percent of Element Entering System That Is Removed Before Stack Emission
Antimony	25-99
Arsenic	60-99
Beryllium	25-99
Boron	25-99
Cadmium	35-99
Chromium	0-99
Cobalt	20-99
Iron	0-99
Lead	60-99
Manganese	0-99
Mercury	90-99
Selenium	70-99
Uranium	0-99
Vanadium	30-99
Zinc	28-99

TABLE 4.1.4-1

ESTIMATED PARTICULATE EMISSIONS FROM OCMHD

Reference	lb/10^6Btu input	lb/kWh output
(General Electric, 1976) base case	0.1	.0008
(General Electric, 1976) SRC	0.06	.00046
(Jackson, <u>et al</u>., Oct. 1976) reference	less than 0.1	-
(Shaw, Cain, 1977) total particulates	0.15 g/kWht	0.32 g/kWhe
(Shaw, Cain, 1977) fine particulates	-	-
(Harris, Shah, 1976)	0.1	.0007
(General Electric, 1976)	0.1	.0007
(REA, 1976)	0.1	-

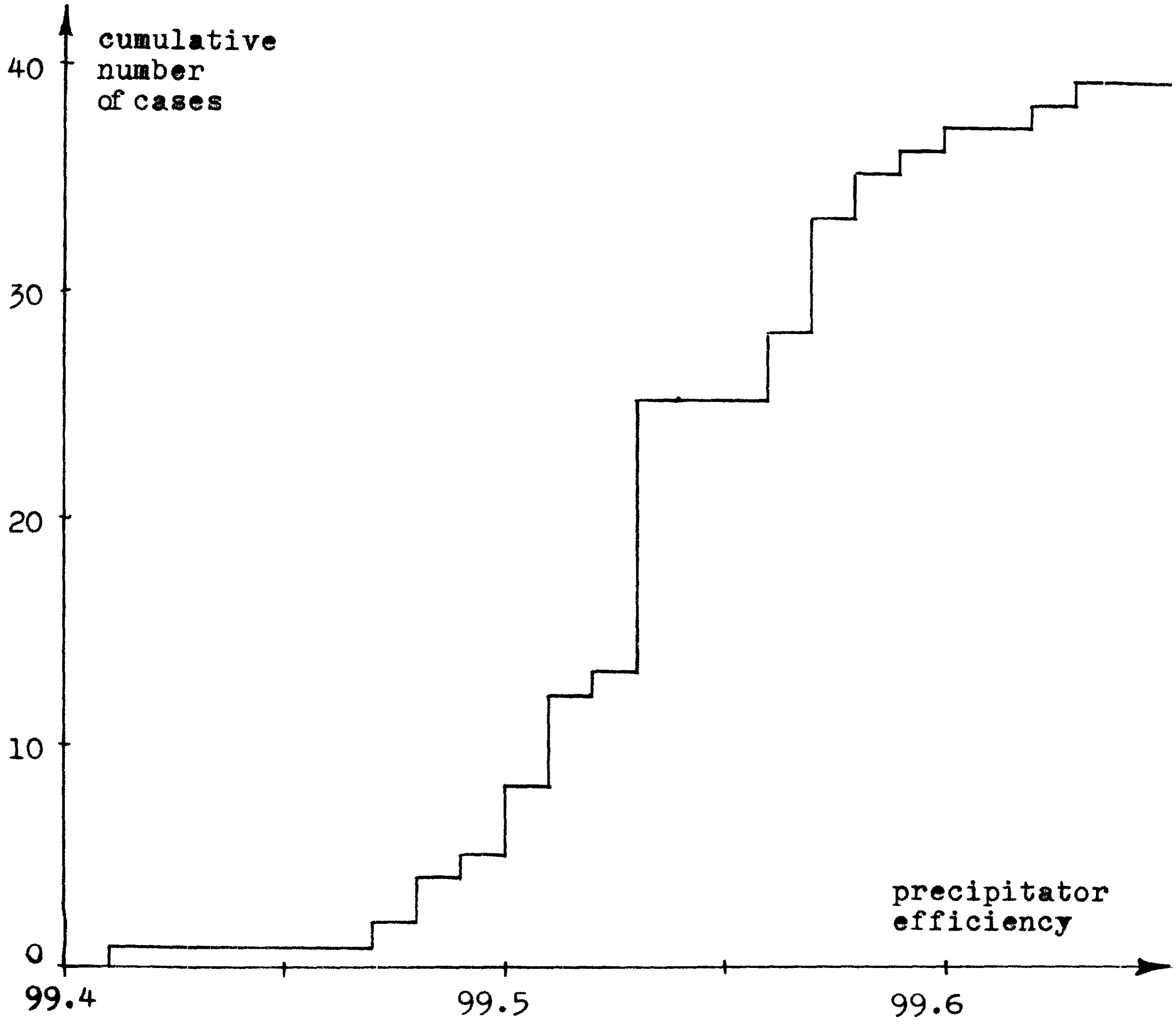


Figure 4.1.4-1 Precipitator **Efficiencies** for 39 **Cases** Investigated in **Westinghouse Phase** I ECAS **Studies** (Hoover, et al., 1976).

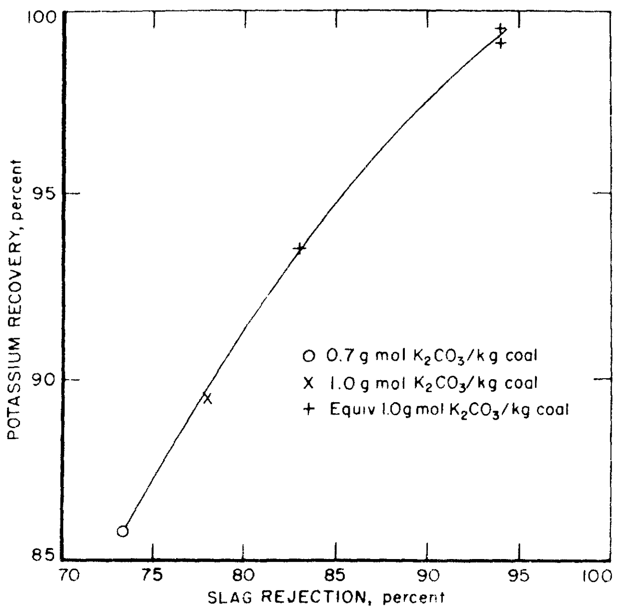


Figure 4.1.4-2 **Potassium Recovery from Fly Ash Versus Slag Rejection in Combustor** (Bienstock,et al.,1973).

A slightly different collection procedure may be required for peaking MHD's, but dust concentrations less than 0.01 grain/SCF are expected (Rosa, et al., 1970).

4.1.5 Other Air Emissions

Estimates of some of the other air emissions from OCMHD are given in Table 4.1.5-1. Thermal discharges to the air would be considerable in an MHD-Gas turbine design, but in the MHD-Steam these would be less than for conventional combustors, due to the greater expected efficiencies of MHDs. Although heat is the pollutant in air most positively correlated with excess mortalities, the heat dispersive potential of the atmosphere is considered so enormous that there have been considerations of pushing additional heat up the stack to increase the buoyancy of the MHD plume (Rosa, et al., 1970) for better disperson of the other gaseous and solid pollutants.

TABLE 4.1.5-1

OTHER AIR EMISSIONS FROM OCMHD

Heat to Air	
(General Electric, 1976) base case	606 Btu/kWh
CO	
(Shaw, Cain, 1977)	nil
(Bienstock, et al., 1971)	0
(General Electric, 1976)	0
(Hals, Lewis, 1972) with single stage	4.0%
(Hals, Lewis, 1972) with secondary stage	0.4 to 0.6%
Hydrocarbons	
(General Electric, 1976)	0
(Rosa, et al., 1970)	0

There is a considerable amount of CO created in the combustion process. The carbon monoxide concentrations exist in accordance with several equilibrium relationships including:

$$2CO_2 = 2CO + O_2$$

$$CO + H_2O = CO_2 + H_2.$$

The fraction of CO in these chambers can be as much as 10.4%, see Table 4.1.2-2. In the OCMHD design currently of interest, however, this CO is completely oxidized in the second stage, see again Table 4.1.2-2.

There is no expectation for MHD exhaust to contain any unburned fuel or hydrocarbons (Rosa, et al., 1970).

Noise from an MHD facility will be less than that from gas turbines of the same power (Rosa, et al., 1970). With the secondary heat recovery cycles attached there should be sufficient suppression of noise so that no additional attenuation will be necessary.

4.2 Emissions to Water

Table 4.2-1 shows estimates of some of the water wastes and emissions from OCMHD facilities. Figure 4.2-1 indicates the substantial reduction in thermal emissions to water from OCMHD. The principal reason for this amount can be seen to be the higher expected efficiency of these facilities. Quantifications have not been attempted of what amounts of total suspended solids, oil, grease, copper, iron and other heavy metals might be released to the water system supporting the OCMHD facility.

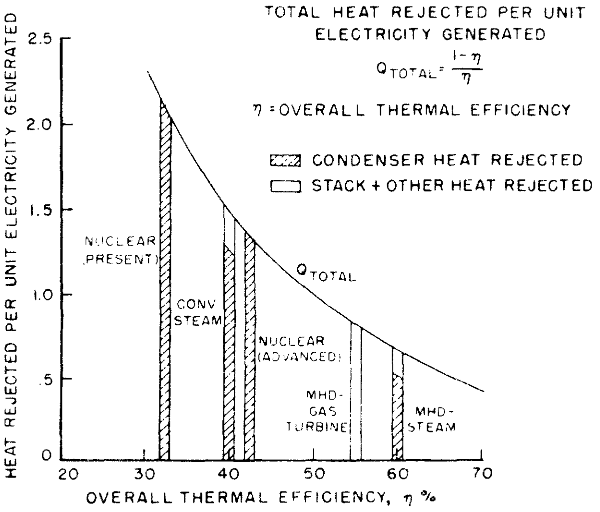


Figure 4.2-1 Effect of Power Generation Efficiency upon Thermal Pollution (Bienstock,et al.,1971).

TABLE 4.2-1

ESTIMATES OF WATER EMISSIONS FROM OCMHD

Heat to Water	
(General Electric, 1976) base case	2468 Btu/kWh
(Harris, Shah, 1976)	2377 Btu/kWh
(General Electric, 1976) SRC	2040 Btu/kWh
Waste Water	
(Shaw, Cain, 1977)	0.051 kg/kWhe
(Harris, Shah, 1976)	0.75 lb/kWh
(General Electric, 1976)	0.09 lb/kWh
Liquid Waste	
(Shaw, Cain, 1977)	24.60 g/kWht
(Shaw, Cain, 1977)	51.0 g/kWhe

4.3 Solids and Resources

The ash wastes shown in Table 4.3-1 are just slightly under the total ash that comes in with the coal. The same is true of the sulfur output shown in Table 4.3-2. The coal input to the plant is held outside in a 60-day supply pile; seed material is held inside. Slag and other wastes are held temporarily onsite before trucking to disposal. With holding ponds and all of this storage for the 30-year life of the plant it can be seen why the plant land requirements are only a small fraction of the total land requirements once disposal needs are considered.

4.4 Other Fuel Cycle Effects

The effects of coal extraction and transportation, facility construction, aesthetics, and other indirect environmental consequences of MHD plants will be very similar to those consequences for conventional

TABLE 4.3-1

ESTIMATES OF SOLID WASTES FROM OCMHD

Furnace Solids	
(General Electric, 1976)	.0534 lb/kWh
Fly Ash	
(General Electric, 1976)	.006 lb/kWh
(Shaw, Cain, 1977)	0.029 kg/kWh
(Harris, Shah, 1976)	0.058 lb/kWh
Total	
(Shaw, Cain, 1977)	14.01 g/kWht
(Shaw, Cain, 1977)	29 g/kWhe
(General Electric, 1976)	0.082 lb/kWh

TABLE 4.3-2

CONSUMPTION OF NATURAL RESOURCES AND SOLIDS

Land (acres/100 MWe)	
(General Electric, 1976) base case main plant	3.71
(General Electric, 1976) SRC main plant	3.71
(Harris, Shah, 1976) main plant	5.1
(Harris, Shah, 1976) disposal land	84.0
(Hoover, *et al*., 1976) main plant	11.64 to 24.38
(Hoover, *et al*., 1976) disposal land	11.36 to 14.75
(Hoover, *et al*., 1976) railroad access	23.05 to 28.13
Total Water (gal/kWh)	
(General Electric, 1976) base case	0.22
(General Electric, 1976) SRC	0.21
(Shaw, Cain, 1977)	0.727 kg/kWhe
(Harris, Shah, 1976) disposal land	0.33
(Hoover, *et al*., 1976)	0.530 to 0.612
Cooling Water (gal/kWh)	
(General Electric, 1976) base case	0.22
(General Electric, 1976) SRC	0.21
(Harris, Shah, 1976)	0.32
(Hoover, *et al*., 1976)	0.516 to 0.596
K_2SO_4 Seed Material	
(Shaw, Cain, 1977)	.00059 kg/kWh
(Harris, Shah, 1976)	.00120 lb/kWh
(Hoover, *et al*., 1976)	.00027 to 00535 lb/kWh
Sulfur Output	
(Shaw, Cain, 1977)	11.4 g/kWhe
(Shaw, Cain, 1977)	4.60 g/kWht
(Harris, Shah, 1976)	0.021 lb/kWh
Coal Input	
(General Electric, 1976) base case	0.65 lb/kWh
(General Electric, 1976) SRC	0.71 lb/kWh
(Shaw, Cain, 1977)	0.297 g/kWhe
(Harris, Shah, 1976)	0.655 lb/kWh
(Hoover, *et al*., 1976)	0.65 to 1.07 lb/kWh

coal-fired facilities. There are computer programs that can be used to simulate some of these effects, such as direct fuel cycle effects from MERES at Brookhaven National Labs or indirect national environmental effects from SEAS at U.S. Environmental Protection Agency. A listing of some of these general impacts from coal-fired facilities can be found in (Jahnig, Shaw, 1977).

5.0 Conclusions

There is considerable trade-off potential between the various performance measures for OCMHD power plants. As such there is little doubt that current source emission standards, or even stricter standards, could be met. As increased demands are put on various aspects of OCMHD performance, however, the ultimate performance measure that is likely to suffer is economic cost. And thus the eventual market penetration of this technology will depend directly upon the comparative degree to which the costs have been held in line after all the problems have been solved and the emission and resource constraints met.

Some of the problems that have been perceived to most severely tax that ultimate performance measure are, in order of priority:

(1) considerable variations in types and severity of problems at different facility sizes;

(2) short life of materials exposed to exhaust gases and particulates, particularly electrodes and insulators, and the mutual compatibility of the materials under thermal cycling;

(3) slag coating of components, particularly the heat exchangers, slag tapping techniques, and high slag rejection in combustion area;

(4) arcs in passage of currents through cooler layers, and power conditioning system;

(5) workable and durable air preheater;

(6) good uniform mixing and feed of air and fuel;

(7) suitability for reuse of regenerated seed, and homogeneous seeding with that regenerated material;

(8) cost of stable superconducting magnet system;

(9) durability of heat exchanger surfaces in secondary furnace;

(10) energy costs of seed recovery system;

(11) cost of seed losses, especially in the slag, and investment cost of seed regenerator;

(12) avoidance of excessive heat losses, and effects of necessary thermal gradients between superhot and supercool areas;

(13) workability of NO_x control;

(14) prediction, optimization, and maintenance of working fluid conductivity, particularly boundary layer and particulate influences, and feedback from channel to combustor;

(15) expense of integrated power plant control system;

(16) costs of high-temperature heat exchangers; and

(17) costs of coal drying and handling.

Although most of these problems are only indirectly related to emissions and energy efficiencies it is believed that the trade-offs involved in solving these problems will significantly affect those performance measures in the commercial OCMHD. To ensure that the most appropriate trade-off of cost versus emissions is reached it seems essential that emission standards be based upon power plant outputs, so investments in high MHD efficiencies are adequately rewarded.

From the standpoint of recommending future work in this area it would be desirable to have maintained an updated data base of MHD emissions and efficiency information. An ongoing project at MIT is concerned with putting together just such a data base for fluidized bed combustors. There are several advantages to having such data bases available for <u>all</u> of the advanced energy technologies:

(1) they can be used as design tools to search for attractive configurations and operating parameters, particularly those unexpected synergistic effects that could be identified and exploited;

(2) they can be a ready source of latest information on the performance of that energy cycle;

(3) analytical models can be systematically tested against such a data base to evaluate the gap between theoretical and experimental information; and finally,

(4) they can be used to systematically identify and quantify the need for key pieces of information that are now inadequately known.

This final objective is perhaps the most important in that it could be a mechanism for developing R&D strategies.

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Appendix A MHD Economic-Environmental Simulation

A computerized model has been developed at the MIT Energy Laboratory that has the capability of simulating the siting of many technologies including MHD power plants. This model, AEGIS - Alternative Electric Generation Impact Simulator, can be obtained from James Gruhl, principal investigator, at the MIT Energy Laboratory. To date the sponsors have been New England Electric System (NEES), Bradley Schrader program manager, and Northeast Utilities Service Co. (NUSCO), Denning Powell and William Renfro program managers.

Table A-1 shows the interactive nature of the program's input routine. Table A-2 displays the listing of the input assumptions and acts both as a means for the user to verify the assumptions and for the formal record of the simulation run.

The output from the OCMHD simulation is shown in Table A-3, displaying the range of uncertainty associated with each of the 109 performance measures. Minus numbers, such as -1., or letters, such as NA, are indications that these are performance values that are not predicted by the particular modules chosen by the user.

Table A-4 presents the code for identifying specific pieces of information that the user may be interested in retrieving from the online documentation. Tables A-5 and A-6 show the retrievals of all OCMHD power plant information and LAMM health impact information. References are almost all available in this report's bibliography. The AEGIS program and bibliography will be available to the public late in 1978 upon completion of the NEES-NUSCO Project.

Table A-1 Input session for use of AEGIS program - terminal responses are in CAPITALS, user responses are in lower case; this is an example of the no-prompt option.

```
exec aegis
CHECK TERMINAL LINESIZE = 120 OR MORE
EXECUTION BEGINS...
    ALTERNATIVE ELECTRIC GENERATION IMPACT SIMULATOR
         AEGIS - VERSION  6
    DATA UPDATED  7/78

         AT ANY TIME USE NAMELIST VARIABLE=0 TO STOP OR RESTART RUN

    IS THIS AN ACTUAL RUN OR DEBUG RUN?  TYPE A OR D
a
    ALL OPTION VARIABLE DEFAULTS ARE 1
    NN=1 TO 10 FOR NUMBER OF EXAMPLES CARRIED, NN=1 ONLY FOR VERSION 2,
    NP=1 FOR PROB OR 2 FOR MEDIAN DISPLAYS,
    ND=1 FOR JUST FINAL DISPLAY OR =2 FOR DISPLAY ALONG THE WAY,
    NQ=1 FOR FULL PROMPTING DESCRIPTIONS OR 2 FOR MINIMUM PROMPTS, 3  FOR NO PROMPTS

 &PRINT NN,NP,ND,NQ &END <AS INTEGERS>
 &print nn=1,np=1,nd=1,nq=3 &end

 Z1=SIZE,Z2=YEAR,Z3=FUEL,Z4=PREC,Z5=COMB,Z6=SORB,Z7=DCAP,Z8=PART
 &ZLIST Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8 &END <AS INT>
 &zlist z1=1900,z2=1998,z3=1,z4=1;z5=6,z6=1,z7=70,z8=1 &end

 Z9=SCRUB,Z10=STACK,Z11=MET,Z12=SULF,Z13=SMOG,Z14=POP,Z15=SCAL,Z16=HEAL,Z17=RAD,Z18=INDEX
 &ZLIST Z9,Z10,Z11,Z12,Z13,Z14,Z15,Z16,Z17,Z18 &END <AS INT, EXC Z15 DEC>
 &zlist z9=1,z10=235,z11=1,z12=1,z13=1,z14=2,z15=.9,z16=3,z17=1,z18=1 &end
    AEGIS - VERSION M  6D 13   UPDATED  7/78
```

Table A-2 Display to user of the assumptions that will be used in this particular session.

```
!-------------!
! ASSUMPTIONS !
!-------------!
  SIZE<MWE>                  1900.0
  YEAR COMPL                 1998.0
  FUEL TYPE             NAT RANGE BITUMINS COALS
  PRECL TYPE            NONE
  GENERATYPE            COALFIRED OPEN CYCLE MHD
    DES CAPAC FAC<%>         70.000
    STORAGE CAP<MWH>         .0
    SORBENT TYPE        NONE
  ABATE TYPES:
    PART TYPE           NONE
    SCRUB TYPE          NONE
    STACK HT<M>              235.00
  MET SITE TYPE         STANDARD AMBIENT SCALING
  AEROCHEM MODELS:
    SULFATION TYPE      NONE
    SMOG TYPE           NONE
  DENSITY PATTERN       INDIAN POINT IN 1980 EST
    SCALED BY                .90000
  HEALTH/IMPACTS:
    CHEM HEALTH MOD     LINEAR ADD MORT MODEL
    RAD HEALTH MOD            NONE
    POLLUTION INDEX           NONE

FOR CHANGES NQ=4,OTHERWISE NQ=3
 &PRINT NQ &END
 &print nq=3 &end
```

Table A-3 Performance measures for the technology/site options chosen for this simulation.

```
!--------------------------------!------------------------------------------------------------------------!
! CUMULATIVE PROB MEASURES       !  MINIMUM         1 DEV LO         MEDIAN           1 DEV HI         MAXIMUM      !
! PROB VALUE < THIS VALUE        !  .0000           .1587            .5000            .8413            1.0000       !
!--------------------------------!------------------------------------------------------------------------!


!------------------!
! ECONOMIC FACTORS !
!------------------!
  INVEST COST<MIL $>               1219.8           1364.2           1529.5           2095.7           2736.0
  NORMALIZED INVEST<$1000/MWE>     642.00           718.00           805.00           1103.0           1440.0
  OPERATING COSTS:
    FIXED OPER COST<$/MWE/YR>      .11248E+06       .12579E+06       .14104E+06       .19325E+06       .25229E+06
    VARIABLE OPER COST<$/MWH>      7.4159           8.8692           11.229           14.377           19.852
      OP&MAIN<$/MWH>               1.6000           1.7000           2.8000           3.2000           4.0000
      FUEL<$/MWH>                  5.8159           7.1692           8.4289           11.177           15.852
  COST OF ELECT<MILS/KWH>          25.759           29.383           34.229           45.892           60.995
    CAP COST<MILS/KWH>             18.343           20.514           23.000           31.514           41.143
    OP COST<MILS/KWH>              1.6000           1.7000           2.8000           3.2000           4.0000
    FUEL COST<MILS/KWH>            5.8159           7.1692           8.4289           11.177           15.852
!---------------------!
! PERFORMANCE FACTORS !
!---------------------!
  OPER CAP FAC<%>                  55.000           63.000           68.000           70.000           75.000
  ENERGY EFF ONSITE<%>             39.819           43.347           46.147           48.068           49.867
!---------------!
! APPLICABILITY !
!---------------!
  COMMERC YR<2000MWE ONLINE>       1995.0           1996.0           1999.0           2003.0           2021.0
  INSTALLED CAP<MWE>               583.00           583.00           583.00           583.00           583.00
  LARGEST FACILITY<MWE>            500.00           500.00           500.00           500.00           500.00
!-----------------------!
! RESOURCE REQUIREMENTS !
!-----------------------!
  LAND USE ONSITE<ACRES>           70.490           96.900           370.50           659.30           1187.5
  LAND DISTURB FUEL<ACRES/YR>      63.776           99.243           120.60           146.74           179.70
  LAND DISPOSE WASTE<ACRES/YR>     59.850           86.450           119.70           151.62           196.84
  WATER CONSUMP<MIL GAL/YR>        2394.0           2926.0           4123.0           5985.0           7315.0
!----------------------------!
! ENVIRONMENTAL CONSEQUENCES !
!----------------------------!
  AIR EMIS ONSITE<GM/MIN>:
    SOX                            101.82           1287.7           42475.           .12990E+06       .48523E+06
      SULFATES                     8.1452           90.141           2973.3           9093.0           33819.
      SULF ACID AEROS              1.2727           12.877           504.40           1515.5           5661.0
    NOX                            5700.0           14250.           17100.           29450.           64600.
      NO                           5700.0           14250.           17100.           29450.           64600.
```

Table A-3 Continued display of performance measures.

O3, OXID	.64600E-03	.20000E-02	.64600E-02	.20330E-01	.64600E-01
PART TOTAL	9690.0	47500.	77900.	98800.	.11590F+06
PART RESPIR	7030.0	32300.	55100.	68400.	81700.
CO	15960.	53200.	.15960E+06	.53200E+06	.15960E+07
CO2	.38000E+07	.47500E+07	.57000E+07	.76000E+07	.11400E+08
HC TOTAL	3.0400	9.8800	30.400	98.800	304.00
INERT HC	2.4320	7.9800	24.320	79.800	243.20
REACTIVE HC	3.0400	.98800	3.0400	9.8800	30.400
OXYG HC	.30400E-01	.98800E-01	.30400	.98800	3.0400
POLY ORG MAT	.26600	.89300	2.6600	8.9300	27.360
TRACE ELEM:					
ARSEN	.34397E-01	3.8291	23.482	150.89	398.10
BERYL	.13759E-01	.79669	5.1235	14.164	32.105
CAD	.68794E-02	.37236	6.9642	134.90	452.14
CHROM	.27518	8.5587	57.575	163.29	577.89
COB	.68794E-01	2.5087	32.058	104.33	368.13
LEAD	.27518	8.0305	58.253	372.98	933.18
MANG	.41276	12.199	206.85	695.96	1937.0
MERC	.13759E-02	.23272E-01	.83745E-01	.29607	1.7123
NICK	.20638	11.500	88.225	256.64	847.57
SELEN	.30957E-01	.45614	2.6128	7.3554	24.721
TIN	.68794E-01	2.2683	20.057	131.24	540.32
VANAD	.75673	19.251	95.875	244.22	584.31
ZINC	.41276	30.254	820.91	9270.6	41223.
RADIOACT TO AIR<CUR/YR>	.31402E-03	.29245E-01	.11002	.23652	.58511
WATER EMIS ONSITE<TONS/YR>	.44245E+06	.52351E+06	.60302E+06	.71259E+06	.88853E+06
INORGANIC<TONS/YR>	.39860E+06	.47140E+06	.54272E+06	.64197E+06	.79868E+06
ORGANIC<TONS/YR>	43846.	52103.	60302.	70617.	88853.
THERMAL<10*12 BTU/YR>	25.510	28.119	30.151	33.016	36.939
RADIOACT TO WAT<CUR/YR>	.0	.0	.0	.0	.0
SOLID WASTES<TONS/YR>	.60753E+06	.26624E+07	.38457E+07	.53221E+07	.11083E+08
RADIOACT SOLIDS<CUR/YR>	.0	.0	.0	.0	.0
ATMOS DILU FAC<UG/M3/G/MIN>					
GASEOUS:					
1 HOUR	.83301E-06	.14072E-05	.33154E-05	.66555E-05	.11353E-04
3 HOUR	.15048E-05	.25421E-05	.59892E-05	.12023E-04	.20509E-04
8 HOUR	.19885E-05	.33592E-05	.79143E-05	.15887E-04	.27101E-04
24 HOUR	.25796E-05	.43578E-05	.10267E-04	.20611E-04	.35158E-04
3 DAY	.32783E-05	.55381E-05	.13048E-04	.26193E-04	.44680F-04
1 MON	.44069E-05	.74446E-05	.17540E-04	.35210E-04	.60062E-04
ANNUAL	.53742E-05	.90788E-05	.21390E-04	.42939E-04	.73246E-04
PARTICULATES:					
1 HOUR	.57056E-06	.74611E-06	.19311E-05	.34233E-05	.51789E-05
3 HOUR	.10307E-05	.13478E-05	.34885E-05	.61841E-05	.93554E-05
8 HOUR	.13620E-05	.17810E-05	.46098E-05	.81719E-05	.12363E-04
24 HOUR	.17669E-05	.23105E-05	.59802E-05	.10601E-04	.16038E-04
3 DAY	.22454E-05	.29363E-05	.75999E-05	.13473E-04	.20381E-04
1 MON	.30184E-05	.39472E-05	.10216E-04	.18111E-04	.27398E-04
ANNUAL	.36810E-05	.48136E-05	.12459E-04	.22086E-04	.33412E-04

Table A-3 Completion of display; -1.0 values indicate information not predicted by modules chosen.

```
OCCUP HEALTH:
  MORT ONSITE<PER YR>          .63776E-01     .82703E-01     .10768         .13757         .17970
  MORB ONSITE<PER YR>          .63776         .87665        1.8521         3.3016         4.4926
  DAYS LOST ONSITE</YR>        239.16         364.72         792.55         1283.9         1797.0
  MORT OFFSITE<PER YR>         .79720E-01     .41351         .86146        1.3757         2.1964
  MORB OFFSITE<PER YR>         2.1524         4.7140         54.617         87.583         100.83
  DAYS LOST OFFSITE</YR>       53.731         154.65         294.62         3466.7         9584.2
PUBLIC HEALTH<ROUTINE>:
  MORTALITIES<PER YR>          .94463E-01    1.0952          6.3197         18.926         56.097
    CANCER<TOTAL>             -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CARDIOVAS                 -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    BRONCHOPULM               -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CNS                       -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MUTATIONS<TOTAL>            -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MORBIDITIES<PER YR>         -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    RESPIR                    -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      ASTHMA                  -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      PNEUM                   -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      CHRONIC                 -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
      CHILDREN                -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    THYROID                   -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CARDIOVAS                 -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MANDAYS LOST<PER YR>        -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
PUBLIC HEALTH<OFFSITE>:
  MORTALITIES<PER YR>         -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
    CANCER<TOTAL>             -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MUTATIONS<TOTAL>            -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MORBIDITIES<PER YR>         -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MANDAYS LOST<PER YR>        -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
PUBLIC HEALTH<CATAST>:
  PROB OF OCCUR<PER YR>        .79720E-07     .39697E-06     .68917E-06     .11739E-05     .15974E-05
  MORTALITIES<PER YR>          .63776        1.2405         1.5506         1.9259         2.7954
    CANCER<TOTAL>              .39860E-05     .25638E-04     .56857E-04     .35767E-03     .86856E-03
    BRONCHOPULM                .11958E-04     .49622E-04     .21537E-03     .50441E-03     .11980E-02
    CARDIOVAS                  .79720E-04     .37216E-03     .86146E-03     .20176E-02     .89851E-02
  MUTATIONS<TOTAL>            -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MORBIDITIES<PER YR>          6.3776         17.368         24.121         32.099         40.932
    THYROID                   -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MANDAYS LOST<PER YR>         637.76         1736.8         2412.1         3209.9         4093.2
INDEXES AND COSTS:
  PUBLIC HEALTH COSTS<$/YR>   -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  BIOTA COSTS<$/YR>           -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  MAT DAMAGE COSTS<$/YR>      -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  AESTH COSTS<$/YR>           -1.0000        -1.0000        -1.0000        -1.0000        -1.0000
  SUBJECTIVE INDEXES          -1.0000        -1.0000        -1.0000        -1.0000        -1.0000

FOR ANOTHER RUN TYPE: DO   OR:  NOT
not
END
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Table A-4 Code and format for on-line documentation retrieval.

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 ___________________________________________
|                                           |
|  AEGIS DOCUMENTATION IDENTIFICATION CODE  |
|___________________________________________|

AEGIS - ALTERNATIVE ELECTRIC GENERATION IMPACT SIMULATOR, VERSION M005D012
FOR FURTHER INFORMATION CONTACT: J. GRUHL, E38-408, 77 MASS. AVE., CAMBRIDGE MA
                                      (617)253-8025 OR MESSAGE AT -3404
D = DOCUMENTATION TEXT IDENTIFIER
|NN = MODULE NUMBER         01=FUELS
|||                         02=PRETREATMENT
|||                         03=COMBUSTION
|||                         04=ADDITIVE
|||                         05=PARTICULATE ABATEMENT
|||                         06=OTHER ABATEMENT
|||                         07=ATMOSPHERIC CHARACTERISTICS AND DISPERSION MODEL
|||                         08=AEROCHEMICAL MODEL
|||                         09=DEMOGRAPHIC CHARACTERISTICS
|||                         10=CHEMICAL HEALTH IMPACTS
|||                         11=RADIATION HEALTH IMPACTS
|||                         12=OTHER IMPACT MEASURES
|||NN = SPECIFIC MODEL (WITHIN MODULE)
|||||NN = DESCRIPTIVE INFORMATION (FOR SPECIFIC MODEL)
|||||||NN = LINE NUMBERS (FOR SAME DESCRIPTIVE INFORMATION)
|||||||||          LINES    01=CONCENSUS PROBABILISTIC BREAKDOWN, FIVE NUMBERS
|||||||||                         MINIMUM, .00 CUMULATIVE PROBABILITY
|||||||||                         ONE DEV LOW, .16 CUMULATIVE PROBABILITY
|||||||||                         MEDIAN, .50 CUMULATIVE PROBABILITY
|||||||||                         ONE DEV HIGH, .84 CUMULATIVE PROBABILITY
|||||||||                         MAXIMUM, 1.00 CUMULATIVE PROBABILITY
|||||||||                02 TO 09=CORRELATED CONDITIONALS
|||||||||                10 TO 99=SPECIFIC SOURCES AND NUMBERS
D11223344
  IS EXAMPLE DOCUMENTATION LINE IDENTIFIER FOR INFORMATION ABOUT MODULE 11,
     MODEL 22, ROW OF DESCRIPTIVE INFORMATION 33, LINE 44
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Table A-5 On-line retrieval of Open Cycle Coal-Fired MHD data.

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D03060000     VERSION D013
D03060001 DESCRIPTION  OPEN CYCLE COAL-FIRED MHD
D03060002  DIRECT AIR PREHEATING AT 1350K, 95% STOICHIOMETRIC AIR, 2 STAGE
D03060003  COMBUSTOR, DIRECT COAL-FIRED, 80% SLAG REJECTION, 1.0% K2CO3 SEEDING,
D03060004  .75 MACH FLOW RATE, 6 ATM, 6 TESLA MAGNETIC FIELD, STEAM BOTTOMING
D03060005  CYCLE OF 24.1MN/M2/811K/811K
D03060101 OVERALL ENERGY EFF%          45.6    47.0    48.3    48.7    49.2
D03060102  +(1.-SULFUR% OF COAL TIMES 0.9)
D03060103  +0 FOR ILL6, -.35 MONT ROSEBUD, -2.0 N.D., -6.05 SRC (GRUHL,NOV1977)
D03060104  TIMES 1. FOR 2%MOISTURE, .97 FOR 10%, .86 FOR 27.4% (CUTTING,1977)
D03060110   (WITWER,1976) 46-55
D03060111   (GRUHL,NOV1977) 45.6-49.2
D03060112   (POMEROY,ET AL,1978) 48.3-49.2
D03060113   (HALS,JACKSON,1969) 50-60
D03060114   (FELDMANN,SIMONS,BIENSTOCK,1970) THERMAL 50.8-51.9
D03060115   (BERGMAN,BIENSTOCK,1976) 45.6-50.14
D03060116   (JACKSON,ET AL,1976) 47
D03060117   (CUTTING,ET AL,1977) 46-46.9
D03060118   (SEIKEL,HARRIS,1976) 41-53,42-50(W.E.CO.),48.3(G.E.CO.)
D03060119   (POWELL,ULMER,1974) 50-55
D03060120   (PENNY,BOURGEOIS,CAIN,1977) 55-60
D03060121   (GENERAL ELECTRIC,1976) 44-55
D03060122   (GENERAL ELECTRIC,1976)SRC 40-46
D03060123   (NASA,1977) 48.3-48.7
D03060124   (PEPPER,YU,1975) 52 THERMAL
D03060125   (WESTINGHOUSE,1976)DIRECT AIR PREHEAT 44-49,44-54
D03060126   (NASA,1976) LOW BTU PREHEAT 46-54
D03060201 CAP INVEST 1978$/KWE         642.    718.    805.    1103.   1440.
D03060210   (WITWER,1976) BASELOAD 1975$ 600
D03060211   (POMEROY,ET AL,1978) 805
D03060212   (HALS,JACKSON,1969) 90-120
D03060213   (ROSA,ET AL,1970) 35-55 PEAKING
D03060214   (SEIKEL,HARRIS,1976) 718
D03060215   (GENERAL ELECTRIC,1976) 910-1440
D03060216   (NASA,1977) 1103 (W.E.CO.)
D03060217   (PEPPER,YU,1975) 340-440
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Table A-5 (continued)

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D03060218   (NASA,1977) 642 (G.E.CO.)
D03060301 C O E 1978MILS/KWH        27.1    36.0    42.0    48.5    55.5
D03060302  THIS HAS A TIGHTER DISTRIBUTION THAN THE SUM OF ITS COMPONENT
D03060303  PROBABILITIES DUE TO INVESTMENT/OPERATING COST TRADEOFFS
D03060310   (WITWER,1976) 1977$ WITH 1$/MBTU COAL  28
D03060311   (LEVI,1978) 32
D03060312   (NASA,1975) 41-48(G.E.CO.),27-35(W.E.CO.),34-42(LOW BTU)
D03060313   (POMEROY,ET AL,1978) 34-43 BASELOAD
D03060314   (POMEROY,ET AL,1978) 130 PEAKING
D03060315   (HALS,JACKSON,1969) 3.34-4.26
D03060316   (SEIKEL,HARRIS,1976) 42-49(G.E.CO.),32-50(W.E.CO),31.8(G.E.CO.)
D03060317   (GENERAL ELECTRIC,1975) 41.5-55.5
D03060318   (NASA,1977) 27.1-43.9
D03060401 C O E CAP 1978MILS/KWH    14.0    22.7    25.5    34.8    37.7
D03060402  COE CAP= CAPITAL INV TOTAL X CAPITAL COST FACTOR /(LOAD FACTOR X CAP)
D03060403  CAP COST FACT = ABOUT 10% PUBLIC, 20% PRIVATE SECTOR
D03060404  20% IS USED IN SIMULATOR, THESE VALUES ARE FOR COMPARISON PURPOSES
D03060405  ONLY WITH THESE VALUES DETERMINED ENDOGENOUSLY
D03060410   (WITWER,1976) CCF 10% 10.6,CCF 20% 21.2
D03060411   (GENERAL ELECTRIC,1976) 22.7,22.7,24.4,25.5,29.5,18.4
D03060412   (CORMAN,ET AL,1976)34.9,33.2,37.7,34.8,35.7,35,35,44.7,32.0
D03060413   (NASA,1977) 22.7
D03060414   (HALS,JACKSON,1969) 2.57-1.93
D03060415   (POMEROY,ET AL,1978)CAP FAC .7=14,.4=24.5,.15=65.3
D03060501 C O E O&M 1978MILS/KWH     1.6     1.7     2.8     3.2     4.0
D03060510   (WITWER,1976) 1.0
D03060511   (GENERAL ELECTRIC,1976) 1.7,1.7,1.7,1.7,1.8,1.7
D03060512   (CORMAN,ET AL,1976)2.8,2.9,3.2,2.9,2.9,2.8,2.8,3.6,2.3
D03060513   (HALS,JACKSON,1969) .27-.33
D03060514   (NASA,1977) 1.7
D03060515   (POMEROY,ET AL,1978)CAP FAC=.7=3.2, .4=3.6, .15=4.8
D03060601 C O E FUEL MILS/KWH        6.1     6.3     7.3     8.8    11.0
D03060602  COE FUEL = $/MBTU COAL X .003412MBTU/KWH / .01EFFICIENCY%
D03060603  DETERMINED ENDOGENOUSLY, THESE VALUES FOR COMPARISON ONLY
D03060610   (WITWER,1976) 6.2 FOR 6200BTU/KWH, $1.00/MBTU COAL
D03060611   (NASA,1977) 7.3
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Table A-5 (continued)

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D03060612   (HALS,JACKSON,1969) .20/MBTU COAL = 1.36
D03060613   (POMEROY,ET AL,1978) 16.5
D03060614   (GENERAL ELECTRIC,1976) 7.3,7.3,7.3,7.3,7.3,11.0
D03060615   (CORMAN,ET AL,1976)6.2,6.3,6.3,6.1,6.3,6.3,6.3,6.6,8.8
D03060616   (CORMAN,ET AL,1976) CHANGE 20% FUEL = 1.3 CHANGE
D03060701 MAX AVAILAB %                55.     63.     68.     70.     75.
D03060702  SHOULD BE DECREASING FN OF SIZE OF MODULES BUT NO DATA
D03060710   (JACKSON ET AL,1976) 70
D03060711   (JACKSON,ET AL,1976) 20% TOTAL UNAVAILABILITY
D03060712   (POMEROY,ET AL,1978) 65 = 100-20FORCED-15PLANNED
D03060801 COMMERC YR                   1995    1996    1999    2003    2021
D03060802  FOR COAL-FIRED FACILITIES, NOT GAS OR OIL WHICH ARE MUCH SOONER
D03060810   (WITWER,1976) 1995
D03060811   (PEPPER,YU,1975) 1988
D03060812   (POMEROY,ET AL,1978) 2003
D03060813   (SEIKEL,HARRIS,1976) 1996-1999
D03060814   (PENNY,BOURGEOIS,CAIN,1977) 2000
D03060815   (CORMAN,ET AL,1976) 1997
D03060901 INSTALLED CAP MWE            83.     583.    583.    2600.   2600.
D03060902  AT YEARS 1985 1990 1995 2000 2005
D03060910   (GRUHL,NOV1977) .2 1978,4.3 1979,13 1981, 83 1985, 583 1989
D03061001 LARGEST FAC MWE              70.     500.    500.    2000.   2000.
D03061002  AT YEARS 1985 1990 1995 2000 2005
D03061010   (GRUHL,NOV1977)  .2 1978,4 1979,9 1981, 70 1985, 500 1989
D03061101 LAND ONSITE ACRES/MW         .0371   .051    .195    .347    .625
D03061110   (GENERAL ELECTRIC,1976) MAIN PLANT 3.71 PER 100MWE
D03061111   (HARRIS,SHAH,1976) 5.1 PER 100MWE
D03061112   (HOOVER,ET AL,1976) 11.64 TO 24.38 PER 100MWE
D03061113   (HOOVER,ET AL,1976) PLUS RAILROAD ACCESS 23.05 TO 28.13 PER 100MWE
D03061201 LAND USE WASTE ACRES/MWY     .045    .065    .090    .114    .148
D03061210   (HARRIS,SHAH,1976) 84/1932MW
D03061211   (HOOVER,ET AL,1976) 11.36 TO 14.75/100MW
D03061301 WATER CONS MIL GAL/MWY       1.8     2.2     3.1     4.5     5.5
D03061310   (JACKSON,ET AL,1977) 24MWE 163GAL/MIN
D03061311   (GENERAL ELECTRIC,1976) .22 GAL/KWH
D03061312   (SHAW,CAIN,1977) .727KG/KWH
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Table A-5 (continued)

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D03061313   (HARRIS,SHAH,1976) .33GAL/KWH
D03061314   (HOOVER,ET AL,1976) .53 TO .612 GAL/KWH
D03061401 OUTLET VEL M3/MIN/MW        17.25   17.25   17.25   17.25   17.25
D03061402  THIS NUMBER NOT USED IN CURRENT VERSION OF PROGRAM
D03061403  HAS NOT BEEN COMPUTED, 17.25 IS CONV COAL NUMBER
D03061410   (GENERAL ELECTRIC,1976) 10.97 MIL LB/HR 14.7PSIA, 1932MW
D03061411   (WESTINGHOUSE,1976) 3435.8 LB/S, 14.7PSIA, 1900MW
D03061501 SOX % REL                   0.4     1.0     16.     30.     66.
D03061510   (ARGYROPOLIS,1976) 0.4
D03061511   (GENERAL ELECTRIC,1976) ASSUMING 3%S COAL 66.
D03061512   (HARRIS,SHAH,1976) ASSUMING 3%S COAL 18.
D03061512   (RESEARCH AND EDUC ASSOC,1976) ASSUMING 3%S COAL 16.
D03061601 SULFATES % REL              0.032   0.07    1.12    2.10    4.60
D03061602  ASSUMPTION ON K2SO4 COLLECT EFF AND SO2/SO3 RATIO THIS IS
D03061603  ABOUT .07 OF THE SOX RELEASE NUMBER
D03061701 SULF ACID % REL             0.005   0.010   0.190   0.350   0.770
D03061702  ABOUT 1/6 OF SULFATES, NO DATA
D03061801 NOX G/MIN/MW                3.0     7.5     9.0     15.5    34.0
D03061802  CONVERSION IS LB/MBTU INPUT = ABOUT 830PPM = .0067LB/KWH
D03061803  OR APPROXIMATELY 50.2 G/MIN/MW
D03061810   (GENERAL ELECTRIC,1976) 0.3 LB/MBTU
D03061811   (SHAW,1978) 0.71 LB/MBTU
D03061812   (FOLSOM,1978) OLD 0.72, NEW .685 LB/MBTU
D03061813   (MORI,TAIRA,1972) 243PPM
D03061814   (MORI,TAIRA,1973) 50PPM
D03061815   (PEPPER,EUSTIS,KRUGER,1972) 283PPM
D03061816   (PENNY,BOURGEOIS,CAIN,1977) 135 TO 300PPM
D03061817   (BIENSTOCK,ET AL,1973) 150PPM
D03061818   (HALS,LEWIS,1972) 160-260PPM
D03061819   (REA,1976) 155PPM
D03061901 NO G/MIN/MW                 3.0     7.5     9.0     15.5    34.0
D03061902  ESSENTIALLY THE SAME AS NOX, UNSTABLE AND GOES TO ZERO
D03062001 OXID MG/MIN/MW              .00034  .0011   .0034   .0107   .0340
D03062002  SET AT ABOUT .0001PPM, ESSENTIALLY ZERO IN FINE-TUNED DEVICE
D03062101 PART TOT G/MIN/MW           5.1     25.     41.     52.     61.
D03062102  PRECIPITATION MUST BE 99.5% OR BETTER TO BE
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Table A-5 (continued)

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D003062103  ECONOMIC IN RECOVERING VALUABLE SEED FOR RECYCLE
D003062104  SRC FUEL YIELDS 1/17TH PARTICULATES OF OTHERS
D003062105  LB/MBTU = .075LB/KWH = ABOUT 570G/MIN/MW
D003062110   (GENERAL ELECTRIC,1976) .1LB/MBTU INPUT, .008LB/KWH
D003062111   (HARRIS,SHAH,1976) .1LB/MBTU INPUT, .007LB/KWH OUTPUT
D003062112   (SHAW,CAIN,1977) 0.15G/KWHT, 0.32G/KWHE
D003062113   (GENERAL ELECTRIC,1976) SRC .06LB/MBTU,.00046LB/KWH
D003062201 PART RESP G/MIN/MW          3.7      17.0     29.0     36.0     43.0
D003062202  PRESUME ABOUT 70% PARTICULATES RESP AFTER SECOND CYCLONE
D003062301 CO G/MIN/MW                 8.4      28.0     84.0     280.     840.
D003062310   (SHAW,CAIN,1977) NIL
D003062311   (BIENSTOCK,ET AL,1971) 0
D003062312   (GENERAL ELECTRIC,1976) 0
D003062313   (HALS,LEWIS,1972) WITH SECONDARY STAGE 0.4 TO 0.6%
D003062314   (GRUHL,NOV1977) TUNED TO YIELD JUST A TRACE
D003062401 CO2 G/MIN/MW                2000.    2500.    3000.    4000.    6000.
D003062402  FLUID BEDS YIELD ABOUT 15% =? 3000G/MIN/MW?
D003062501 TOTAL HC G/MIN/MW           .0016    .0052    .016     .052     .160
D003062502  1.6 FROM FLUID BEDS
D003062510   (GENERAL ELECTRIC,1976) 0
D003062511   (ROSA,ET AL,1970) 0
D003062601 INERT HC MG/MIN/MW          1.28     4.20     12.8     42.0     128.0
D003062602  PRESUME ABOUT 80% OF HC
D003062701 REACT HC MG/MIN/MW          .16      .52      1.60     5.20     16.00
D003062702  PRESUME ABOUT 10% OF HC
D003062801 OXYG HC MG/MIN/MW           .016     .052     .160     .520     1.600
D003062802  PRESUME ABOUT 1% OF HC
D003062901 POM MG/MIN/MW               .14      .47      1.40     4.70     14.40
D003062902  PRESUME ABOUT 9% OF HC
D003063001 ARSEN % REL                 1.0      8.0      20.      33.      40.
D003063010   (GRUHL,NOV1977) 1-40
D003063101 BERYL % REL                 1.0      13.0     38.0     63.0     75.0
D003063110   (GRUHL,NOV1977) 1-75
D003063201 CAD % REL                   1.0      12.0     33.0     54.0     65.0
D003063210   (GRUHL,NOV1977) 1-65
D003063301 CHROM % REL                 1.0      17.0     50.0     84.0     100.
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Table A-5 (continued)

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D03063310   (GRUHL,NOV1977) 1-100
D03063401 COB % REL                  1.0      14.0     40.0     67.0     80.0
D03063410   (GRUHL,NOV1977) 1-80
D03063501 LEAD % REL                 1.0      8.0      20.0     33.0     40.0
D03063510   (GRUHL,NOV1977) 1-40
D03063601 MANG % REL                 1.0      17.0     50.0     84.0     100.0
D03063610   (GRUHL,NOV1977) 1-100
D03063701 MERC % REL                 1.0      3.0      5.0      8.0      10.0
D03063710   (GRUHL,NOV1977) 1-10
D03063801 NICK % REL                 1.0      17.0     50.0     83.0     99.0
D03063802  TOP VALUE SHOULD REFLECT GOOD NUMBER FROM CONVENTIONAL COAL PLANT
D03063810   (HARRIS,SHAH,1976) 1
D03063901 SELEN % REL                1.0      6.0      15.0     25.0     30.0
D03063910   (GRUHL,NOV1977) 1-30
D03064001 TIN % REL                  1.0      17.0     50.0     83.0     99.0
D03064002  TOP VALUE SHOULD REFLECT GOOD NUMBER FROM CONVENTIONAL COAL PLANT
D03064010   (HARRIS,SHAH,1976) 1
D03064101 VANAD % REL                1.0      12.0     35.0     59.0     70.0
D03064110   (GRUHL,NOV1977) 1-70
D03064201 ZINC % REL                 1.0      13.0     36.0     60.0     72.0
D03064210   (GRUHL,NOV1977) 1-72
D03064301 RAD226 % REL               1.0      17.0     50.0     84.0     100.0
D03064310   (GRUHL,NOV1977) 1-100
D03064401 RAD228 % REL               1.0      17.0     50.0     84.0     100.0
D03064410   (GRUHL,NOV1977) 1-100
D03064501 WAT EM TOT TONS/10*12BTU IN5500.   6300.    7000.    7700.    8900.
D03064502  LB/KWHE = ABOUT 70600 TONS/10*12BTU IN
D03064510   (SHAW,CAIN,1977) 24.6 G/KWHT, 51.G/KWHE
D03064511   (HARRIS,SHAH,1976) .75LB/KWH
D03064512   (GENERAL ELECTRIC,1976) .09LB/KWH
D03064601 WAT EM INORG T/10*12BTU IN 5000.   5700.    6300.    7000.    8000.
D03064602  ASSUMING APPROXIMATELY 90% OF TOTAL WASTE IS INORGANIC
D03064701 WAT EM ORG T/10*12BTU IN   550.    630.     700.     770.     890.
D03064702  ASSUMING APPROXIMATELY 10% OF TOTAL WASTE IS ORGANIC
D03064801 WAT EM THERM % OF BTU IN   32.     34.      35.      36.      37.
D03064802  EARLIER DATA SET VERSION WAS BTU THERMAL/10*12BTU IN
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Table A-5 (continued)

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D03064810  (GENERAL ELECTRIC,1976) 2468BTU/KWH, SRC 2040BTU/KWH
D03064811  (HARRIS,SHAH,1976) 2377BTU/KWH
D03064901 RAD TO WAT CUR/10*12BTU IN 0.0      0.0     0.0     0.0     0.0
D03065001 SOL WASTES T/10*12BTU IN   4500.   5100.   5600.   6200.   7100.
D03065002  LB/KWHE = ABOUT 70600TONS/10*12BTU IN
D03065003  ASSUMING 48.3% EFFICIENCY, SOLID WASTES SHOULD BE
D03065004  COMPUTED AS 99.5% OF ASH OF INCOMING COAL
D03065010   (SHAW,CAIN,1977) 14.01G/KWHT, 29.G/KWHE
D03065011   (GENERAL ELECTRIC,1976) 0.082LB/KWH
D03065101 OTHER SOL WASTES T/10*12   0.0     0.0     0.0     0.0     0.0
D03065102  SULFUR IS RECOVERED THAT ENTERS SYSTEM AND DOES NOT EXHAUST BUT
D03065103  THIS IS CONSIDERED (MARGINALLY) SALEABLE PRODUCT, NO SEED LOSS
D03065201 RAD SOL CUR/10*12BTU IN    0.0     0.0     0.0     0.0     0.0
D03065301 OCC HEALTH MORT/10*12BTU IN.00080  .00100  .00125  .00150  .00180
D03065302  IN ABSENSE OF DATA SAME AS COAL PLANT, ALTHOUGH PRESSURIZED
D03065303  VESSEL SHOULD INCREASE THESE NUMBERS
D03065401 OCC HEALTH MORB/10*12BTU IN.008    .0106   .0215   .0360   .0450
D03065402  AGAIN SAME AS COAL PLANT IN ABSENSE OF DATA
D03065501 OCC HEALTH WDL/10*12BTU IN 3.0     4.41    9.20    14.0    18.0
D03065502  WORK DAYS LOST ALSO PRESUMED SAME AS CONVENT COAL IN ABSENSE OF DATA
D03065601 PUB H CATAST PROB/10*12    .10E-08 .48E-08 .80E-08 1.28E-08 1.6E-08
D03065602  REFLECTS THE PROBABILITY OF EXPLOSION OR COALPILE FIRE
D03065603  ASSUMES COAL FIRE 1/100 TO 1/1000 PROBABILITY OF OIL FIRE
D03065604  1000MWYR=29.89X10*12BTU IN X .01CAPFAC%/.01EFFIC%
D03065610   (BECKMAN,1976) 10-4 FOR OIL-FIRED PLANT WHERE > 10 MORTALITIES
D03065701 PUB H CATAST MORT/10*12    .008    .015    .018    .021    .028
D03065702  FOR CONVENT 36%EFF 100%CAPFAC COAL PLANT 12.0MWY=ABOUT 10*12BTU IN
D03065703  SHOULD INCLUDE MORTALITIES RESULTING FROM COALPILE FIRE PLUME
D03065704  AS WELL AS PUBLIC MORTALITIES FROM PRESSURIZED VESSEL EXPLOSION
D03065705  AND PUBLIC MORTALITIES FROM COAL TRANSPORT
D03065710   (CEQ,1973) 2.30/750MWY AT RR CROSSINGS
D03065711   (SAGAN,1974) 1.3/1000MWPLANT/YR
D03065712   (AEC,1974,WASH-1224) 0.55/1000MWPLANT/YR
D03065713   (GRUHL,SEP1976) 1.8X10*2 OIL-FIRE MORT / PLANT / FIRE / 10*7 POP
D03065801 PUB H CATAST CANC/10*12    .05E-06 .31E-06 .66E-06 3.9E-06 8.7E-06
D03065802  SHOULD BE CANCINOGENIC IMPACTS OF COALPILE FIRE PLUME
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Table A-5 (continued)

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D03065803  ASSUMING BETWEEN 1 AND 10 MILLION PERSONS EXPOSED TO PLUME
D03065810   (HICKEY,ET AL,1970) 54.6 ADDIT CANCERS PER MILLION FROM SO4
D03065901 PUB H CATAST BRPU/10*12    1.5E-07 0.6E-06 2.5E-06 5.5E-06 12.E-06
D03065902  SHOULD BE BRONCHOPULM CASES FROM COALPILE FIRE PLUME
D03065903  ASSUME ABOUT SAME AS ANNUAL CASES
D03065910   (NAS,1975) .9-3.6X10*4 FOR 1000MWE REGULAR OPERATION
D03066001 PUB H CATAST CRVS/10*12     .1E-05  .45E-05 1.0E-05 2.2E-05 9.E-05
D03066002  SHOULD BE CARDIOVASCULAR CASES FROM COALPILE FIRE PLUME
D03066003  ASSUME ABOUT SAME AS ANNUAL CASES FROM NORMAL OPERATION
D03066010   (NAS,1975) .7-2.8X10*5 FOR 1000MWE NORMAL OPERATION
D03066101 PUB H CATAST MORB/10*12 IN .08     .21     .28     .35     .41
D03066102  SHOULD INCLUDE COALPILE FIRE CASES
D03066110   (CEQ,1973) 23.4/750MWY AT RR CROSSINGS
D03066201 PUB H CATAST WDL/10*12 IN  8.0     21.     28.     35.     41.
D03066202  SHOULD INCLUDE COALPILE FIRE CASES
D03066210   (CEQ,1973) 2340./750MWY AT RR CROSSINGS
D03066301 AIR EM THERM % OF BTU IN   7.2     8.0     8.9     9.8     10.5
D03066302  NOT DISPLAYED AS EMISSION, JUST USED FOR PLUME RISE COMPUTATIONS
D03066310   (GENERAL ELECTRIC,1976) 606BTU/KWH
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Table A-6 On-line retrieval of documentation of LAMM health impact model.

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D10030000     VERSION D013
D10030001 DESCRIPTION  LINEAR ADDITIVE MORTALITY MODEL - LAMM
D10030002  CRUDE, LINEAR MODEL BASED UPON CONCENSUS STANDARDS, IT ONLY
D10030003  PREDICTS ANNUAL INCREASES IN MORTALITY RATES, SOURCE IS
D10030004  (GRUHL,ET AL,NOV1976,P106), ACCURACY DEPENDS ON AMONG OTHER THINGS
D10030005  SMALLNESS OF REGIONS CONSIDERED
D10030010   TOTAL ADDITIONAL ANNUAL MORTALITIES PER 10*6 PERSONS IN SOME
D10030011   REGION NEAR POINT SOURCE = SUMMATION (REGIONAL MAXIMUM UG/M3 24HR
D10030012   AVERAGE CONCENTRATIONS OF NOX/455 + SOX/365 + CO/710000 + PART/260
D10030013   + ARSEN/.15 + BERYL/.01 + MERC/.10 + NICK/.03 +
D10030014   + RADIUMS(CURIES/YR)/.02 )
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