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MASTER

ENVIRONMENTAL READINESS
DOCUMENT
MAGNETOHYDRODYNAMICS

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SUMMARY

Open cycle magnetohydrodynamics (MHD) is an efficient way to use coal in the production of electric power. MHD technology potentially can achieve power conversion efficiencies near 50%. Additionally, it is envisioned as an economical and environmentally acceptable way to generate electricity.

The U.S. Department of Energy (DOE) MHD program presently is envisioned as a three-step approach to commercialization. Phase I lays the engineering groundwork and depends heavily on tests conducted in two government-owned facilities: the Component Development and Integration Facility (CDIF) and the Coal-Fired Flow Facility (CFFF). Because these two facilities will not begin full operation until 1980, some uncertainties still exist in both engineering and environmental parameters. The ultimate design of the Engineering Test Facility (Phase II) and the Commercial Development Plant (Phase III) will depend on the results of Phase I testing.

Three major areas of environmental concern appear to exist with regard to the commercialization of MHD: 1) degradation of air quality and ability to meet federal and local standards; 2) human health effects; and 3) solid waste disposal.

The air emissions from MHD considered to be of concern are nitrogen oxides (NO_x), particulates, and sulfur dioxide (SO_2). Although MHD has a built-in SO_2 removal system that has been tested successfully at the 5 MW_t level, the final design of the recovery and regeneration process at commercial scale (i.e., $\geq 250 \text{ MW}_t$) is still being developed. Several systems have been proposed and the final choice of a system will determine the total engineering and cost effectiveness of SO_2 control. NO_x emissions could be a major problem if appropriate control measures are not employed. High temperatures encourage NO_x formation, but component design features are being built into the proposed system to reduce NO_x emissions below present and anticipated New Source Performance Standards (NSPS). Most particulates will be collected by conventional electrostatic precipitator fabric filter or scrubbing

devices, and advanced fine particulate control technologies currently are being researched and developed. It presently is assumed that expected control methods will reduce emissions to a level of regulatory compliance. Pilot scale (20-50 MW_t) monitoring work will initiate the testing of effective pollution control technologies.

Two additional areas of concern are solid waste disposal and the health effects of strong magnetic fields. The disposal of solid waste generated by the facility must comply with the Resource Conservation and Recovery Act (RCRA) of 1976 (PL 94-580). Regulations not yet promulgated by the U.S. Environmental Protection Agency (EPA) will have a direct bearing on the costs associated with the disposal of MHD-generated solid waste. Research pertaining to worker exposure to strong magnetic fields continues to be formulated.

Present EPA and Occupational Safety and Health Administration regulations will necessarily result in increased overall energy costs. Present and projected future regulations, requiring control technology and safety features, must be considered by any developing energy technology as an additional cost per unit kilowatt generated. An environmental research program related to the MHD program has been outlined by DOE.

State-of-the-art research and technology show MHD to be an acceptable and environmentally compatible energy source. Concurrent with commercialization, MHD should be judged to be environmentally ready.

The conclusions of this report, stated as probabilities, are given in Table 1-1. It should be emphasized that these probabilities are the synthesis of the collective judgements of Office of Environment (EV) scientists which are rendered in greater detail in the technology and governmental milestones shown in Section II and in the discussion of significant environmental concerns in Section III. Three factors are evaluated in terms of probability of occurrence: 1) an adverse finding as a result of future environmental research and development, 2) that given this finding the

Table 1-1.--Conclusions for Magnetohydrodynamics*

	Probability				
	0.1-----	0.5-----	0.9		
	Low	Low-Med	Med	Med-High	High
The probability of determining an adverse finding in the conduct of environmental R&D		X			
*The probability of technology program delays in event of an adverse finding		X			
The probability that energy costs will increase 10% in event of adverse finding		X			

* Probability of technology program delays:

Low-----Assessment of environmental factors will be substantially complete prior to commercialization.
 Medium--Assessment of environmental factors will be concurrent with DOE commercialization development, or
 High----Assessment of environmental factors will not be complete until after commercialization.

Note: These conclusions are based on an assessment of the information contained in Table 3-1

commercialization program will encounter delays, and 3) that the consequence of an adverse finding will result in increased costs of control. The term "adverse finding" is used to reflect a research and development outcome identifying an environmental impact which must be dealt with. The later in the commercialization schedule that this determination is made, the greater the likelihood that the full commercialization program will be delayed somewhat while appropriate mitigation measures are chosen. No judgements are made concerning the length of the delay. The last judgement, regarding the increase in abatement costs takes into consideration the extent and difficulty of control, as well as the possibility that additional measures may be required to deal with each of several environmental problems.

SECTION I. INTRODUCTION

This Environmental Readiness Document (ERD) is one of a series of independent reviews prepared by DOE's Office of Environment (EV) of the status of environmental concerns associated with energy technologies being developed by DOE. An ERD is prepared at appropriate times in the development cycle of a technology program to inform decision makers and the public about the readiness of a technology for commercialization from an environmental point of view. The ERD summarizes the professional judgements of EV scientists on the magnitude or significance of potential environmental problems in the light of current information. When new information is available and it is appropriate to the timing of the decision process, this ERD will be updated.

The document addresses the uncertainties about environmental aspects of magnetohydrodynamics that remain to be resolved through MHD Phase I activities. The resolutions of these uncertainties may require adjustments in the development program before the technology can be commercialized.

Site-specific concerns are discussed in the ERD but are not treated in detail, since specific sites usually have not been determined. The document emphasizes those impacts and concerns which are generic to the technology.

Section II of this document describes the technology and expectations about its future utilization. Information pertinent to the technology was drawn from the DOE technology program office and from an Environmental Development Plan developed for the technology by EV and the program office through an Environmental Coordinating Committee.

Section III examines the environmental concerns associated with the technology and discusses the current status of knowledge about each concern and its potential seriousness and manageability through regulation and control technology.

Section IV summarizes present and projected societal capabilities to reduce and control undesirable environmental, health, safety, and related social impacts to a level of public acceptability--as reflected in current and proposed environmental standards--which will allow the technology to be commercialized and utilized in a timely manner.

The ERD as a whole thus provides an assessment, within the limits of available knowledge and remaining uncertainties, of the future environmental readiness of the technology to contribute to the meeting of the Nation's energy needs.

"The lack of appropriate National Environmental Policy Act (NEPA) documentation can cause a significant delay in the development and commercialization cycle. However, no attempt has been made in this presentation to identify formal NEPA requirements (the type of NEPA document required and its schedule). There is a prescription, however, that Programmatic Environmental Reviews, as appropriate will be prepared pursuant to 10 CFR 1021, 'Compliance with the National Environmental Policy Act' (Federal Register Volume 43, No. 35, February 21, 1978), prior to the DOE taking action to commercialize any technology or process."

SECTION II. THE TECHNOLOGY

A. Technology Characterization

MHD power generation is based on the direct conversion of heat to electricity by passing a high temperature, high velocity, electrically conducting potassium-seeded plasma through a magnetic field. The objective of the DOE MHD program is to develop MHD technology to determine the commercial viability of MHD/steam power generation systems. This technology is being pursued because of the potential of MHD as a future source of low-cost, central station electric power.

A typical open-cycle MHD topping cycle with a conventional steam turbine bottoming cycle is illustrated schematically in Figure 2-1. Preheated air and fuel are burned in a fuel-rich environment under pressure and at a very high temperature in a combustor. The seed (potassium salts) is injected to increase electrical conductivity; the combustion gas/seed mixture is fed into the MHD channel where d-c electrical power is generated. Combustion gases then pass through a diffuser where the remaining kinetic energy is recovered.

The residual heat in the exhaust gases can be utilized downstream in a conventional steam power plant. The combustion gas passes through a radiant boiler where the gas stream is cooled slowly to reduce NO_x emissions before additional air is added to complete combustion. Waste heat is extracted from the radiant boiler for use in the bottoming (conventional steam-electric) cycle. Combustion gas then flows to the air preheater where heat is extracted to warm the air which is fed to the combustor. Heat from the walls of the radiant boiler is heated further prior to utilization in the steam turbine. Spent seed is condensed in the seed condenser as potassium sulfate (K_2SO_4). After leaving the air heaters, combustion gases flow through economizers to particulate control devices where additional seed material and ash are collected before leaving the stack.

Figure 2-1.--Open-Cycle Coal-Fired MHD System *

*Taken from Reference 5.

B. Implications of Scale, Timing, and Location

The three major goals of DOE's MHD program are to 1) achieve overall power conversion efficiencies near 50%, 2) demonstrate economic feasibility, and 3) meet existing or proposed federal standards which have been announced for SO_2 , NO_x , and particulate emissions.¹ The third goal involves pollutants associated with both MHD and conventional coal-fired systems; these may differ qualitatively and quantitatively as result of four MHD-related factors: 1) high temperature, 2) addition of seed material, 3) emission control technology, and 4) use of a superconducting magnet.

The current program assumes a flexible three-step approach to commercialization (Figure 2-2). Engineering development progress in Phase I is monitored through a succession of critical 50 MW_t tests in the Component Development and Integration Facility (CDIF). These tests will help determine the Engineering Test Facility (ETF) design, which leads to Phase II. Presently, several Phase II alternatives are being considered: 1) retrofitting an existing fossil-fueled power plant by adding an MHD topping generator (several designs are under consideration) or 2) design and construction of a new 500-750 MW_e coal-fired plant incorporating a 250 MW_t MHD topping generator.^{2,3,4} The retrofit options are designed to provide the demonstration in conjunction with an on-line utility of a retrofit option which will make the large and expensive so-called commercialization demonstration (i.e., Phase III) unnecessary.

The MHD program utilizes numerous research facilities in 15 states around the United States (Table 2-1). The two major government test facilities, the CFFF and the CDIF, are being constructed to accommodate key development and integrated engineering tests (Phase I) at larger scales than are available elsewhere in the United States; both will be completed during FY 1980. The CDIF is located in Butte, Montana. This facility will be the principal facility within the MHD program for continuous testing of engineering-scale power trains of 50 MW_t , an intermediate level between existing facilities

Legend: AEDC/U-25 = Arnold Engineering Development Center/U.S.S.R. Facility
 CDIF = Component Development and Integration Facility.
 CFFF = Coal-Fired Flow Facility.
 ETF = Environmental Test Facility.

Figure 2-2.--MHD Program Development Alternatives*

*Taken from Reference 1 (does not include ETF retrofit options).

Table 2-1.--Summary of MHD Research Facilities*

Air Force Aero Propulsion Laboratory, Wright Patterson Air Force Base, Ohio.
Argonne National Laboratory, Argonne, Illinois.
Arnold Engineering Development Center, Arnold Air Force Station, Tennessee..
AVCO-Everett Research Laboratory, Everett, Massachusetts.
Battelle Pacific Northwest Laboratory, Richland, Washington.

Fluidyne Engineering Corporation, Minneapolis, Minnesota.
Francis Bitter National Magnet Laboratory, Cambridge, Massachusetts.
General Electric Company-Space Science Laboratory, Philadelphia, Pennsylvania.
Massachusetts Institute of Technology, Cambridge, Massachusetts.
Mississippi State University, Mississippi State, Mississippi.
Montana Energy and MHD Research and Development Institute, Butte, Montana.
NASA Lewis Research Center, Cleveland, Ohio.
National Bureau of Standards, Washington, D. C.
Pittsburgh Energy Technology Center, Pittsburgh, Pennsylvania.
Reynolds Metal Company, Sheffield, Alabama.
Rocketdyne Division Rockwell International, Canoga Park, California.
Stanford University, Stanford, California.
STD Research Corporation, Arcadia, California.
TRW, Incorporated, Redondo Beach, California.
University of Tennessee Space Institute (UTSI), Tullahoma, Tennessee.
Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.

*Includes support and development facilities in the United States.

and Phase II. It is expected that a major portion of the data for the Phase II MHD power train design will be validated through CDIF testing before 1984. The facility can accommodate multi-stage combustors that may have a slag rejection of up to 90%. The CFFF is located at the University of Tennessee Space Institute near Tullahoma, Tennessee. It will be capable of continuous operation at an input of 20 MW_t and short duration testing of 50 MW_t . A high slagging power train/coal-fired combustor will be developed at CFFF at the 20 MW_t level. The major objectives of DOE's MHD facilities are presented in Table 2-2.

The commercial demonstration baseload will show performance at a scale of several hundred megawatts by constructing/retrofitting and operating a fully integrated combined cycle MHD/steam utility plant. This plant presently is anticipated to become operational prior to FY 97 (Figure 2-3). Presently it is planned to be a government-owned and operated MHD utility plant.

Table 2-2.--Objectives of DOE's MHD Facilities*

TEST FACILITY	OBJECTIVES
Coal-Fired Flow Facility (CFFF)	<ul style="list-style-type: none"> • Test MHD Concepts at the 20 MW_t Level • Test and Verify the Total Slag Carry-Over Concept • Test Simulated System Components • Develop MHD Concepts • Verify Steam Bottoming Cycle Component Concepts
Component Development and Integration Facility (CDIF)	<ul style="list-style-type: none"> • Test Components in 50 MW_t Range • Test Individually or in Subsystem Test Train
Engineering Test Facility (ETF)	<ul style="list-style-type: none"> • Provide Design and Operation Data for MHD/Steam Power Plant • Verify Component Performance at 250 MW_t Scale at Commercial Operating Durations • Provide Scale-up Data for MHD Baseline Plant • Provide Advanced Systems Integration
Commercial Demonstration (CDP)	<ul style="list-style-type: none"> • Demonstrate Direct Coal-Fired, Open-Cycle MHD Power Generation Ready for Commercial Application

*Taken from Reference 5 (does not include ETF retrofit options).

Figure 2.3.--MHD Development Schedules*

*Taken from Reference 1.

SECTION III. ENVIRONMENTAL CONCERNS

The environmental concerns associated with MHD technology are expected to be similar to those encountered in a conventional coal-fired power plant. However, the higher temperatures required in the MHD process, and several other unique engineering design characteristics may cause potential emissions to differ in certain respects from those generated in a conventional coal-fired power plant. As a result of the higher overall plant efficiencies envisioned for an MHD/steam turbine power plant and the inherent nature of the MHD process, the environmental impacts associated with plant operation are expected to be less per unit of electrical power produced than those from a conventional coal-fired power plant.⁵

The major environmental concerns (Table 3-1) currently perceived as affecting the future acceptability of MHD for commercial development, listed according to seriousness or severity, are as follows.

- If uncontrolled, air pollution caused by the high combustion temperatures (4500-5000°F) used in open-cycle MHD could produce greater quantities of NO_x than in conventional coal combustors.
- Fine particles of fly ash (<3 microns)⁵ in the exhaust gases may contain trace elements. These particles could be inhaled into the lungs; thus representing a potential human health hazard.
- The adverse effects of chronic exposure to three to six Tesla d-c magnetic fields are not well understood and may pose a threat to the health of workers.
- SO₂ emission control utilizing large quantities of potassium carbonate (K₂CO₃) seed material has been demonstrated for 5 MW_t MHD facilities. The seed recovery/regeneration system will have a great deal to do with this ultimate SO₂ control and potential emissions.⁶

Table 3-1.--Significance of Concerns

Environmental Concern (In Order of Severity)	Significance	Uncertainty	Program Delay	Additional Product/ Energy Costs (\$)
1. NO _x Emissions	Moderate--There is a potential for 10 times the NO _x emissions of a conventional coal-fired generator, if uncontrolled.	Moderate--A satisfactory control technology has been identified and has been tested on the 5 MW _t scale.	Possibly--Could delay commercialization.	Moderate--Costs are related to component design and are being built into the system.
2. Fine Particulate	Moderate--Trace elements contained on fine particles of fly ash may pose a health hazard.	High--The application of existing control technologies is uncertain.	Possibly--Could delay commercialization.	Moderate
3. Magnetic Fields	Moderate--Worker exposure to strong magnetic fields may pose a health hazard.	Moderate--Regulations are pending.	Unlikely	Minor
4. SO ₂ Emissions	Minimal--Seed recovery should control SO ₂ emissions.	Moderate--An adequate control technology has been demonstrated at the 5 MW _t level.	Unlikely	Minor--Costs are related to seed recovery/regeneration technology which are presently being developed.
5. Solid Wastes	Minimal--Proper disposal of wastes to holding ponds or landfills will reduce any hazard.	Moderate--Regulations are pending.	Unlikely	Major--If deemed hazardous under RCRA Minor--If deemed non-hazardous under RCRA.
6. Secondary Concerns	Minimal	Low	Unlikely	Minor

A variety of wastes, including seed, fly ash, and slag, may be toxic or mutagenic, corrosive, or otherwise hazardous according to the pending RCRA regulations.

In addition to these primary environmental concerns, there are several areas of secondary concern including in-plant noise, vibration, volatilization of hazardous compounds during coal combustion, hydrocarbons, safety hazards, and site-specific impacts such as fugitive dust, land use, and socioeconomic factors. These concerns should not be driving factors in the timing of MHD commercialization and are detailed in the MHD Environmental Development Plan (EDP).⁵

Nitrogen Oxide (NO_x)

NO_x emissions produced in an MHD combustor without sufficient control technology could have a significant impact on plants, animals, and humans⁷ in the area adjacent to, and down-wind of, an MHD facility. An open-cycle MHD plant utilizes combustion temperatures approaching 5000°F with the potential for greater NO_x emissions than conventional coal combustion.^{8,9,10} Predictions of NO_x emissions have ranged from less than 50 parts per million (ppm) to over 400 ppm.⁵ Bienstock, et al. indicate the capability to successfully control NO_x emissions in an MHD system.¹¹ Experimental work at the University of Tennessee Space Institute (UTSI) confirm that NO_x emissions can be kept within existing and proposed standards¹² by initial fuel rich combustion, completing combustion at lower temperatures and controlling the cooling rate of exhaust gases. Allowable emissions are 0.5 lb. NO_x/10⁶ Btu of heat input, or about 350 parts per million velocity (ppmv), depending upon the coal characteristics. Presently it appears that NO_x emissions will be controlled by minimizing its concentration in the effluent stream through combustion modification and design of the radiant furnace to enhance NO_x decomposition. This is an uncertainty because the technology has not been tested.

Fine Particulate

Particulate matter existing in the exhaust gases mainly will consist of fly ash and unrecovered seed material. The fly ash produced in the MHD process is expected to differ in size and structure relative to conventional coal-fired power plants as a result of very high combustion temperatures ($\sim 5000^{\circ}\text{F}$), and possibly due to the superconducting magnet¹³ and NO_x control methods.^{14,15} Total fly ash will be considerably less from an MHD facility (relative to conventional coal-fired plants) because the major fraction is removed from the system as liquid slag.⁵ However, a portion of this total quantity will be composed of fine particles (<3 microns) which are difficult to efficiently remove using conventional control techniques.^{16,17} The collection efficiency of scrubbers and, to a lesser extent, electrostatic precipitators, decreases with decreasing particle size, typically reaching a minimum value in the 0.1 to 1.0 micron size range.^{18,19} These are potentially harmful emissions, since the finer particles are more readily retained in the human respiratory system.²⁰ In anticipation of the potential problem with submicron particulates the EPA probably will set a fine particulate emission standard during the 1980's.⁵

These fine particles may contain, on and within their structure, various trace elements. Many elements are vaporized in the high temperature MHD stream and then condense out as the stream cools. The elements vaporizing at the highest temperature condense out first, and those with the lowest boiling point condense out last. This mechanism accounts for the observation that certain trace elements are enriched preferentially in fly ash as compared to bottom ash and that some elements increase in concentration with a decrease in particle size (because of the greater available surface area). This phenomena has been observed in conventional coal burning processes and may be amplified by the higher temperatures of MHD.¹⁶

Preliminary investigations on the extent of preferential enrichment of trace elements on fine particulates from prototype MHD facilities

have been conducted by the Montana Energy and MHD Research and Development Institute (MERDI) under a DOE contract. Similar studies for conventional coal-fired facilities are being conducted by Battelle Pacific Northwest Laboratory.²¹ Comparative data contrasting various coal combustion processes will require additional testing at more advanced MHD facilities. The emission control strategy and equipment will depend on the details of particulate concentration, sizing, composition, and other variables unique to MHD technology.

The impact of fine particulate on human health and the natural environment is dependent upon the control technology utilized. The expected level of impact cannot be assessed until further engineering tests have been completed. With present and on-going research, the possibility of major interference with the timing and readiness of MHD commercialization is slight.

Magnetic Fields

MHD facilities have the potential for human exposure to highly intense magnetic fields of up to six Tesla at the source. The apparent effects on the nervous, cardiovascular, and other vital systems are not understood completely and are, at times, controversial.^{22,23} Recommendations for guidelines on occupational exposure to d-c magnetic fields currently are being formulated.²⁴ Recently, a committee chaired by Dr. Edward L. Alpen has reviewed the existing experimental data and anecdotal occupational exposure data to magnetic fields. Their study has resulted in proposed interim standards for occupational exposure to time-constant d-c magnetic fields as shown in Table 3-2. Following promulgation, a three-to five-year research program would gather the necessary data to evaluate the initial standards effectiveness in protecting worker health. It should be noted that certain combinations of partial body and whole body exposure are allowable, e.g., 0.1 Tesla exposure of hands and arms per work day and 0.01 Tesla exposure of the remainder of the body for the same time period. The criteria for

Table 3-2.--Recommended Occupational Exposure
Interim Standards for Constant
Magnetic Fields

	<u>8-Hour Work Day</u>	<u>1 Hour or Less</u>	<u>10 Min. or Less</u>
Whole Body or Head Exposure	0.01 Tesla	0.1 Tesla	0.5 Tesla
Exposure of Extremities	0.1 Tesla	1.0 Tesla	2.0 Tesla

Source: July 23, 1979 correspondence to Dr. Kenneth R. Baker, Division of Safety, Standards, and Compliance, U.S. Department of Energy from Dr. Edward L. Alpen, Lawrence Berkeley Laboratory.

exposure to magnetic fields in MHD facilities should be developed based on the results of environmental and biomedical monitoring programs. Controls for worker protection from such fields during operation have been developed for use in the U-25 250 MW_t MHD facility located in Moscow, U.S.S.R.²⁵

Until successful personal dosimeters for magnetic fields have been developed, the expected levels of worker exposure, and the efficiency of control cannot be adequately assessed. At this time only instantaneous measures via gaussmeters can be acquired. The example of the U-25 MHD facility shows that magnetic fields can be contained sufficiently to protect worker health and safety.

Sulfur Dioxide (SO₂)

The most impressive environmental advantage to MHD is its built-in sulfur removal capability. No flue gas scrubbing system available today can remove SO₂ as economically as the potassium seed reaction in the MHD process, assuming cost-effective recovery/regeneration technology and low-sulfur coals are used. The potassium carbonate (K₂CO₃) seed used to increase the conductivity of the gas stream reacts readily with the SO₂ to form potassium sulfate (K₂SO₄) or sulfite (K₂SO₃).

Preliminary experimental results have shown that seeding can reduce SO₂ emissions significantly in 2-5 MW_t systems.⁶ Efficient seed recovery and regeneration (back to K₂CO₃) of the potassium sulfate appears to be necessary to make MHD economical and to meet future SO₂ NSPS standards. Several options have been identified and economic and technical evaluations have been conducted by Westinghouse,²⁶ Exxon,²⁷ and UTSI.²⁸ The options incorporated into the various MHD systems will bear directly on the quality and quantity of SO₂ emissions (as well as the potential solid waste disposal levels).

The efficacy of present control technologies primarily will be determined by cost-effectiveness. Completed tests indicate that the level of potential impact should be sufficiently within the presently established standards requiring 70 to 90% SO_2 removal for large coal-fired power plants with the emission ceiling of $1.2 \text{ lb}/10^6 \text{ Btu}$.

Solid Waste

MHD-generated wastes include seed, fly ash, and slag; these materials should differ from wastes generated by conventional coal-fired power plants in several respects: 1) there will be a higher concentration of potassium compounds (K_2CO_3 , K_2SO_4) resulting from the injection of the seed material; 2) slag from the combustor may have different properties than slag and bottom ash from a conventional coal-fired system primarily because of the high temperatures and seed injection; 3) fly ash and spent seed collected in emission control devices probably will contain a greater proportion of fine particles; and 4) trace elements adhering to the surface of the fine particles may be more toxic (mutagenic, carcinogenic, or teratogenic) to biological systems through leaching^{30,31} or fugitive emissions. At present, more of the envisioned effluents appear to be subject to RCRA hazardous substance criteria.³² In addition to toxicity, three additional areas of potentially regulated concerns are corrosivity, ignitability, and radioactivity.³³

The quantity and physiochemical characteristics of solid waste will depend largely upon the overall facility design and the final design of the seed regeneration system^{26,27,28} plus emission control devices incorporated into the system. For example, it is anticipated that the CDIF will generate in excess of 3 million gallons of wastes from the coal-fired test train during the first 2000 operating hours.³⁴ These wastes will include exit gas bottoms, thickener dump, combustor and scrubber slag, cooling tower dump, and coal pile runoff. If SO_2 is removed via scrubbers rather than through seed reaction, then the solid waste generated will have different properties. The final design of DOE's MHD Engineering Test Facility (ETF) planned for the 1980's has not yet been finalized, but it will bear directly on the solid waste problem.

A physiochemical characterization of MHD-related effluent streams, including mass balances, currently is underway for the CDIF operation. Operations at the facility will be site- and facility-specific, and not representative necessarily of the total MHD system technology. Pending the promulgation of final RCRA regulations, no definitive assessment of MHD readiness relative to toxic, corrosive, radioactive, or ignitable criteria can be delineated.

SECTION IV. REGULATORY AND CONTROL CONSIDERATIONS

A. Environmental Regulations and Standards

The major environmental constraints of emerging MHD technology are related to legal compliance.^{35,36} The most important regulations are reviewed in Table 4-1. These include standards for air, water, solid wastes, worker safety, and toxic substances.

There are three major EPA regulations affecting air quality: 1) New Source Performance Standards (NSPS), 2) National Ambient Air Quality Standards (NAAQS), and 3) Prevention of Significant Deterioration of Air Quality (PSD). NSPS are designed to limit stack emissions from particular sources, NAAQS seek to limit the pollutants in ambient air (from whatever source), and PSD regulations are established to prevent a deterioration of air quality. The current NSPS for large coal-fired steam generators (larger than 250 million Btu/h) regulate emissions of SO_2 , NO_x , and particulate. Fine particulate emission standards are envisioned for the 1980's.^{20,37} It is assumed that MHD will have to meet the minimal standards set for large coal-fired steam generators. Work performed to date on SO_2 and NO_x control technologies for MHD indicate that these pollutants can be controlled effectively to levels at or below current NSPS for coal-fired power plants. These conclusions are based on experimental work.^{12,17} The cost-competitiveness of best available control devices should be the primary influence on the timing and readiness of MHD technology. Initially MHD emission control will rely largely on controls developed for conventional power plants. However, new or modified control methods also may be required for unique MHD emissions such as potassium compounds, elevated levels of NO_x , and fine particulates.

Water discharge, solid waste disposal, toxic substances, and worker safety and health are other regulated parameters that are connected with further implementation of the DOE MHD program. A National Pollutant

Table 4-1.--Regulatory Impacts of Magnetohydrodynamics

Legislation	Pollutant/Concern	Current/Proposed Standards	Possible New Standards
<u>Clean Air Act</u>			
NSPS	Emissions from fossil fuel-fired stationary sources.	NSPS currently do not exist for coal-fired MHD facilities.	It is not known whether NSPS for conventional coal-fired power plants will be applied to MHD, or if separate NSPS will be established.
PSD	SO ₂ , total suspended particulates.	Siting may be restricted due to PSD requirements.	
Non-Attainment	SO ₂ , total suspended particulates, NO ₂ , CO, O ₃ , hydrocarbons.	Environmental Assessment and possibly Environmental Impact Statement, needed.	States may classify areas as non-attainment.
Visibility			Fine particulate standards.
<u>Federal Water Pollution Control Act</u>	Non-degradable organics, dissolved solids, trace elements	A NPDES permit is required if wastewater and solids are discharged into a navigable water. A state permit may be required for point-source discharge.	Wastewater discharges may require additional treatment for removal of heavy metals or organic waste if they enter drinking supplies.
<u>Resource Conservation and Recovery Act</u>	Slag, fly ash, potassium seed, liquid wastes, sludge.	If waste is classified as hazardous, the facilities will have to meet RCRA requirements. Waste stream will require testing.	New RCRA guidelines are under-going review. Facilities engaged in treatment, storage, or handling of hazardous waste will require permits.

Table 4-1.--(Continued)

Legislation	Pollutant/Concern	Current/Proposed Standards	Possible New Standards
<u>Toxic Substances Control Act</u>	MHD process related materials, e.g., cooling tower blowdown.	EPA implementation of TOSCA is oriented toward the manufacture and use of chemicals.	
<u>Occupational Safety and Health Act</u>	Noise, magnetic field, explosion potential, vibration. Exposure to toxic mutagenic chemicals.	Health and safety regulations must be met for workers.	Standards currently do not exist but will most likely be promulgated for worker exposure to magnetic fields. Characterization of toxic chemicals not known.

Discharge Elimination System (NPDES) permit will be required if waste water is discharged into a navigable water. RCRA standards for solid wastes presently are being reviewed and modified; these may effect the classification of MHD-related waste products as either hazardous or non-hazardous. Although unlikely, certain MHD materials (primarily chemical treatment substances) may be regulated by the Toxic Substances Control Act. Finally, the standards established under the Occupational Safety and Health Act must be met prior to MHD plant operation. Additional worker safety standards may be implemented for human exposure to magnetic fields.

No constraints presently are considered to be insurmountable to the timing and readiness of MHD technology, but implementation of the environmental program (Figures 4-1, 4-2, and 4-3) will be necessary to ensure that sufficient data is available to assure regulatory compliance and/or suggest needed system modifications.

B. Control Technology and Estimated Costs

MHD-related air emissions and the integration of appropriate emission control devices are still being researched. It is assumed that the stack emissions will be similar to a conventional coal-fired power plant, but additional data must be collected to ascertain the validity of this assumption.

NO_x formation will be encouraged by high operating temperatures,^{8,10,12} but control is anticipated through combustion modification and controlled cooling of combustion gases.^{10,38} Engineering tests performed on 2-5 MW_t MHD units indicate that NO_x control is possible. Further refinements produced by the CFFF and CDIF evaluation results will be applied as feasible to the design of a more representative power generation train. The collective data will provide the essential information for designing an ETF engineering plan which complies with the NSPS NO_x standards.

CDIF TECHNOLOGY DEVELOPMENT

Design/Fabricate
Construction
Testing - Train 1A
Train 1B
Advanced Testing
ETF Design Support Testing

Baseline and Operating Ambient Monitoring Programs for the CDIF

Characterize and Monitor Air Emissions and Water Effluents During Operation

Analysis of the Chemical and Physical Stability of MHD Slag and Fly Ash and the Implications of Treatment and Disposal

Design and Implementation of an Occupational Health and Safety Monitoring Program at MHD Facilities

Assessment of Ecological Impacts of CDIF Emissions

Development of a Water Conservation Plan for the MHD CDIF

Evaluation and Assessment of Effluent Data

Preparation of CDIF Program Environmental Plan (PEP)

Preparation of ERD

*Taken from Reference 5 (certain information may require updating).

Figure 4-1.--Environmental Action Plan for the MHD CDIF*

Conceptual Design &
System Engineering Studies
Preliminary Design (Title I)
Detailed Design (Title II)
Construction

Baseline and Operating Ambient Monitoring Programs for the ETF

Characterize and Monitor Air Emissions and Water Effluents During Operation

Design and Implementation of an Occupational Health and Safety Monitoring Program at MHD Facilities

Assessment of Ecological Impacts of ETF Emissions

Preparation of an EA and EIS, if necessary, for the MHD ETF

Development of a Water Conservation Plan
for the MHD ETF

Preparation of ERD

Preparation of ETF Program Environmental Plan (PEP)

Evaluation and Assessment of Effluent Data

CFFF TECHNOLOGY DEVELOPMENT

Design
Construction
Operation

CDIF TECHNOLOGY DEVELOPMENT

Design/Fabricate
Construction
Operation

ETF TECHNOLOGY DEVELOPMENT

Design
Construction
Operation (1990 ▲)

Characterize and Monitor Air Emissions
from the CFFF

Analysis of the Chemical and Physical
Stability of MHD Slag and Fly Ash and
the Implications for Treatment and Dis-
posal

Assessment of Nitrogen Oxides Emission
Control Technologies for MHD Power Plants

Assessment of Particulate Control Tech-
nologies for MHD Facilities

Environmental Impact of MHD Seed Regen-
eration Systems

*Taken from Reference 5 (certain information may require updating).

Figure 4-3.--Environmental Action for General MHD Development
Supporting Technology Centers*

Analysis of Alternative Means of Solid Waste Management

Design and Implementation of an Occupational Health and Safety Monitoring Program at the CFFF

Determination of Health Effects of Trace Elements and Organic Compounds Identified in the MID Process

Definition of Biological Effects Induced by High Intensity Magnetic Fields Associated with MID Systems

Assessment of Ecological Impacts of CFFF Emissions

MID Plant Siting Evaluation

Correlation, Evaluation, and Assessment of MID Effluent Data

Figure 4-3.--(Continued)

Most particulate emissions can be controlled by fabric filters, scrubbers, or electrostatic precipitators.^{16,17} One uncertainty is that MHD presently is anticipated to produce a significant quantity of fine particulates. The extent to which fine particle emissions will be a problem must be assessed; if necessary, non-conventional control technologies may have to be utilized. Additional monitoring is required to verify the necessity for more advanced control technologies.¹⁷

MHD has a built-in SO₂ removal system (via seed recovery) which can function more efficiently than any known flue gas scrubbing system.^{6,11,39} The actual design of an economical and environmentally sound seed recovery/regeneration process has not been ascertained yet, but several are being evaluated.^{26,27,28} Monitoring SO₂ stack emissions will be essential in evaluating the efficiency of this proposed seed recovery/regeneration system. The CDIF and the CFFF will not contain such a system, but seeding and downstream recovery should mitigate SO₂ as an emission problem.

Presently, human data are very limited on the effect of the superconducting magnet on facility personnel, and much of what is available is open to question.⁵ There are no formal guidelines or standards applicable to human exposure to strong magnetic fields. Research on occupational health and safety has been initiated to qualitatively and quantitatively evaluate the potential adverse effects of worker exposure to MHD-related magnetic fields (see Table 3-2).

Disposal of solid wastes from MHD facilities must comply with the provisions of the RCRA. This act requires that all wastes generated by utility companies be designated as hazardous or non-hazardous. The criteria used to establish these categories has not yet been fully formulated by EPA. If a solid waste is designated hazardous, then it must be handled, stored, and disposed of in a manner prescribed by the EPA and administered through a state-implemented solid waste management plan. A non-hazardous designation probably would result in the disposal of solid waste in a fashion similar to the methods used for conventional coal-fired power

plants. Present indications are that MHD slag and fly ash will be classified as non-hazardous.³²

An estimate of the relative costs attributable to environmental control for an MHD system has been included in a report prepared by Exxon.²⁷ These estimates should, however, be viewed as imprecise, because of the difficulty in categorizing particular equipment as part of an environmental control system. The conceptual power plant design incorporates control technology into the developing system design and results in the entire plant functioning, to a certain extent, in the control of emissions.

Lahoda and Lippert²⁶ summarize the costs of eight candidate sulfur removal schemes. They include the installed capital cost, the annual cost, and the cost per kilogram K_2CO_3 . The control technology to be utilized in the final MHD system design has not been determined yet. Other control costs (NO_x , solid waste, etc.) are speculative because the data are incomplete. CDIF and CFFF monitoring results will contribute greatly to understanding MHD environmental concerns. The comparison of pre-and post-operational data should allow a more informed estimate of the environmental impact of MHD as well as the cost-competitiveness and necessity for various control technologies.

The costs to implement an environmental plan, including monitoring, for the CDIF are outlined in a Project Environmental Plan (PEP).⁴⁰ These monies would be spent in seven areas outlined in the PEP: 1) Compliance with Environmental Regulations, 2) Environmental Controls, 3) Characterization and Monitoring, 4) Occupational, Health and Safety, 5) Ecological Effects, 6) Solid Waste, and 7) Assessments and Socioeconomic Impacts. The funding would be handled through the Office of Energy Technology and the Office of Environment. Figures presented in the PEP are estimates and will change as research data is accumulated, new standards are set, engineering designs are modified, etc. Environmental health and ecological effects of regulated materials, however, can be mitigated at some dollar cost.

The comprehensive site-specific environmental program established for the CDIF, and an environmental monitoring program being developed for the CFFF, assume that MHD-related environmental research will include air emissions, solid waste toxicity and disposal, occupational health and safety (especially magnetic fields), and related regulatory constraints. Baseline air quality and meteorology/climatology currently are monitored at the CDIF. A water quality/biological surveillance program also is being conducted to establish a quantified environmental baseline for chemical, physical, and biological factors. Operational data will be collected after facility operations commence in 1980.

The environmental control costs presented in Table 4-2 represent first-order estimates for process configurations that have been arbitrarily selected to represent each energy conversion technology. The intent of these costs is to give the reader an appreciation for the relative contribution the imposition of environmental controls may make to total energy costs for a particular technology.

Two environmental control scenarios have been chosen to further indicate the degree of impact that more stringent emerging Federal environmental standards may have on energy cost and ultimate marketplace competitiveness. The first scenario is based on meeting near-term compliance environmental standards similar to those in effect for new utility plants. The second scenario assumes that very stringent environmental standards are promulgated (i.e., for emissions: tougher SO_2 , NO_2 and fine particulate control; for effluents: organics and trace metal control; for solids: long-term organics and trace elements control).

There are several points that must be stressed to emphasize the uncertainty of the numbers presented:

- The variability of the reference technology. Most cost data are highly sensitive to site-specific criteria, e.g., feedstock, process configuration, end product mix, environmental and boundary conditions. Thus, there is a high natural variability of baseline energy costs.

Table 4-2.--Anticipated Contribution of Pollution Control Costs to
Energy Costs For Magnetohydrodynamics in Estimated
Mid-1980 Dollars

	Current Standards		Future Stringent (Worst Case) Standards	
	Energy Cost Mills/kwhr	Environmental Cost Mills/kwhr	Energy Cost Mills/kwhr	Environmental Cost Mills/kwhr
<u>NO_x</u> ^{a)}	0.00	0.00	0.00	0.00
<u>Particulate</u> ^{b)}				
1. Fabric Filters:				
a. Western Coal ^{c)}	0.08 ^{e)}	1.96 ^{e)}	0.08 ^{e)}	1.96 ^{e)}
b. Eastern Coal ^{d)}	0.07 ^{e)}	1.72 ^{e)}	0.07 ^{e)}	1.72 ^{e)}
2. Electrostatic Precipitators				
a. Western Coal	0.26 ^{e)}	3.77 ^{e)}	0.26 ^{e)}	3.77 ^{e)}
b. Eastern Coal	0.08 ^{e)}	1.49 ^{e)}	0.08 ^{e)}	1.49 ^{e)}
3. Venturi Scrubbers				
a. Western Coal	0.12 ^{f)}	3.17 ^{f)}	-- ^{g)}	--
b. Eastern Coal	0.11 ^{f)}	3.22 ^{f)}	--	--
<u>SO₂</u> ^{b)}				
1. Limestone				
a. Western Coal	1.02 ^{h)}	8.57 ^{h)}	0.85 ⁱ⁾	7.58 ⁱ⁾
b. Eastern Coal	0.85 ^{h)}	10.45 ^{h)}	12.68 ^{j)}	--
2. Double Alkali				
a. Western Coal	1.02 ^{h)}	--	--	--
b. Eastern Coal	0.85 ^{h)}	8.57 ^{h)}	--	--
3. Seed Recovery	0.13 - 0.70 ^{k)}		--	--

a) The cost and efficacy of NO_x control is a function of boiler design (see C.D. Kalfadelis, et al, Environmental Assessment of a Coal-Fired Open-Cycle MHD Power Plant, Exxon Government Research Laboratories, Linden, New Jersey, May 1978).

b) See U.S. Environmental Protection Agency, Particulate and Sulfur Dioxide Emission Control Costs for Large Coal-Fired Boilers, EPA-450/3-78-007, February 1978, Tables 3-4 and 3-5.

Table 4-2.--Anticipated Contribution of Pollution Control Costs to
Energy Costs for Magnetohydrodynamics in Estimated
Mid-1980 Dollars (Continued)

- c) 0.8% sulfur and 8.0% ash.
- d) 3.5% sulfur and 14.0% ash.
- e) At the 500 MW_e level, total cost, assuming the new regulatory standard of 13.0 ng/j.
- f) At the 500 MW_e level, total cost, assuming the old regulatory standard of 43.0 ng/j. It is unlikely that the Venturi option will be cost effective at the new standard of 13.0 ng/j.
- g) No information available.
- h) At the 500 MW_e level, total cost, assuming 90% SO₂ removal.
- i) At the 500 MW_e level, total cost, assuming a standard of 215 ng/j.
- j) Assumes 7.0% sulfur.
- k) The seed loss fractions for various regeneration processes represent an increment in cost of electricity that ranges from about 0.13 mill/kwhr (scrubber) to 0.7 mill/kwhr (formate process). See E.J. Lahoda and T.E. Lippert, "An Evaluation of Candidate Seed Processing Systems for Open-Cycle MHD," Proceedings of the 18th Symposium on Engineering Aspects of Magnetohydrodynamics, Butte, Montana, 1979, p. C.3.5.

- The lack of actual confirmatory costs. The costs presented, especially for the scenario dealing with future regulations, are based on paper studies, not actual experience. These costs may be subject to drastic change as scale-up and commercial cost data become available.
- The uncertainty of the environmental targets. For most technologies, a complex matrix of overlapping Federal, state, and local environmental standards is evolving. It is therefore extremely difficult to extrapolate to the controlling standards for technologies that are, themselves, developing rapidly. This situation is further complicated by the potential advent of more stringent standards.
- The uncertainty of secondary effects associated with controls. Environmental controls should not be isolated from the total energy system: they are an integral part of it. Thus, process efficiency loss, secondary waste production, additional resource consumption, etc., must be accounted for in assessing the efficacy of the control option. Only cursory consideration was given to these factors in this study. Additionally, the identification of environmental control systems apart from the energy system itself is largely subjective.

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GLOSSARY

AEDC--Arnold Engineering Development Center.
CDIF--Component Development and Integration Facility.
CDP--Commercial Demonstration Plant.
CFFF--Coal-Fired Flow Facility.
DOE--Department of Energy.
ECAS--Energy Conversion Alternatives Study.
EDP--Environmental Development Plan.
EPA--Environmental Protection Agency.
ERD--Environmental Readiness Document.
ETF--Engineering Test Facility.
EV--Office of Environment.
MHD--Magnetohydrodynamics.
NPDES--National Pollutant Discharge Elimination System.
NSPS--New Source Performance Standards.
OCMHD--Open-Cycle Magnetohydrodynamics.
PEP--Project Environment Plan.
PSD--Prevention of Significant Deterioration.
RCRA--Resource Conservation and Recovery Act.
R&D--Research and Development.
TOSCA--Toxic Substance Control Act.
TSP--Total Suspended Particulate.