MHD Advanced Power Train

Phase I Final Report

Volume 1 Executive Summary

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Prepared For

**THE UNITED STATES DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER**

Contract DE-AC22-83PC60575

AUGUST 1985

Westinghouse

Advanced Energy Systems Division
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THE UNITED STATES DEPARTMENT OF ENERGY PITTSBURGH ENERGY TECHNOLOGY CENTER

Government Technical Project Officer:

Dr. Harold F. Chambers, Jr

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AUGUST 1985

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VOLUME 1
TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1.0 Background	1-1
1.1 Starting Point for the Study	1-2
1.2 Integrated Approach	1-2
1.3 Study Participants	1-4
2.0 Study Scope	2-1
3.0 Technical Report: Volume II Synopsis	3-1
4.0 Engineering Approach to the Advanced Power Train	4-1
4.1 Study Methodology	4-1
4.2 System Analysis	4-3
4.2.1 Studies of Early Commercial Plants	4-4
4.2.2 Studies of Integrated Facilities for MHD Program Options	4-8
4.3 MHD Generator	4-8
4.4 Combustor	4-10
4.5 Diffuser	4-12
4.6 Power Conditioning	4-13
4.7 Scaling Considerations	4-14
4.8 Requirements for Coal	4-14
4.9 Reliability and Lifetime	4-16
4.10 Other Components and Subsystems	4-18
5.0 Results and Conclusions	5-1
5.1 The Power Train Development Program Plan has been Delineated: The Objective of the Contract has been Achieved	5-1
5.2 The Potential of MHD/Steam Power Plants Justifies the National Program	5-6
5.3 The Technological Base for the Program has been Demonstrated	5-9
5.4 Technical Success in the Shortest Schedule and at Lowest Cost will be Realized through an Integrated Development Program	5-15
5.5 The Management and Engineering Tools, Expertise and Concepts to Carry Out the Program to a Successful Conclusion have been Justified	5-17

VOLUME 1
LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page No.</u>
1	MHD Power Train in Relation to Total MHD/Steam Power Plant	1-1
2	Classical Systems Engineering Approach	1-3
3	The Advanced Power Train is Part of an Overall Systems Definition Tree. Elements of the APT System are Shown.	4-1
4	Westinghouse Analytical Program Handling Systems	4-3
5	500 MW _e MHD/Steam Plant Arrangement	4-7
6	MHD Channel Concept	4-11
7	Combustor Concept	4-12
8	Diffuser Concept	4-13
9	Power Conditioning Concepts, Schematic	4-15
10	Power Train Program Schedule	5-4
11	Effect of Rating on Relative Cost of Electricity	5-8
12	Effect of Rating on Performance	5-8
13	MHD Program Phases	5-10
14	Work Breakdown Structure First and Second Level	5-16

LIST OF TABLES

1	Summary of Reference MHD/Steam Plant Descriptions	4-5
2	Integrated Facilities	4-9
3	Current Status of MHD Reliability/Durability	4-17
4	Coal Fired Power Train with Power Conditioning Scale-Up Considerations	5-3
5	Power Train Program Cost Estimate - by Objective	5-7

ABSTRACT

The objective of the MHD Advanced Power Train Project, Phase I, is to define a Plan for the Development program that will "... provide qualification of the engineering data base required for the design, fabrication and operation of MHD Power Trains for MHD/steam plants with an $\sim 200 \text{ MW}_e$ capacity".

The project objective has been achieved. A program has been defined that addresses: a) the engineering development of components prototypical of the rugged, reliable and cost effective equipment required in the electric utility application, b) the scale-up, in reasonable steps in both performance and lifetime, of the power train components to reach the $\sim 200 \text{ MW}_e$ plant capacity goals, c) the integration of the components into proof-of-concept power train systems at two logical ratings, and d) the integration of the power train system into the total plant at the larger of the two ratings.

The development program has been justified. The U.S. citizenry will realize the benefits of MHD/steam plants including cleaner air, insured supply of energy resources, reduced oil imports, reduced demand for cooling water and new plant sites, and reduced creep of electric power cost. Beneficial and cost effective power train and MHD/steam plant performance and cost goals have been defined. The development program requirements are established and the plan will be implemented consistent with the goals.

The technological base for the program has been demonstrated. The remaining system and plant proof-of-concept steps, and cost reduction are engineering development scale-up in performance and lifetime, extensions of existing technology and there is no requirement for scientific breakthrough. This conclusion was confirmed in detailed program reviews by panels of senior equipment supplier and utility advisors.

The Plan is an integrated program that will produce technical success in the shortest schedule and at lowest cost. The plan includes the technical integration necessary to focus the component development efforts into a cohesive power

train technology. It recognizes and provides for the design and development of the MHD Generator (the channel, magnet and power conditioning) as a closely integrated unit so that opportunities for overall generator optimization will be realized. The plan also identifies the need, and provides appropriate effort, for coordination of the development program efforts with the testing facilities.

The plan identifies the management and engineering tools and expertise required for the cost effective technical integration and implementation of the development program. Typical examples of management techniques include: appropriate application of the System Engineering Approach, document control with a formal document change control procedure, regular progress reviews with subsequent variance reporting to focus management and DOE attention on critical issues. Typical examples of engineering tools include: computer aided design (CAD) for rapid technical communication and cost reduction through elimination of expensive models, and the Westinghouse SPA/SUMMARY computer model for prompt evaluation of effects of suggested development actions on total power train and MHD/steam plant performance and/or economics.

1.0 BACKGROUND

The successful development and application of magnetohydrodynamic (MHD) electric power generation technology would make a significant contribution toward meeting the national energy requirements. MHD/steam plants would be fueled by the direct combustion of coal, the nation's abundant fossil energy resource.

Numerous studies have confirmed that MHD/steam plants have the potential to be economically competitive and to produce up to 50 percent more electricity per ton of coal consumed compared to the conventional coal/steam plant. This automatically reduces the ecological impact of coal mining and transportation. MHD plants will also significantly ameliorate environmental concerns, including waste heat and oxides of sulfur, nitrogen and carbon.

The study reported here deals with the key enabling technology for the construction of such plants, the MHD power train, see Figure 1. The major components of the power train are: the coal combustor, the MHD generator, the diffuser, and the power train controls. The MHD generator, analogous to gas turbine-generators, consists of the channel, power conditioning and the magnet (the magnet was excluded from the contract work scope).

Figure 1. MHD Power Train in Relation to Total MHD/Steam Power Plant

Particular emphasis in this study was placed on concepts that offer potential as early commercial plants, on the requirements for the power trains for such plants, and on the engineering development and proof-of-concept testing requirements for these power trains.

1.1 STARTING POINT FOR THE STUDY

The Government primarily through the Department of Energy, and industry, have carried out an extensive effort to design and develop MHD/steam combined cycle electric power plants. Significant progress has been achieved in several component and subsystem areas. A 20 MW_t combustor with high slag rejection has been demonstrated by TRW. The first stage of a 50 MW_t combustor is under test at the Component Development and Integration Facility (CDIF). Platinum capped copper anodes, for the MHD generator, have been operated for 1300 hours at the AVCo Everett Research Laboratory. A superconducting magnet has been operated at 6 Tesla at the Argonne National Laboratory. The High Performance Demonstration Experiment at the U. S. Air Force Arnold Engineering Development Center has produced an enthalpy extraction of about 12 percent at a magnet field strength of 3.9 Tesla and a power output of 36 mW. Inversion of dc MHD power to ac electric power for the Montana Power Co. system has been demonstrated with Westinghouse designed and constructed hardware at the CDIF. Seed deposition and collection tests, as well as experiments to demonstrate low emission of oxides of sulfur and nitrogen have been performed at the University of Tennessee Space Institute.

Supported by numerous other analytical and experimental activities, the feasibility of the MHD concept for power generation has been established. Extensive preliminary engineering or technology base experience has been gained for individual components at small scale (up to 50 MW_t thermal), and partial "bread-board" systems have been successfully operated.

1.2 INTEGRATED APPROACH

This component by component development is impressive, but it is not adequate for the scale-up of the MHD power train and its components. This requires

SEA is sometimes called the "top-down" approach. Its early stages are illustrated in Figure 2 with reference to the power train subsystem. The utility needs define the ultimate use and from this starting point requirements tier down for the plant, the early commercial power train, the advanced power train (APT), and finally, the system and equipment specifications. Sources of supplementary requirements during the top-down requirements definition are indicated on the right of the figure. The influence indicated by "Design Guidelines" pervades the entire process and refers to the disciplinary requirements and procedures which are at the heart of the systems approach to practical equipment design.

The three tasks of the contract study reported herein (Phase I) are enclosed in the dot-dash lines. Activities which would show up below the figure are the design and fabrication of APT test hardware, construction of the APT, test operation of power trains, and data reduction and analysis to establish the Engineering Data Bases. The results then would logically feed back to refine the early commercial power train and full commercial plant requirements.

1.3 STUDY PARTICIPANTS

This System Engineering Approach has been applied by a Westinghouse led team including Applied Energetics, Burns & Roe, HMJ Corp, SEITEC, and TRW. A Utility Advisory Council was convened to review the total power plant requirements, the Council included representatives from Boston Edison, Duke Power Co., Montana Power Co., Nevada Power Co., Northeast Utilities, Penn. Power & Light, Pub. Service Electric & Gas Co., Southern California Edison Co., Southern Services, and TVA.

2.0 STUDY SCOPE

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The Phase I contract study purpose is the "...Definition of a Development Program for a MHD Advanced Power Train (APT)." The work scope is made up of three tasks, as follows:

Task I	Analysis of MHD Steam Power Plants, Determination of MHD Performance requirements and Design Criteria, and Critical Evaluation of the State of Technology
Task II	Definition of MHD Power Train Design Approaches
Task III	Definition of a Program Plan for MHD Advanced Power Train Development

The Task I effort is divided into three subtasks:

- Analysis of MHD/Steam Power Plants and Power Train Requirements.
- Scaling Relationships and APT Performance (Testing) Requirements.
- Critical Evaluation of State of Technology.

The Task II effort is divided into three subtasks:

- Detailed MHD Generator Studies for a Plant of 200 MW_e Capacity.
- Identification and Assessment of Power Train Design Approaches.
- Preliminary Conceptual Design Study of the Preferred Power Train for a Plant of 200 MW_e Capacity.

3.0 TECHNICAL REPORT: VOLUME II SYNOPSIS

3.0 TECHNICAL REPORT: VOLUME II SYNOPSIS

The Phase I study results are reported in six volumes in addition to this Executive Summary as follows:

<u>Volume</u>	<u>Title</u>	<u>Content</u>
2	MHD/APT Development Program Plan	Describes the recommended PT engineering development and test effort to be implemented in Phase II. Provides a suggested Work Breakdown Structure, task descriptions, schedule, management plan and cost estimate. (Task III results.)
3	APT System Description and Specification for 200MW _e Plant	Provides the format and currently available definitive data with emphasis on the PT and component interface. (Task II, subtask 3 results.)
4	Power Train Design Approaches and Detailed MHD Generator Studies	Describes innovative approaches and concepts devised to guide the Development Program Planning effort (Task II, subtasks 1 and 2 results.)
5	Plant Analyses, Scaling Studies, Technology Assessment, Testing Requirements, and Competitive MHD/Steam Plant Requirements	Describes the analyses and related efforts that form the bases for the Development Program Planning (Task I results.)
6	Special Studies - Evaluation of MHD Program Options	Describes studies of 50 and 80 MW _t and Frank E. Bird Retrofit integrated facility conceptual designs. (Added task results.)
7	Appendices	

4.0 ENGINEERING APPROACH TO THE ADVANCED POWER TRAIN

4.1 STUDY METHODOLOGY

The MHD power train subsystem is one of several major subsystems that comprise a MHD/steam power plant. It is distinguished from the others by the preponderance of new technology required for its components. Its integration with other subsystems must be taken into account in the technology development to ensure that an efficient and cost-effective power plant results. In establishing APT design and development requirements, the integrated system needs must be satisfied.

The APT and APT program can be displayed as part of a systems definition tree shown in Figure 3. In the figure, the tree has been extended to define the major components of the MHD power train subsystem, as defined in the contract work scope.

Figure 3. The Advanced Power Train is Part of an Overall Systems Definition Tree. Elements of the APT System are Shown.

In the first step of the study, MHD/steam plants were conceptually designed and their competitive potential was established in a comparison with a modern conventional coal/steam power plant. The designs were carried to the point where specific design, rating, lifetime and cost goals and requirements were established for the MHD power train and its individual components.

These MHD/steam power plant designs also produced design, rating, lifetime and cost goals for all of the other power plant subsystems. This provides useful information for other MHD subsystem development work.

In the second step, methods were defined to relate engineering data over the range from small test facility to commercial plant sizes. These methods can be thought of as the "pathways" along which the technology must be developed and demonstrated as the commercialization of MHD is realized. The scaling relationships are specific to components (and even to subcomponents) of the MHD power train.

In the third step, the existing state-of-technology was explored through literature search and visits to several U. S. development centers active in the national MHD program. The results were correlated with the scaling relationships. An assessment was made of the testing requirements remaining to be realized in the commercialization of the power train and its components.

In the fourth step, the MHD generator (including the channel, power conditioning subsystem and the magnet) was studied in some detail. Concepts of innovative components were devised to indicate development directions to produce the engineering data base for rugged, reliable and cost effective MHD generators.

In the fifth step, the subsystems and components of the power train (individually and collectively) were studied to identify and recommend design approaches to be considered in the Development Program Plan.

In the sixth step, a MHD/APT System Description and Specification was prepared. Particular attention was given to definition of the Specification format to make it of continuing value throughout the Phase II development

effort and future design phases. Special attention was focused on the detailed definition of interfaces (and interactions) between components within the Power Train and between the Power Train and the balance of plant.

In the seventh and final step of the reported effort, the detailed Development Program Plan was prepared. The Program Plan scope was delineated to "...provide qualification of the engineering data base required for the design, fabrication and operation of MHD Power Trains for MHD/steam plants with an 200 MW_e capacity."

Thus, it can be seen that the contract study is a partial progression through the steps of the classical Systems Engineering Approach (SEA). This is a successful approach that has been evolved from many utility, aerospace and military projects. If the MHD program is to be successful in the current era of restricted development program funding, it must be focused. SEA is an excellent way to provide that focus.

4.2 SYSTEM ANALYSIS

To define efficient and cost-effective MHD/steam power plant designs an extensive study was carried out using the total plant design code displayed in Figure 4. The Westinghouse System Performance Analysis (SPA/SUMMARY) code provided the capability to perform design optimization studies for each design change, including cost trade-offs.

Figure 4. Westinghouse Analytical Program Handling Systems

The SPA code accepts fuel data compiled by the NASA TRANS 72 code. In the SPA code, algorithms of up to 100 integrated plant elements can be analyzed simultaneously. The SUMMARY code accepts the SPA output and presents tabulated data on performance, cost and physical features. Data for the total plant and also each component are presented. The cost data are also presented in the Uniform System of Accounts format, showing: component cost, balance of plant cost, installation cost, indirects, and contingency. Cost of electricity is also computed and displayed.

4.2.1 STUDIES OF EARLY COMMERCIAL PLANTS

Making use of previous DOE/NASA studies as a starting point, ten carefully selected MHD/steam power plant basic configurational arrangements or size variations were considered in-depth. Each of these ten cases was examined parametrically with respect to MHD cycle pressure ratio, enrichment of combustion air above the natural 21% oxygen content, and MHD generator loading factor. The analyses were based on the use of Montana Rosebud coal and steam (bottoming) cycle conditions of 2400 psi/1000°F initially with reheat to 1000°F.

Based on (1) efficiency (resource parameter), (2) cost of energy (utility worth parameter) and (3) siteability (environmental parameter), three attractive reference early commercial MHD/steam power plant designs were defined from among the variations studied. The reference designs cover a range of potential commercial plant rating: 200 MW_e, 500 MW_e, and 1000 MW_e. These designs are described in Table 1. A fourth case, a 200 MW_e plant based on the use of a supersonic channel is also shown.

A plot plan of the 500 MW_e plant is shown in Figure 5. The 200 MW_e and 1000 MW_e plants have similar arrangements.

The major criterion for establishing the Figure 5 plant arrangement was to achieve minimum cost of electricity while satisfying the practical constraints associated with construction, maintenance, operation, and safety.

TABLE 1
SUMMARY OF REFERENCE MHD/STEAM PLANT DESCRIPTIONS

	<u>1000</u>	<u>500</u>	<u>200</u>	<u>200 (Supersonic)</u>
<u>Plant Data</u>				
Coal Thermal Input, MW _t	2278	1163	483	483
Net Power Output, MW _e	989	495	195	193
Plant Efficiency, %	43.4	42.6	40.4	40.5
Plant Capital Cost, \$M	760	449	236	234
Cost of Electricity, M/kWh	62.6	70.5	88.8	90.5
<u>Selected Component Data</u>				
Oxygen Content in Combustion Air, %	36	36	36	36
Preheat Temp, °K	922	922	922	922
Combustor Exit Pressure, Atm	7.3	6.2	4.8	4.9
Slag Removal, %	85	85	85	85
MHD Channel Dimensions, M				
- Inlet	0.97 x 0.97	0.77 x 0.77	0.54 x 0.54	0.56 x 0.56
- Outlet	2.50 x 2.50	1.79 x 1.79	1.18 x 1.18	1.13 x 1.13
- Length	15.9	11.7	10.6	9.5
MHD Enthalpy Extraction, %	21.7	19.6	16.8	15.5
Mach. No.	0.875	0.875	0.875	1.3 - 1.0
Number of Electrode Pairs	1060	782	710	557
Number of dc/ac Inverters	5	3	2	2
Magnet Field Strength, Tesla	6	6	6	6

A major consideration in establishing the plant arrangement was the cost of piping, ducting, and wiring. Both operating (power loss) cost and capital cost impacts of the piping, ducting, and wiring were considered in arriving at the preferred plant arrangement.

The concept consists of carefully integrated MHD topping cycle and bottoming steam cycle. The optimum net electrical power from the MHD portion is slightly less than half the total plant output. This requires that the MHD generator extract 16 to 22 percent of the total plant heat input in the form of electric power.

To provide structural viability, the MHD power train operates with water-cooled and slag coated "cold" walls. The heat rejected to this cooling is substantial, being on the order of 20 percent of the total plant input. Proper integration of this heat into the bottoming steam cycle is an important facet of plant efficiency. A total plant design code, such as SPA/SUMARY, is an efficient tool for the study and design of such plant interfaces.

The MHD process requires a plasma (gas stream) with an electrical conductivity of 6 mho/meter or better. Combustion of coal with atmospheric air would require a high degree of preheat that is impractical with current technology. For early commercial plants the desired electrical conductivity can be produced by oxygen enrichment of the air and this approach is utilized in all plants considered in this study.

While this study is concentrated on the power train components, see Figure 3, it is important that the other components necessary to accomplish the total plant function be carefully integrated into the design. These include: the oxygen plant for enrichment of the combustion air, "seed" recovery and reprocessing, heat recovery subsystems, instrumentation and control subsystems, and magnet system. The study results clearly demonstrate that the minimum cost of energy is achieved by optimizing the total plant, resulting in a power train that is significantly off-optimum on a component by component basis.

Figure 5. 500 MWe MHD/Steam Plant Arrangement

4.2.2 STUDIES OF INTEGRATED FACILITIES FOR MHD PROGRAM OPTIONS

An additional subtask was assigned to the project. The study was to assess 50 MW_t, 80 MW_t and possible retrofit facilities. The study was to evaluate system performance, capital costs, construction schedules, resource requirements and technical risk.

The 50 and 80 MW_t integrated facilities were studied based on their installation at the CDIF. The Fank E. Bird unit, owned by Montana Power Company, was selected as the candidate retrofit unit.

These studies utilized the SPA/SUMARY code package. The cost data and schedule assessment were based on data obtained from candidate component suppliers.

Summary results, for the four cases analyzed, are shown in Table 2. The 50 MW_e and the 40 MW_e retrofit cases both assume use of the Fank E. Bird Unit. The difference in MHD generator size arises from consideration of both steam and electric drive for the combustor oxidant compressor.

4.3 MHD GENERATOR

The MHD generator concept used herein employs a linear channel, see Figure 6. The channel concept has platinum capped (at least in the higher power sections) copper electrodes and segmented copper sidewall bars, maintained at low (cold wall) temperature, operated in a fully slagged condition, Faraday loaded and supported in fiberglass box walls. The walls require external strengthening members to allow a relatively thin fiberglass wall and to make maximum use of the magnet warm bore. The electrical and cooling fluid arrangements have also to be developed to be as economical of warm bore space as possible, and these must also be engineered for high reliability and long duration operation. The electrical power has to be removed through a power conditioning system (power management plus inverters). Sidewall potential distribution is fixed through conducting but interrupted sidebars placed along essentially equipotential lines between anode and cathode. It will be designed with modern solid-state

TABLE 2
INTEGRATED FACILITIES

Item	50MW _t	80MW _t	40MW _t	50MW _t
Location	-----CDIF-----		-----Frank E. Bird-----	
Compressor Drive	-----Electric-----		-----Steam-----	
Thermal Input, MW _t	50	80	276	316
Net Electric Power, MW _t	13.5	23.2	89	106
Capital Cost, \$ Million	112	138	283	319
Constr. Schedule, Months	63	63	57	57
Cost of consumables, \$/hr. (Coal and seed)	<288	<441		
Value of power, \$/hr.	675	1160		
Risk (Based on immediate start)	-----Minimal-----		-----Significant-----	

power electronic components to reduce, to the minimum practical extent, the losses in the subsystem. It will be designed to assist in establishing uniform current distribution over the anode surface and to limit fault currents. This is an important objective because the major electrode life limiting mechanism is erosion due to high local current density. The consolidated dc power will be conditioned for the electric utility grid in multiple inverters. The MHD generator will utilize a 6 Tesla (peak magnetic flux) superconducting magnet. A control system will insure proper operation of the generator (and the rest of the plant) under all conditions over the power range from at least 75 to 100 percent power. It must also handle normal start-up, network transients, and both normal and emergency shutdown situations.

The engineering development of such a MHD generator is judged to require an extensive and focused program. The channel must be designed and developed, in all aspects, to have a minimum life of six months in early plants and at least one year in later plants. To meet this goal, the designers must have detailed engineering data and information in all of the detailed areas of design. The combined design of the nozzle, channel (with wiring and cooling arrangements), magnet and diffuser must provide for rapid removal, replacement, reconnection and checkout of the channel.

4.4 COMBUSTOR

The combustor concept used in the study, see Figure 7, is the two-stage slagging combustor under development by TRW. Combustors of the 10 MW_t and 20 MW_t sizes have been built and tested successfully for operation and performance. The 20 MW_t size has also been used in limited successful power train testing. Performance prediction methodology check experimental results at the 10 MW_t and 20 MW_t sizes. The slagging stage of a 50 MW_t combustor has been produced and is being tested.

Figure 6. MHD Channel Concept

Figure 7. Combustor Concept

The major development areas are: slag removal systems, electrical isolation and support structures, seed injection system to ensure uniform plasma conductivity, and engineering impacts due to scale-up from the existing 20 MW_t size. Many of the tests to provide these data can be obtained in stand-alone tests and in existing or anticipated facilities. Both performance and lifetime tests are recommended at 50 MW_t and component tests are recommended at 100 MW_t , or above. It must be proved experimentally that adequate performance can be achieved at large power levels.

4.5 DIFFUSER

The diffuser concept, see Figure 8, employs a constant area section followed by a subsonic diffuser section. This subsonic section is followed by a blast plate (slag baffle) in a dump tank. The key concerns are the selection of a unit that interfaces properly with the MHD channel (Mach No.), provides adequate (at least 0.5) pressure recovery factor, and interfaces properly with the heat recovery equipment. Cold flow modeling can be an effective and economic

tool and an extensive test series is anticipated. Hot flow performance evaluation and comparisons can be carried out in small (20 mW thermal) power trains and in conjunction with other test programs.

Figure 8. Diffuser Concept

4.6 POWER CONDITIONING

The MHD power conditioning subsystem, see Figure 9, consists of a power management subsystem (Figure 9b), which consolidates the hundreds of individual channel electrode outputs, and then bulk inversion (Figure 9a) to utility quality 60 Hertz output. To date, the consolidation and control function has been accomplished with resistance networks. These have been adequate for experimentation with small channels. More efficient elements for consolidation and control are feasible with today's state-of-the-art in power electronics.

Power control (power management) concepts to limit internal channel fault power and maintain current distribution over the electrodes appear to offer potential

for achieving the full design endurance (life) of the channel. The engineering development should include analytical efforts, breadboard tests and integrated demonstration. Bulk inversion of the consolidated power from dc to utility quality ac is well established engineering as exemplified by HVDC installations. Application to MHD has been demonstrated by the CDIF inverter, built by Westinghouse under EPRI contract. Large electric utility MHD generators are expected to be operated into multiple dc/ac inverters. Satisfactory operation and appropriate control should be demonstrated with actual MHD generators. It is recommended that all future MHD generator development and testing be conducted with active power management subsystems. Inversion to the ac utility grid is desirable.

4.7 SCALING CONSIDERATIONS

Power train, and even component, tests to define and confirm the engineering data for commercial MHD plants are very costly. Hence, it is desirable to conduct such tests at the smallest rating that will produce the necessary results. Scaling relationships and the SPA code were used to explore the usefulness of tests at 20, 50, and 100 MW_t ratings. Many MHD power train development concerns can be resolved at 50 MW_t. Almost all concerns can be resolved at 100 MW_t except that demonstration of adequate values of key performance related parameters such as enthalpy extraction (the ratio of generated electric power to fuel input) require tests at 250 MW_t level or more.

4.8 REQUIREMENTS FOR COAL

A good understanding of the interactions of coal slag with the electrical and mechanical aspects of MHD generators appears vital for successful power train design. This is so for achievement of both high performance and long lifetime.

To date very little MHD operation with coal has been accomplished. Most operation has been with a simulation of coal burning using a liquid fuel such as toluene with the introduction of simulated coal slag using ash.

9a. Inverter Connection - 5 Unit Example

DERIVATION, CONTINUED

EACH PHASE CAN HANDLE SEVERAL ELECTRODES
 BY USING PARALLEL CONNECTED CONVERTERS

9b. Principle of Power Management

Figure 9. Power Conditioning Concepts, Schematic

Coal burned in a slagging coal combustor should be standard in all MHD power train or generator tests. The major U. S. MHD laboratories should be equipped to do this and other combustors should only be used in special circumstances (e.g., short duration testing).

4.9 RELIABILITY AND LIFETIME

Most MHD hardware built to date has been for the purposes of experimenting with one or more detail aspects of MHD technology. As such, the equipment, while mostly adequate for the intended test purposes has not been engineered or manufactured to commercial quality assurance standards. To move MHD to commercial reality, hardware (along with auxiliaries) of good overall quality must be evident. The preparation of the engineering and manufacturing data and information is the Engineering Development phase of a new technology program. It is now time to embark on this engineering development effort. Building and testing hardware, so designed and qualified, is a vital part of the effort.

Channel lifetime, between refurbishments, is a key element in utility acceptance. The maximum acceptable replacement frequency is twice per year, timed to match the usual Spring and Autumn low utility demand periods. This, along with other consistent criteria, was taken as the basis for the study leading to the findings shown in Table 3.

Life testing pertinent to the subcomponent level for some components can be performed in rig testing. Examples include: elastomer seals, plastic electric isolation components, and the fiberglass box wall elements. All life testing must be planned to take maximum advantage of the smallest feasible test facilities to minimize the cost of the Engineering Development phase.

Readiness to design and construct viable commercial MHD/Steam power plants must incorporate adequate technology for all of the plant components. Therefore, it will be necessary to carry out development programs on other components, in addition to those included in the Advanced Power Train.

TABLE 3
CURRENT STATUS OF MHD RELIABILITY/DURABILITY

	TEST STATUS (HOURS)	CDIF 38 POWER TRAIN SPEC ⁵⁻⁹⁷ DURABILITY WITHOUT "RELEVANT" FAILURE (HOURS)	PROPOSED COMMERCIAL PLANT, FORCED OUTAGE MTBF (HOURS)
• COMBUSTOR	188 ⁵⁻⁹⁵	2000	16,667
• GENERATOR	TBD	<1000	8,000
NOZZLE	TBD	TBD	100,000
CHANNEL	TBD	2000	9,524
ANODES	>1000 ⁵⁻⁹⁶	TBD	18,182
BALANCE	TBD	TBD	20,000
DIFFUSER	TBD	2000	100,000
• POWER CONDITIONING	TBD	<1000	40,000
POWER TAKEOFF	TBD	2000	80,000
INVERTER	TBD	2000	80,000
• BALANCE MHD SYSTEM	TBD	TBD	33,333
• OVERALL MHD SYSTEM	TBD	<500	4,000

4.10 OTHER COMPONENTS AND SUBSYSTEMS

The magnet technology is well advanced and continues to be improved as a spinoff from other programs such as fusion. However, the magnet is a major cost item and effort should be devoted to engineering studies that correlate the magnet/channel interface to the improvement of both.

The heat recovery boiler will require extensive development, including testing at 20 MW_t and larger rating, prior to commercial plant commitment.

Seed recovery, from slag and spent combustion gas will require extensive development. Seed regeneration R&D is indicated, starting with comparative assessment of the formate process against alternatives. The low level of experimental data on dust collection in MHD systems must be rectified.

The total environmental impact of MHD systems needs to be examined. The results obtained in this study, and corroborated by others, indicate that MHD systems can make a significant contribution to the reduction of oxides of sulfur and nitrogen in the electric power generation process. Other aspects, such as particulates and solid wastes, should be examined.

Finally, engineering study of total MHD/steam power plant instrumentation and control is indicated. In any planned or inadvertent off-design operation of the power train, the interactions with the bottoming steam plant and the utility grid are likely to be significant. Start-up and shutdown transients, in a closely integrated MHD/steam plant must be examined. Plant trip-off, from the ac grid, is more complex than normal because of the two different sources of electric power.

6.0 RESULTS AND CONCLUSIONS

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The results achieved in Phase I of the MHD Advanced Power Train Program can be summarized under five major conclusions:

- 5.1 - The Power Train Development Program Plan has been Delineated: The Objective of the Contract has been Achieved,
- 5.2 - The Potential of MHD/steam Power Plants justifies the National Program,
- 5.3 - The Technological Base for the Program has been Demonstrated,
- 5.4 - Technical Success in the Shortest Schedule and at Lowest Cost will be Realized through an Integrated Development Program, and
- 5.5 - The Management and Engineering Tools, Expertise and Concepts to Carry the Program to a Successful Conclusion have been Identified.

5.1 THE POWER TRAIN DEVELOPMENT PROGRAM PLAN HAS BEEN DELINEATED: THE OBJECTIVE OF THE CONTRACT HAS BEEN ACHIEVED

The MHD/APT project is unique in that it addresses, for the first time, the complete program to carry one of the MHD systems through all the myriad development steps remaining to be accomplished before the utilities can apply MHD/steam power plants with confidence. The project has also made unique contributions to the understanding of the design of the MHD generator as an integrated subsystem.

The plan for a development program that will produce the engineering data base for the design of competitive early commercial power trains has been delineated. Direct correlation between the requirements for the commercial plants and the information to be provided by execution of the plan has been

established. The present state-of-technology was assessed and generally accepted design limits and parameters were used as the starting point for the development program. A conscious decision was taken to preclude any assumption of new science or "breakthrough" in the program. The program is concentrated on the engineering development of components from the presently defined laboratory and breadboard devices to prototypes of the rugged, reliable and low cost equipment that will be necessary in the commercial electric utility plants. The present low level of both performance and lifetime demonstration was recognized and the plan includes power train tests at two ratings with progressive lifetime increases and cost reduction goals to minimize the risk associated with the scale-up ratios. The choice of ratings for the two development steps, compared to the present status on the one hand and to the required status for the early commercial plant on the other hand are shown in Table 4. The first step provides the integration of the power train system. The second step provides the opportunity to carry out total plant integration, assuming that the development and integration of other developmental systems (heat recovery/seed recovery and seed regeneration) are carried out on the appropriate schedule -- an assumption that is considered reasonable by experts in those fields.

In the area of the MHD generator (channel, magnet and power conditioning) new design approaches have been identified, and their development planned, that have the potential to contribute significantly: a) Toward making full use of the generally accepted limits on channel design and operating parameters, b) Toward realizing the full theoretical channel lifetime, c) Toward a power train control system with the flexibility for easy plant operation, and d) Toward realization of a channel with low production cost and high reliability.

TABLE 4
COAL FIRED POWER TRAIN WITH POWER CONDITIONING SCALE-UP CONSIDERATIONS

	STATUS	ENGINEERING DEVELOPMENT	PLANT INTEGRATION (RETROFIT)	COMMERCIAL PLANT
PERFORMANCE MW(t)	20 - 50*	50	150 - 250	500
MW(e)	2*	2 - 3.5	15 - 35	70
LIFETIME, HOURS POWER TRAIN ELECTRODES	FEW 1500*	500	2000	4000 - 8000
COST (Channel) \$/kW(e)	2500	1428	405	40

*SIMULATED COAL

The plan recognizes the need for continued application of the System Engineering Approach to provide the management and technical integration of the development and testing efforts of many organizations to bring the best of the nation's talents to bear directly on the program in the most efficient manner. A summary of the major elements of the plan are shown in Figure 10. The 50 MW_t Endurance Power Train element provides the system integration. The Retrofit Power Train element provides the opportunity for further scale-up and the total plant integration. Early conceptual design of the power train for the Retrofit facility is important to proper integration of the power train development program and to preparation for early identification of a request for the capital funds for the Retrofit facility as noted by the caret at the middle of the third year.

The MHD Generator Development element is planned to be carried out at 50 MW_t. The generator, and especially the channel, is particularly important to reliable MHD power plant operation and to low cost of energy. The requirements for the channel include performance, lifetime, economical of warm bore, readily replaced, rugged, reliable, and low fabrication and assembly cost.

The development of the channel with features suitable for use in a superconducting magnet will be necessary for the Retrofit program. Further development of the low-production-cost structure, devised in the MHD Generator study, may require more time for final demonstration and may not be available in time for the first channel in the Retrofit program. It will, however, be a vital factor in achieving competitive commercial MHD power. The program to develop the data and information for design and manufacture of low-productioncost channels for the early commercial plants can be carried out within the schedule for the Retrofit program.

The total power train development program, exclusive of testing facilities and supplies, is estimated to cost \$278 million. The direct cost of testing is estimated to cost \$10 million. The cost of the Retrofit plant was estimated by the MHD Industrial Forum to cost \$310 million in addition to the contribution of the existing steam plant. Since the power train components, for the Retrofit plant, are included in the power train development program, some \$60 million might be charged against the Retrofit plant. All other major test

facilities are already available at University of Tennessee Space Institute, CDIF, or at industrial organizations. The cost estimate, by element, is shown in Table 5.

5.2 THE POTENTIAL OF MHD/STEAM POWER PLANTS JUSTIFIES THE NATIONAL PROGRAM

The potential benefits of MHD will accrue to the general citizenry more than to industry. This is so because the benefits will be clean air, insured supply of energy resources, reduced oil imports, reduced demand for cooling water and new plant sites, and reduced creep of electric power cost.

It was noted in the Background Section that the advantages of MHD/steam power plants, when they are developed and commercially applied, can make a significant contribution toward meeting the nation's energy requirements with coal while ameliorating the environmental impact of coal power production. MHD has, in fact, a number of potential advantages. It has been indicated in previous studies and confirmed in the Task I plant studies that MHD/steam power plants can be developed that will be competitive with modern Coal/steam power plants at and above about 200 MW(e) total plant output. The economic comparisons obtained in this study are presented in Figure 11. The reduced fuel cost for these early commercial MHD plants will more than compensate for the relatively larger (than for Coal/steam plants of the same rating) capital cost. The reduction in fuel cost is, of course, achieved through the relatively higher efficiency attainable with the MHD plants. The comparative efficiency data are presented in Figure 12.

The increased efficiency realizable with MHD plants also produces advantages. The amount of coal to be mined and transported, per unit of energy produced, is reduced. This reduces the environmental impact of both fuel recovery and plant operation. The amount of waste heat, i.e., cooling water requirement, is reduced. The concept of retrofitting existing plants with MHD topping cycles is an example. Additional electric output could be realized from an existing site without increasing the waste heat. This would contribute to meeting load growth without developing new power plant sites.

TABLE 5
POWER TRAIN PROGRAM COST ESTIMATE - BY OBJECTIVE

	\$'s — Millions
RETROFIT POWER TRAIN Development & Test Equip.	122
50 MW(t) POWER TRAIN	78
CHANNEL DEVELOPMENT	78
	<hr/>
TOTAL TO PRODUCE PT ENGINEERING DATA BASE	278

**Facilities, Modifications, Operation and Escalation are not
included.**

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Figure 11. Effect of Rating on Relative Cost of Electricity

Figure 12. Effect of Rating on Performance

*Seikel, G. P., "Status of Coal Fired Open Cycle MHD Steam Power Plant Studies in the United States," Specialists Meeting on Coal Fired MHD Power Generation, Sidney, Australia, 1981, The Institution of Engineers, Australia, National Conference Publication No. 8217, Vol. II, p. 7.1.1-7.1.13.

The plant study results may be considered with confidence since, as noted above, these efficiency improvements are predicated on power train design limits and parameters that are presently accepted or are judged to be demonstrable in the proposed development and test program described in Section 5.1. Scale-up in rating and lifetime, increase in reliability, and production approaches to meet component cost goals are the primary remaining uncertainties. It is also noted that these results are consistent with other studies such as the Evaluation of Conversion Alternatives Studies (ECAS) conducted for DOE/NASA some years ago.

The concept of retrofitting existing oil/gas fired units with MHD topping cycles is feasible and the MHD units should be readily permitted since they offer the potential of very low emissions of oxides of sulfur and nitrogen. The confirmation of low emission capability is well underway in programs at the University of Tennessee Space Institute and their results support the analyses conducted in this project. This application could contribute to the reduction of need for imported oil.

Incidentally, the potential for low emissions of sulfur exists for eastern high sulfur coal as well as for the low sulfur western coals. This advantage might be a contributing factor to the economic rebirth of Appalachia as well as to the resolution of the pollution problems threatening the entire northeast region of the nation. Therefore testing with various coals is recommended.

5.3 THE TECHNOLOGICAL BASE FOR THE PROGRAM HAS BEEN DEMONSTRATED

Every high technology program proceeds through six fairly well defined phases between inception and commercial acceptance. These are depicted in Figure 13. The MHD technology was demonstrated to be at the early stage of the Engineering Development phase. The concept of MHD power is quite old and extensive research and development has been accomplished over the past decades. Numerous preliminary engineering studies and conceptual designs, of which the APT studies are the latest, have been completed. Breadboard components and systems have been tested. Long operating times have been achieved in very small

Figure 13. MHD Program Phases

(kilowatt) systems. Very high power has been achieved for very short times (seconds). Engineering concepts of suitable components have been devised and tested for short times (hours).

The MHD/APT project has made unique contributions to the understanding of the design of the MHD generator by considering the three principal elements of the generator (channel, magnet and power conditioning) as an integrated unit. MHD generator operation at high (6.5 Tesla, peak) magnetic field strength (with concomitant substantial performance improvement) is now possible. Further, this improvement was demonstrated to be achievable within present limitations on electrical, gas-dynamics and thermal operating parameters and stresses.

Specific unique and original contributions to MHD generator technology include:

- a) local plasma management through active control of individual electrode currents (and voltages),
- b) generator performance improvement and optimization through design for mixed loading (drawing Hall generator as well as Faraday currents),
- c) reliability and lifetime enhancement through I&C concepts that can be developed to recognize and ameliorate the effects of electrode-to-electrode fault conditions, along with other supporting design features,
- d) generator production cost reduction through concepts that minimize dimensions, hand labor, and the number of special parts.

A power management subsystem concept was devised with the capability to provide the already recognized current collection and consolidation (from the hundreds of electrode pairs that make up the channel) function and provide other advantages. The proposed power electronics package can be used to control and/or limit the voltage or current at each electrode independently of all others. The control can be flexible in that it may control voltage at one time and current at another. The control can be varied as the operating mode of the

plant is changed. It is anticipated that the system can be developed to recognize and eliminate, or at least limit the consequential damage of, electrode-to-electrode faults.

The versatility of the power management concept also provides new freedom for the channel designer. For example, the ability to control local currents makes it possible to select different operating modes (drawing Hall current as well as Faraday current) in selected sections of the channel. This technique permits the designer to take full advantage of the permissible design parameters to realize the highest overall power density and operating efficiency.

In summary, this power management concept offers the possibility of managing the MHD plasma through control of the boundary conditions to avoid the local stress conditions in the channel that are life-limiting. It will, therefore, contribute to realizing the full potential of the MHD generator in performance, reliability and lifetime.

The confidence that this power management concept can be developed and utilized is supported by work that Westinghouse has done for DOE and EPRI in the development and demonstration of power conditioning systems for CDIF and fuel cell and photovoltaic power systems. The power electronic devices with which the power management system will be constructed are commercially available. The remaining efforts are in the areas of definition of the specific channel conditions to be controlled, and development of software to produce the desired power management element actions. The first requires channel design definition and very detailed operating data that do not now exist. These must be obtained in actual power train tests and translated into the interface data and information with which the power electronics experts can define the power management software. The second is (to software experts) a straightforward engineering development assignment.

The power management system should be applied to the 50 MW_t power train because every effort should be made to demonstrate channel lifetime and reliability in that test. To meet the projected schedule, the hardware will have to be overdesigned (expanded ranges of voltage and current capability) and

the software will have to be developed as the program proceeds, probably including modification during the actual test. The system flexibility that makes such modification possible is a merit of the concept.

Another innovative Phase I result is a channel structure concept having the potential for very low production cost and enhanced reliability. The state-of-technology channel features are retained and incorporated into the proposed approach. For example, copper electrodes with platinum and/or stainless steel caps and internal water cooling (that represent the state-of-technology at AVCo Everett Research Laboratory) are not changed except to add a feature that will provide for the necessary retention of slag and eliminate the need for machining grooves in each electrode. The thrust of the concept, therefore, has been to take the proven channel features and the known channel requirements and devise low cost manufacturing and assembly means that combine the two. The features and approaches that were selected are all based on technology that has been successfully applied in other fields, so that the probability of success in transferring these technologies to the MHD field is high.

This channel structural development and demonstration is a major thrust in the Generator Development element of the development plan, because a reliable and low cost channel is absolutely essential for the achievement of the national advantages of MHD plants. The engineering development to bring this transfer to pass will be time consuming. The ultimate evaluation of these methods must be carried out in actual and complete power train tests of some duration because the time related concerns, such as creep under thermal stress in the full MHD environment, cannot be fully and finally resolved in any other manner.

High power and energy extraction experiments are planned to insure that the analytical code packages for the design of large MHD generators include adequate representation of all performance impacted phenomena (such as secondary flow and magneto-aero-thermal instability). These very short time (seconds) tests will continue to build on experiments begun at the Air Force High Power Demonstration Experiment and later limited tests at AVCo. The early use of the superconducting magnet now in storage at Argonne is recommended, prior to its use in the more conventional tasks of the MHD generator development element.

The remaining components of the power train are under development or represent reasonable extensions of existing technology. The combustor development effort that DOE is funding at TRW and CDIF must continue until the practicality of simultaneously meeting the requirements (high slag rejection, tolerance of practical coal grind variability and low moisture content, uniform and steady plasma generation, efficient recovery of waste heat, and durability) is thoroughly demonstrated. The nozzle to produce the required plasma velocity at the channel entrance is considered to be a reasonable engineering effort. The diffuser will require engineering development that can be carried out in the course of other power train tests augmented by cold-flow component tests. The power train instrumentation and control (I&C) system will require design and analytical attention and some instruments will require component development. Integration of the I&C with the total plant I&C system will require similar attention and must await the plant integration program for final detailed definition.

This and indeed all of the interfaces with the balance of plant will be a continuing concern until the plant integration is carried out. It was demonstrated in the Task I plant studies that every power train component has numerous interfaces, above and beyond the obvious mechanical ones, with the balance of plant. These interfaces have been qualitatively defined in Task II in the preparation of the APT System Description and Specification. However, the detailed quantitative definition of some of these interfaces must await the development of the Heat Recovery/Seed Recovery and Seed Regeneration systems.

This is one cogent reason for the recommendation that these system development programs be pursued in parallel with that for the power train, rather than to proceed with a progressive development program. The opportunity to make the most effective technical and cost trade-offs between the power train and the other systems approaches will be lost unless all the systems are carried forward together and properly coordinated -- the most important function of the integration effort. Fortunately, the DOE program on downstream development (at B&W, UTSI, Argonne and Miss. St. U) has provided the technological base for the engineering development of the HRSR and Seed Regeneration systems.

5.4 TECHNICAL SUCCESS IN THE SHORTEST SCHEDULE AND AT LOWEST COST WILL BE REALIZED THROUGH AN INTEGRATED DEVELOPMENT PROGRAM

The APT program, through implementation of the Phase II effort, offers the opportunity for an effective and efficient program. The entire effort on the power train will be focused and directed to the key objective of demonstrating, in the Retrofit project and the MHD Generator development, the practicality of and the engineering basis for realizing the national benefits of MHD power. The various component development and system studies can be evaluated in a cohesive model structure (already established in the SPA/SUMARY code package) so that DOE has the technical tools and data to manage and direct the pieces of the MHD program to come together in and contribute directly to the Retrofit program and to the ultimate commercialization of MHD.

The value of the existing component-by-component development is recognized but it is not adequate for the scale-up phase of the power train program. The APT program plan is predicated on maintaining these programs along with the continued involvement of the developing organizations. The existing technology, along with on-going parallel program results, will be transferred as opposed to initiating programs of re-invention. It is an application of the make-or-buy decision process, in which equipment and/or services are purchased if practical in preference to embarking on new efforts. Experience teaches that there will be sufficient new business opportunities remaining in new large programs such as MHD after the outside sources are exhausted. The objectives of the program can be realized through the integration of these programs into the Westinghouse APT program through either subcontracting or GFE methods.

The integration effort to realize these benefits of a truly national program on the power train was considered and incorporated into the development plan as shown in the Work Breakdown Structure given in Figure 14. The technical integration to focus the component development into a cohesive power train is an important part of WBS 1100. The coordination of the development with the existing testing facilities and their program plans is an equally important part of the WBS 1800.

The WBS 1200 was established to provide the design and development consideration of the MHD generator as an integrated subsystem. This WBS element will accomplish the advantages of the new and innovative power management system and channel structural concepts discussed above.

The necessity for including the magnet as an integral part of the generator was recognized. The magnet is not included as a WBS component element (note the inclusion of an unnumbered WBS element) because it was defined as out of scope in the APT contract. It should be included in scope in the Phase II effort.

Figure 14. Work Breakdown Structure
First and Second Level

It must be considered in detail in the WBS 1200 effort, again either as a subcontract or as an integrated GFE system. It is impossible to design and develop the optimum (or even adequate) power train, and especially the MHD generator, without firm decisions and detailed information on the magnets in which these equipment must operate.

5.5 THE MANAGEMENT AND ENGINEERING TOOLS, EXPERTISE AND CONCEPTS TO CARRY OUT THE PROGRAM TO A SUCCESSFUL CONCLUSION HAVE BEEN IDENTIFIED

Most of the techniques for technical management of large developmental programs such as the power train are well known and many large organizations, especially serving the defense and space markets, practice them on a regular basis. The industrial organizations serving the utility market are generally less familiar with these tools. Westinghouse is one of a very few organizations that are not only familiar with these tools but have already adapted them to utility oriented programs. The success in the Phase I APT effort was largely due to this capability.

Adapting the tools to the specific needs of MHD is not an easy task. It is important to select those elements of technical management that are necessary and reject those that are not required but would add significantly to the program cost if retained. The experience gained in applying Air Force 375 to the Nuclear Rocket Engine Application, PMS to the Clinch River Breeder Program, and adaptations of these tools to total plant and development programs in commercial nuclear and new conventional power projects, was applied. Most of the personnel working on the Phase II effort have had personal hands-on experience in both levels of system management methods. Successful performance of the Phase I effort was the result, described herein, achieved within budget and schedule.

The level and degree of application of these tools will be raised as required in the execution of Phase II of the project. This will be particularly important where numerous organizations are carrying out portions of the program. The documentation for proper and economical direction of the various efforts will be provided for use by Westinghouse and DOE management.

Typical examples of such documentation include the Power Train System Description and Specification, and the Development Plan both produced in Phase I. On initiation of Phase II, agreed upon versions of these and other related documents will be placed under control procedures and will be changed only after agreement by the affected parties and approval by DOE. Made available to all parties participating in the program, they will form the framework within which each organization will perform their portion of the power train development effort so that the various results will conform to the coordinated and integrated whole power train.

Appropriate progress review and reporting procedures will also be applied to insure that the Westinghouse APT effort is properly directed and that DOE has the latest data and information for their management of the various related projects. A key responsibility of the APT Project Manager will be the call and conduct of regular project reviews that include all participants in the program. These reviews will be conducted in such manner as to identify progress against the Development Program Plan and to identify potential problem areas at the earliest moment. Such problem areas will be recorded in a follow-up Variance Report designed to provide APT and DOE management with information to focus their attention on the critical issues. These reviews will also be conducted to identify new information that can update the System Description and Specification (and related documents such as Equipment Specifications on individual components) or call out needs for changes in data or information previously included in these documents. Such needs will be presented in Change Request format that will describe the requested change and rationale. Such Change Requests will be evaluated for impact on other elements of the program and referred to a Change Control Board. The Change Control Board will be made up of senior personnel drawn from the various participating organizations to provide the best available expertise to the deliberations. Recommended changes will be referred to DOE for approval and/or implementation, depending on the affected organizations. Once approved, the change will be reflected into the control documents (Plans and Specifications).

Technical as well as management tools have been identified. For example, Computer Aided Design (CAD) will be applied. By establishing terminals at the

various organizational locations, agreed upon configurational changes can be implemented on very short notice and all parties will be assured of data that is up to the minute and that their design is thoroughly consistent with that of mating equipment. Design information can be exchanged rapidly without the delay and cost of conventional drawings.

The continued use of the SPA/SUMARY code package and plant models will allow the rapid consideration of potential design alternatives at very reasonable cost. As problems arise in the development of any component (for whatever reason such as availability of adequate materials or dimensional interferences) the power train integration function, WBS 1100, will be prepared to study and recommend options that can resolve the concern.

The examples cited above, along with many others, will be used in the successful execution of Phase II of the MHD Advanced Power Train program.