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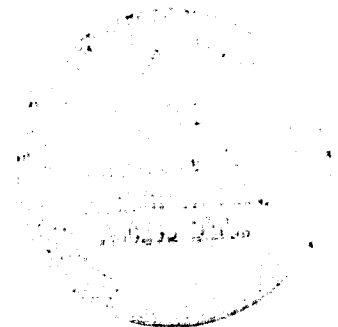
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RAPPORTEUR REPORT: MHD ELECTRIC POWER PLANTS

George R. Seikel
National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Magnetohydrodynamics

Prepared for
Seventh International Conference on
MHD Electrical Power Generation
Cambridge, Massachusetts, June 16-20, 1980



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I. INTRODUCTION

I will be reporting on the five following U.S. papers dealing with MHD electric power plants:

"Results from Study of Potential Early Commercial MHD Power Plants and from Recent ETF Work" by F. Hals, R. Kessler, D. Swallow, L. Westra, and J. Zar, Avco Everett Research Laboratory, Inc., Everett, Massachusetts 02149; W. Morgan, Charles T. Main, Inc., Boston, Massachusetts 02199; and C. Bozzuto, Combustion Engineering, Inc., Windsor, Connecticut 06095.

"Parametric Study of Prospective Early Commercial OCMHD Power Plants (PSPEC)" by C. H. Marston, D. J. Bender, J. G. Hnat, and T. C. Dellinger, General Electric Company, Advanced Energy Department, Philadelphia, Pennsylvania 19101.

"Engineering Test Facility Design Definition" by R. W. Bercaw and G. R. Seikel, NASA Lewis Research Center, Cleveland, Ohio 44135.

"Optimized Utility Integration of a 500 MW_T MHD Power Train" by R. E. Weinstein, L. M. Bartone, Jr.; and J. C. Cutting, Gilbert/Commonwealth, Reading, Pennsylvania 19603.

"Optimization of Disk Generator Performance for Base-load Power Plant Systems Applications" by J. D. Teare, W. J. Loubsky, J. K. Lytle, and J. F. Louis, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

The first two papers report on the results of the initial Parametric phase of the U.S. effort on the Study of Potential Early Commercial (PSPEC) MHD plants. The third, fourth, and part of the first paper deal with aspects of the smaller commercial prototype plant termed the Engineering Test Facility (ETF). The fifth paper addresses the alternative of using a disk geometry generator rather than a linear generator in baseload MHD plants. It is the only paper that addresses closed-cycle as well as open-cycle MHD plants.

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II. PARAMETRIC STUDY OF POTENTIAL EARLY COMMERCIAL (PSPEC) MHD POWER PLANTS

Previous studies such as the NASA Lewis Research Center managed Energy Conversion Alternatives Study (ECAS) indicated the long-range potential of MHD compared to alternative coal-fired power plant concepts. Open-cycle MHD topped steam power plants were shown to have both one of the lowest costs of electricity and one of the highest efficiencies. The ECAS results show that MHD plants could achieve efficiencies (coal-pile-to-bus-bar) of approximately 50%, a 50% improvement over present steam plants. Two preliminary market penetration studies performed under EPRI contract indicated that such MHD plants could capture the future baseload power plant market.

Coal-fired open-cycle MHD/steam power plants can be categorized by the method used to achieve the necessary MHD combustor temperature. These include variations in the MHD combustor oxidant (air or oxygen-enriched air) and its temperature and method of preheat. Figure 1 illustrates the three major types of MHD steam power plants. In the "High-Temperature Directly Preheated" plant, the combustor oxidant (air) is preheated to high temperatures by the MHD generator exhaust in a combination of recuperative plus high-temperature, regenerative, refractory cored-brick heat exchangers. In ECAS the evaluation of the potential of mature MHD technology was based on this type plant because it has the highest performance potential. It is anticipated that the high-temperature air heaters would be the critical path technology for construction of such plants, although significant progress is being made as reported in the Fluidyne paper at this conference.

As a result, studies were initiated for the United States Department of Energy by NASA Lewis Research Center to evaluate the potential of the alternative MHD plants illustrated in Figure 1 which do not require directly-preheated high-temperature air heaters. Parallel "Studies of Potential Early Commercial (SPEC)" MHD plant contracts were awarded to industrial teams led by the Avco Everett Research Laboratory and the General Electric Company. In the initial "Parametric" phase (PSPEC), the teams investigated both plants using separately-fired high-temperature preheaters and plants using intermediate temperature preheat and oxygen enrichment. These teams limited their studies to plants in which a large fraction of the coal slag is rejected by the MHD combustor. A third PSPEC effort being conducted by the University of Tennessee Space Institute, under a NASA grant, is examining plants in which no slag is rejected by the MHD combustor.

The PSPEC contractors investigated two categories of plants with separately-fired high-temperature preheaters: plants using essentially state-of-the-art gasifier and preheater technology and plants using advanced gasifier and/or preheater technology. The contractors evaluation of the intermediate-temperature preheat, oxygen-enriched MHD plants was based on NASA supplied oxygen plant data. This information had been developed in a separate contract with the Lotepro Corporation in conjunction with its parent company, Linde AG. The ongoing Lotepro oxygen plant studies are discussed in a separate paper at this conference.

Another rapporteur will also discuss the paper by Staiger and Abbott which is the NASA Lewis Research Center "Summary and Evaluation of the PSPEC MHD Power Plant Contractors Results."

The Avco and G.E. PSPEC results, as shown in Figure 2, indicate that these first generation MHD plants should obtain reasonable cost of electricity (COE) and efficiencies of approximately 45%, a 33% improvement over present steam plants. For comparison, both Avco and G.E. estimate that the levelized CO_e for conventional large coal-fired steam plants would be 44-48 mills/kw-hr in the same year dollars shown in Figure 2.

Both the Avco and G.E. PSPEC results, as will be discussed, indicate that the most attractive early commercial MHD plants are those which use intermediate temperature recuperative preheat and oxygen enrichment of the MHD combustor oxidant. Both contractors are presently performing a more detailed Conceptual effort, CSPEC, to more completely define large reference 1000 MWe commercial plants of this type. Subsequent CSPEC follow-on efforts are planned to investigate plants down to less than 500 MWe, the anticipated size of initial first commercial plants.

Avco PSPEC Results

Avco investigated three base case plants with 29 total parametric cases. The Base Case 1 plant, the state-of-the-art high-temperature air heater and gasifier case, used commercial Wellman-Galusha gasifiers and 2700F air preheat. To meet environmental regulations, Avco found it necessary to use cold gas cleanup on one half of the gas produced by the gasifier. The Base Case 2 plant, the advanced high-temperature air heater and gasifier case, assumed an entrained-bed Combustion Engineering atmospheric low BTU gasifier. Cold gas cleanup of the LBTU gas was used. The char carryover from the gasifier is captured in a particulate removal system and utilized as additional fuel for the MHD combustor. Air preheat of 3000F was assumed. The Base Case 3 plant, the oxygen-enriched intermediate temperature preheat case, assumed a nominal oxygen enrichment of 34% by volume and an oxidant preheat temperature of 1100F.

The parametric cases considered by Avco included variation of plant size from the nominal 900 MW_e size down to 400 MW_e, variation of oxygen enrichment, variation of MHD channel load parameter and diffuser recovery factor, use of Illinois #6 rather than Montana subbituminous coal, an increase of maximum magnetic field strength from 6 to 7 tesla, an increase in MHD channel coolant temperature, increase in seed concentration from 1% to 1-1/2% potassium by weight, and variation in MHD combustor stoichiometry and coal moisture.

As indicated in Figure 2, the Avco separately-fired high-temperature air heater advanced cases are generally two points higher in efficiency than the state-of-the-art cases. They are, however, essentially comparable in COE. The alternative oxygen-enriched plants with intermediate-temperature preheat are lower in COE than all of the plants with separately-fired preheaters. The efficiency of the oxygen-enriched plants increases from approximately 43 to 45% as the preheat temperature is increased from 1000 to 1400F.

The Avco results show that plant efficiency drops only slightly as the size is reduced from 900 MW_e to 600 MW_e, but drops almost an additional point in efficiency as the plant size is further reduced to 400 MW_e. Avco indicates slight efficiency improvement for plants using Illinois coal, drier coal, improved diffusers, higher temperature channel cooling, higher magnetic fields, and 1-1/2% rather than 1% seed concentrations. The results also show that an optimum exists in oxygen enrichment and channel load parameter and that the carbon reduction process for seed regeneration appears to be less desirable than the Formate process.

The Avco study concludes that the oxygen-enriched plants with a moderate preheat temperature: 1) "avoids the need for high-temperature air preheater and any development requirements associated with this," 2) "yielded the lowest estimated cost of generating electricity of any of the three different moderate technology plants investigated," and 3) "are still attractive compared to conventional steam plants."

General Electric PSPEC Results

General Electric investigated 33 parametric variations on the three base cases. For Base Case 1, the state-of-the-art high-temperature air heater and gasifier case, G.E. also used Wellman-Galusha gasifiers to produce the low BTU gas to fuel the separately-fired air heater, and assumed 2700F preheat. G.E., however, used dry scrubbers to clean up all effluents from the plant. For Base Case 2, the advanced plant with separately-fired high-temperature air heater, 3000F preheat was assumed with the reheat being accomplished by a two-stage slagging cyclone combustor. The reheat combustion gas is pressurized to reduce the size

of the preheaters. A gas turbine on the preheater exhaust drives the compressor supplying the air for the preheater combustor. Dry scrubbing of this stream is used to meet environmental requirements. The main MHD flow utilizes potassium seed to remove sulfur. The formate process is used to reprocess the seed. For Base Case 3, the oxygen-enriched plant with intermediate-temperature preheat, 1300F preheat of an oxidant enriched to 42 mole % oxygen is assumed.

The emphasis of the G.E. study was on Base Case 2 for which 21 parametric variations were costed. Only five and four parametric cases variations were costed for Base Cases 1 and 3, respectively. The G.E. parametric cases included variation of plant size from their nominal 1200 MWe down to 600 MWe, use of both one and two-stage MHD combustors with varying slag rejection, use of Illinois #6 as an alternative to the reference Montana subbituminous coal, variation of recuperative heat exchanger output temperature, and variation of the field strength and other generator parameters.

Overall efficiency and cost of electricity for the G.E. plants are also shown in Figure 2. The G.E. MHD plants have much higher efficiency than conventional steam power plants, but the G.E. levelized cost of electricity for their MHD plants is higher than that for conventional steam plants. The significant MHD plant cost discrepancies between G.E. and Avco is discussed in the previously referenced NASA paper of this conference by Staiger and Abbott.

Comparing only the G.E. data for the various cases, it is clear that G.E. agrees with Avco in that the oxygen-enriched plants with intermediate temperature preheat appears substantially superior to the plants with state-of-the-art separately-fired high-temperature air heaters. The wide of range of efficiency and cost of electricity obtained by G.E. for the plants with advanced separately-fired high-temperature air heaters reflects the wide range of parametric points examined for this case. The highest performance and lowest cost of electricity cases use very advanced air heater technology; pressurized, hot bottom preheaters which operate with some slag carryover from the reheat combustor. These preheaters could be as difficult to develop as direct-fired high-temperature air preheaters.

The limited range of efficiency and cost for the oxygen-enriched plants reflects the limited study of this case. The only enrichment level investigated by G.E. was above that found by Avco to yield optimum efficiency. The efficiency calculated by G.E., however, generally agrees with an extrapolation of the Avco lower enrichment level results.

Concluding Remarks

The level of discrepancy between the Avco and G.E. PSPEC results, in terms of efficiency and cost of electricity, is of the order of that which might be expected for studies conducted at the parametric level of detail. Many of these discrepancies should be resolved in the presently ongoing Conceptual Study of Potential Early Commercial (CSPEC) MHD plants.

ENGINEERING TEST FACILITY

The Engineering Test Facility (ETF) is the major focus of the United States Department of Energy (DOE) MHD program to facilitate commercialization and to demonstrate the commercial operability of MHD/steam electric power plants. The Lewis Research Center of NASA is serving as DOE's lead field center for managing the ETF Definition Project.

ETF Definition

The paper by Bercaw and Seikel describes the current DOE ETF concept, the basis for its selection, and the process which will be followed in further defining and updating the conceptual design.

DOE has defined the ETF to be a nominal 200 MW_e size prototype of an initial commercial plant. The ETF shall surpass environmental regulations. Its performance shall meet or surpass existing utility standards for fuel, maintenance, and operating costs; plant availability; load following characteristics; durability; and safety.

The power level selected places the ETF within the range of smallest plants being ordered by electric utilities and within a factor of 2-3 of the currently most popular size (400-600 MW_e) for new utility plants (the size where MHD is expected to become cost competitive).

The ETF will be large enough to be commercially competitive with regards to performance and operating costs, but not from the viewpoint of capital cost. Government funding would, thus, be required for ETF construction, but after an initial testing phase it is anticipated that ETF could be profitably operated by utility. Therefore, government cost for testing and operating would be minimal. To reduce the risk associated with scaling to ETF from the engineering basis demonstrated in CDIF, DOE is assessing in parallel the requirements for increasing the thermal power level of CDIF from 50 MW_{th} up to as high 100 MW_{th}.

The previously discussed Studies of Early Commercial Plants serve as a basis for defining the commercial plant for which ETF must be a prototype. On the basis of the PSPEC results, the DOE Director of MHD decided in August 1979 that the ETF and its target commercial plant would use oxygen-enrichment and intermediate-temperature recuperative preheat.

DOE funded conceptual ETF studies by Avco, General Electric, and Westinghouse. These were conducted in parallel to the PSPEC plant effort. The paper by Hals et al. includes the Avco ETF results for oxygen-enriched plants of various sizes. Figure 3 is a pictorial view of the Avco 300 MW_{th} oxygen-enriched design. The ETF study and PSPEC results were combined with the DOE ETF programmatic decisions to form the basis of the "Basic ETF Requirements" indicated by Bercaw and Seikel.

The approach to the MHD ETF definition is to define a baseline "stand-alone" ETF design which will be periodically revised to assure consistency with the MHD Engineering Development and System Engineering efforts and with the evolution and definition of national and utility needs. ETF may ultimately be constructed either as a stand-alone plant or integrated with an existing or new steam plant. The latter two alternatives will be evaluated as permutations of the baseline "stand-alone" design.

NASA Lewis will prepare at least two generations of ETF conceptual designs with the assistance of DOE Chicago Operations Regional Office, Argonne National Laboratory, MIT National Magnet Laboratory, and Gilbert Associates, Inc. The designs will be prepared in accordance with DOE approved Design Requirements Documents.

The ETF and early commercial MHD plants are envisioned to contain only four unique MHD systems: the MHD power train, the MHD magnet, the Heat and Seed Recovery, and the Seed Reprocessing. In the initial ETF conceptual design, scaled-up versions of the unique MHD systems developed under the previous study contracts will be utilized. Therefore, this initial ETF conceptual design will not be fully consistent with the DOE MHD Engineering Development Program, but it will provide the first design of the balance of plant which is consistent with the approved design requirements and will define tentative interfaces between the systems comprising the plant. The second conceptual design will be based on an updated Design Requirements Document and MHD system designs which are consistent with the engineering development program. These MHD system designs will be prepared either by or through the major MHD field center responsible for each system.

It is currently envisioned that the preliminary design, final design, construction, checkout, startup, and operation of ETF will be competitively procured by DOE. The ETF Design Requirements Document and final conceptual design will be utilized by DOE to support the Congressional funding request and subsequent procurement. The DOE schedule to request funding could vary from post-1987 to 1984 depending on interim MHD Program funding.

ETF Integration with a 400 MWe Steam Power Plant

As previously indicated, various potential alternatives exist for implementing the design and construction of a commercial prototype MHD steam power plant, ETF. The paper by Weinstein, Bertone, and Cutting studies integration of 500 MW_T ETF with a 400 MW_e conventional steam utility power plant. In previous studies reported at the 18th Symposium on the Engineering Aspects of MHD, integration of a smaller ETF with various size steam power plants was examined. These previous Gilbert studies and parallel studies by Southern California Edison concluded that the most attractive method of integrating an ETF with a steam power plant, new or existing, was via a steam path connection. The basic MHD combustion gas flow, therefore, is unaffected by the method of implementing the ETF design and construction.

Figure 4 illustrates the method proposed by Gilbert for integrating an ETF with a nominal 400 MW_e steam plant. The MHD power train, heat and seed recovery, emission controls, oxidizer preparation including the air separation unit, and seed reprocessing systems would be identical to those of a free-standing ETF plant. As indicated in the schematic, Gilbert contends that the topping cycle and air separation unit compressors should be driven by a steam turbine(s) operating on reheat steam; the same approach is envisioned for the free-standing ETF conceptual design.

For the specific 372 MW_e steam power plant studied, the steam plant boiler operates at approximately 70% rated duty when the MHD plant is in operation. The balance of the steam is generated by the MHD Heat and Seed Recovery system. The steam flow to the high pressure turbine is thus designed to be constant whether the MHD plant is in or out of service. In contrast, because of the extraction of reheat steam to drive the MHD oxidant and air separation unit compressors, the reheat steam flow to the turbine/generator is reduced to approximately 90% of the MHD out-of-service flow when the MHD plant is in operation.

Gilbert estimates that the net power output of the combined plant would be 447 MW_e at an efficiency of 35.2%. The net power would drop to 372 MW_e at an efficiency of 34.4% when the MHD cycle is out of service. The total facility is estimated to require 6-1/2 years to construct and to have an overnight construction cost (in mid-1978 dollars) of 520 million; of this, 270 million is for construction of the conventional coal-fired plant. Some of this total cost is associated with the increased size of component which is needed to permit the flexibility of operating with or without the MHD plant.

The unique advantages associated with implementing the EIT through such an approach are:

- o Steam plant output can be maintained whether the MHD is in or out of service.
- o The relative size of the steam plant and MHD plant decreases the steam plant's sensitivity to MHD system changes.

DISK GENERATORS FOR MHD PLANTS

The MIT paper on the design of disk generators for open and closed-cycle MHD power plants is a part of a larger Westinghouse contract for NASA LeRC to determine the capabilities of coal-fired MHD plants using disk generators. If the disk generator were constrained to operate at the same electrical stresses, i.e., Hall field, as a linear generator, then the disk generator would have poorer performance due to its higher surface to volume ratio. However, the allowable Hall field in a generator is determined by breakdown; breakdown is more likely on electrode walls than on the insulator walls. Since disk generators only have insulator walls, their allowable Hall field is much larger. For the subject MIT disk studies, an allowable Hall field of 12 KV per meter is assumed; this is three times the maximum assumed in linear generator studies.

Additional inherent issues of disk generators are that swirl must be added to the radial flow to avoid the inefficiencies of a Hall machine, and that although the disk generator requires a relatively simple magnet to construct, it tends to poorly utilize its stored energy.

The subject MIT studies assumed that a swirl ratio of up to a factor of 0.5 can be obtained from a two-stage open-cycle MHD combustor without the use of inlet guide vanes. Additional losses have been included when swirl ratios greater than a half are assumed. As a result, a swirl ratio of one half is generally found to be near optimum for open-cycle generators. The question of utilization of the stored energy of the disk magnet may impact the magnet cost and overall plant cost of electricity; this is outside the scope of the MIT effort but will be considered in the subsequent Westinghouse studies.

The open-cycle disk generator studies reported in the MIT paper were primarily performed for generators seeded with 0.7% potassium by weight. Resulting conductivities calculated by MIT/Westinghouse were somewhat lower than those calculated by Avco in PSPEC, which are generally in agreement with the NASA LeRC estimates. As a crude estimate of the performance as a function of conductivity, MIT recalculated the performance assuming both a 30 and 60% increase in conductivity over their calculated value for 0.7% potassium seed. The 30% higher conductivity corresponds to the difference between the MIT/Westinghouse value and the Avco PSPEC value at the entrance of the Avco PSPEC generator.

As indicated in Table 1 of the MIT paper, even a 60% increase in conductivity only affects the disk enthalpy extraction and electrical efficiency by one percentage point. The required disk radius, however, is nearly inversely proportional to the conductivity. The cost of the corresponding disk generator magnet, which is outside of the scope of the presently reported work, would thus be strongly affected by the conductivity. This should be no surprise; even for conventional electric machines, the chief effect of conductivity is to determine the size more than the performance of the machine.

In their performance comparison between the linear and disk generator configurations, MIT also assumed that a supersonic disk generator could be built with an equivalent performance combustor, nozzle, and diffuser to the subsonic linear Avco PSPEC generator. These assumptions remain to be validated.

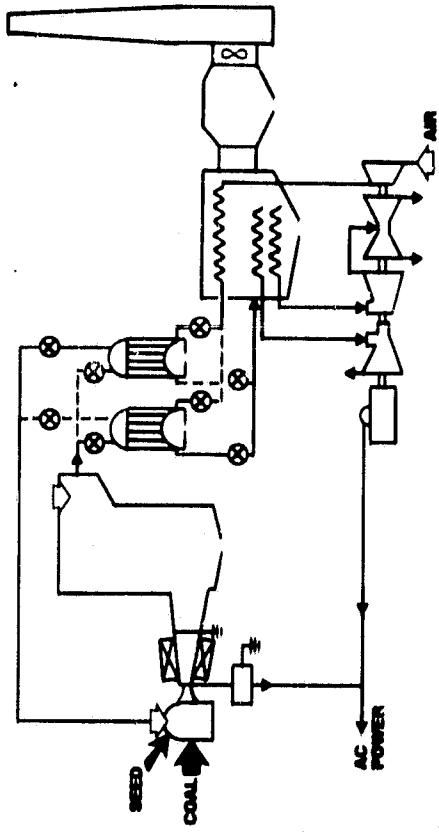
The MIT open-cycle disk generator study results show: 1) high enthalpy extraction and efficiency disk generators can be designed for use in MHD plants, 2) swirl ratios anticipated to be obtainable from open-cycle combustors without inlet guide vanes are adequate to yield attractive performance, 3) a constant Hall field design yields the minimum radius disk generators, 4) disk generator performance increases with increasing disk radius as does a linear channel with length. Regarding the last point, for large MHD plants, generator size will primarily be determined by economic considerations. The simplified one-dimensional analysis used in this paper and most other plant studies does not, however, account for the decreased diffuser pressure recovery as a function of generator length (radius for the disk) nor the decrease in steam plant efficiency associated with an increased amount of low-grade generator cooling.

The MIT closed-cycle disk results indicate that very small high performance designs appear possible. Design of a closed-cycle disk generator is more complex than an open-cycle generator because of the coupling of the currents with the non-equilibrium conductivity. The MIT paper presents 33 "optimized" closed-cycle disk generator cases. These generators are designed to operate in plants which use the total output of the steam turbine to drive the topping cycle compressor(s). Prior studies have indicated that somewhat higher plant efficiencies can be obtained if compressor power is increased above that available from the steam turbine by utilizing partially electrically driven compressors, but the resulting plant complexity may not be warranted.

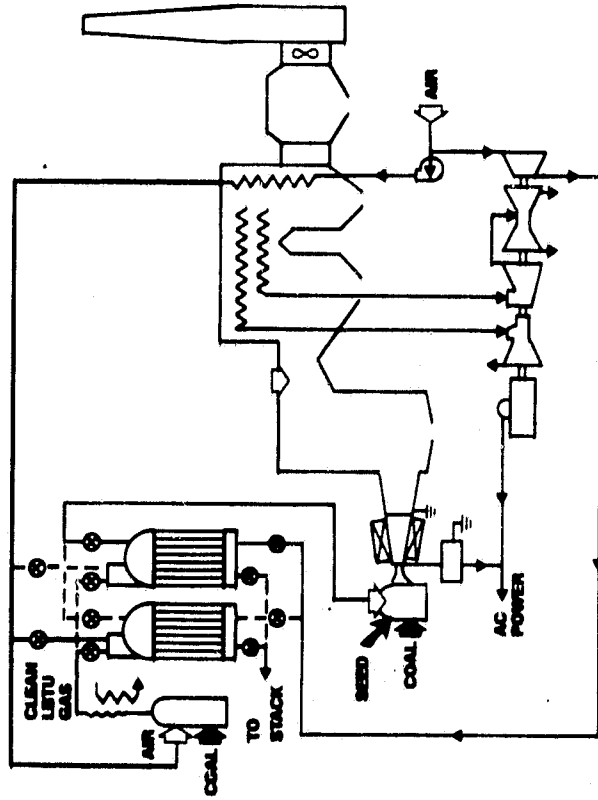
The MIT results indicate that closed-cycle disk generators can obtain performance comparable to that of closed-cycle linear generators. The disk generators require high swirl and need swirl vanes, but at the temperatures of the closed-cycle generator (3000F) swirl vanes may not pose a serious problem. The very short lengths of the disk generators (on the order of a meter) does raise questions regarding the sufficiency of one-dimensional calculations for these generators. Unfortunately, the disk generator plants to be costed by Westinghouse will only include open-cycle plants and will not include any closed-cycle plants.

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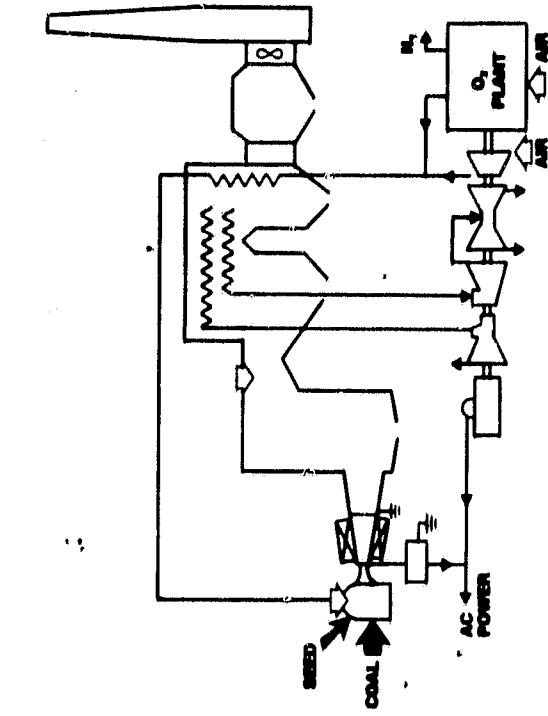
Figure 1. Types of Coal-Fired MHD/Steam Power Plants



HIGH-TEMP DIRECTLY PREHEATED



HIGH-TEMP SEPARATELY-FIRED PREHEAT



INTERMEDIATE TEMP PREHEAT, O₂ ENRICHED

Summary of PSPEC Results

COMPARISON OF ALTERNATIVE OXIDIZER SYSTEMS

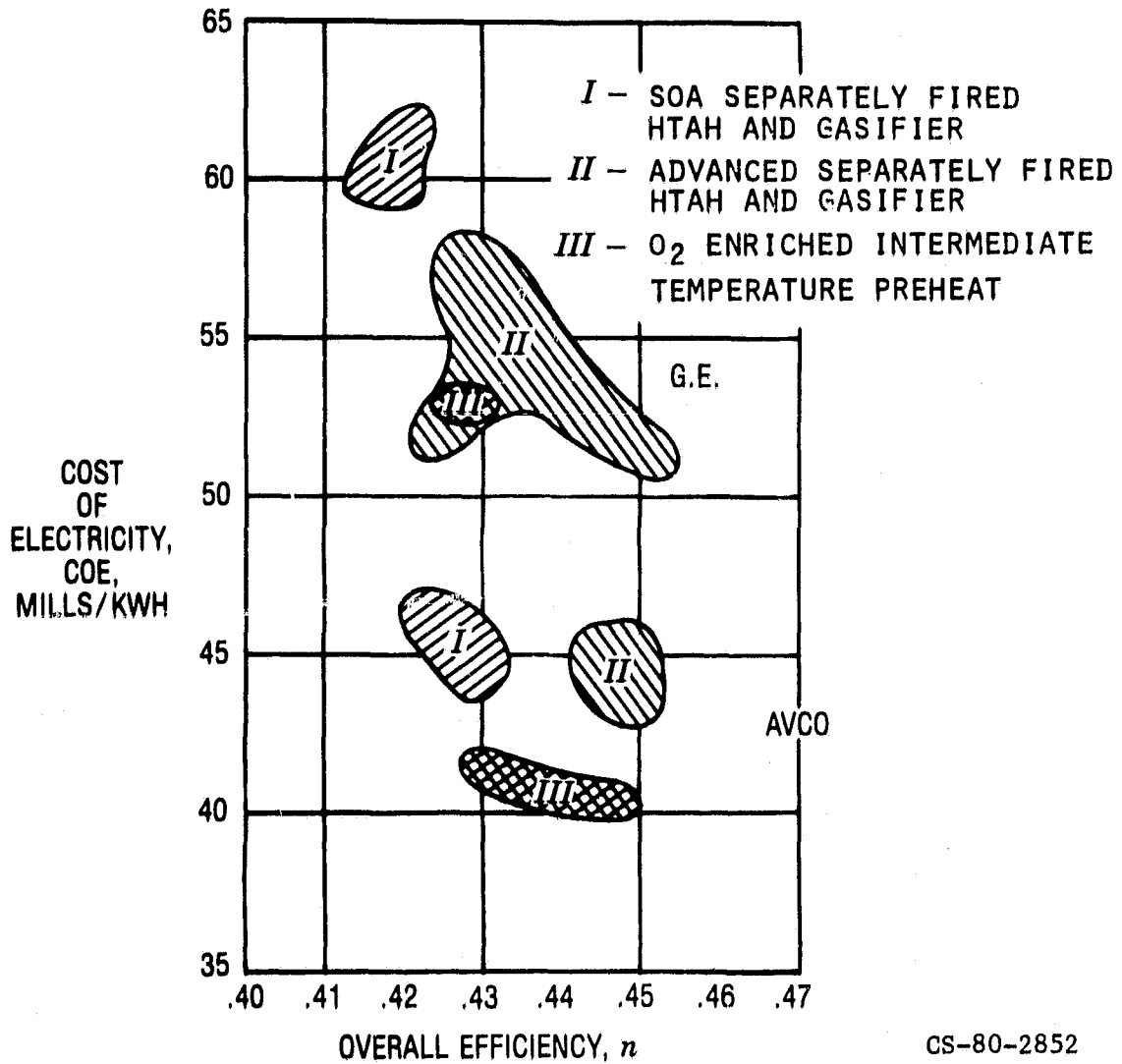
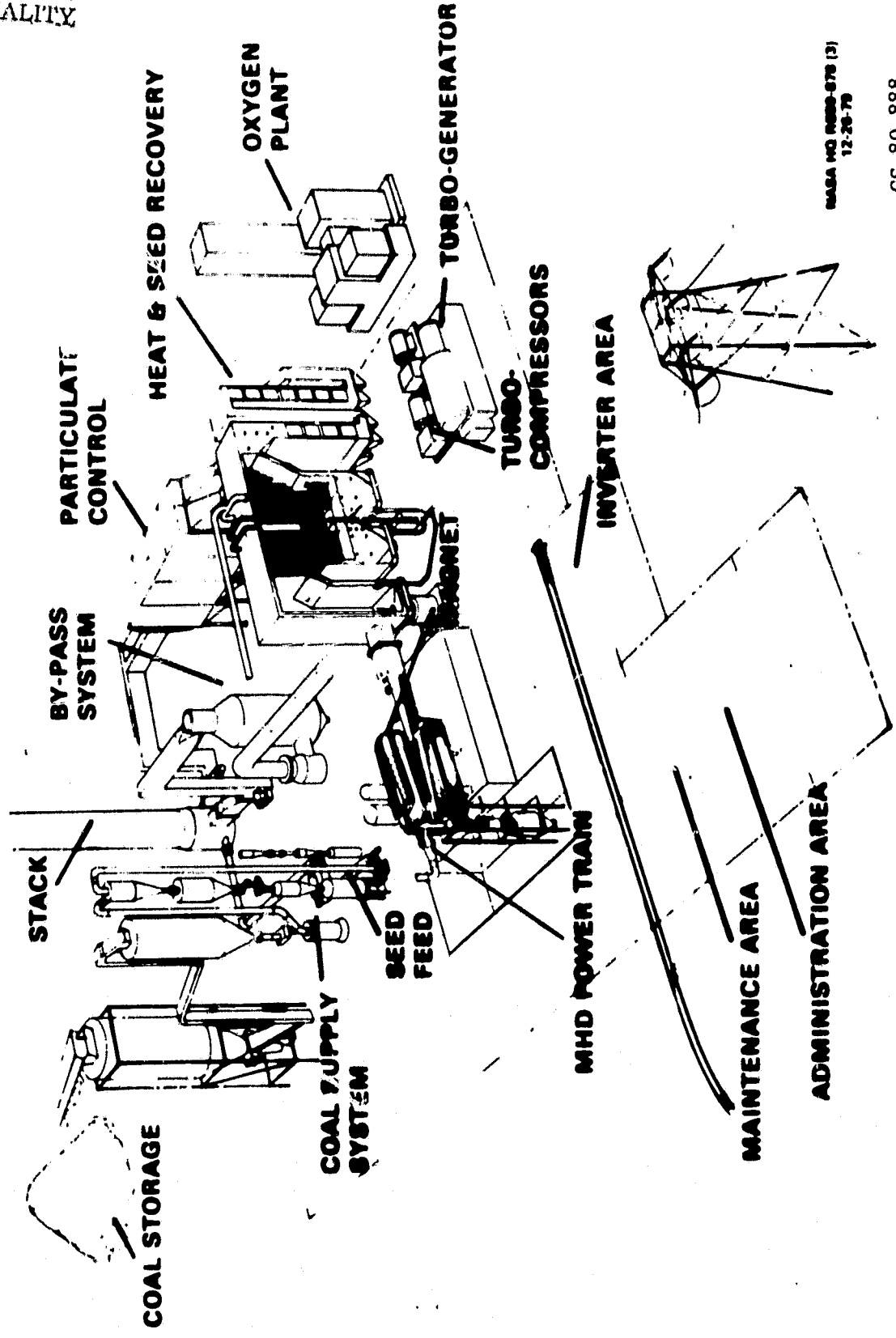


Figure 2. Summary of PSPEC Results. Comparison of Alternative Oxidizer Systems.

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MHD ENGINEERING TEST FACILITY

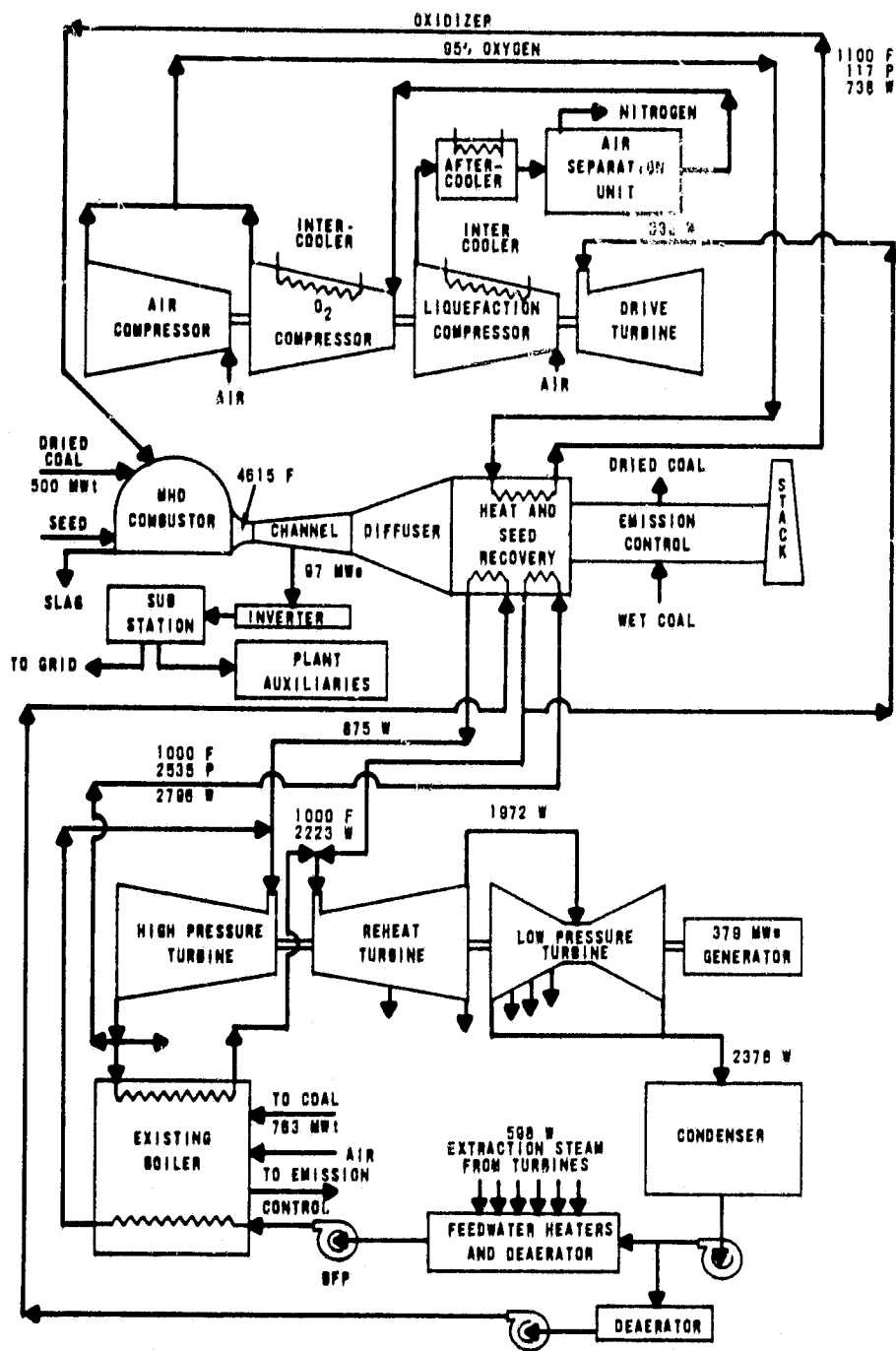


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Figure 3. MHD Engineering Test Facility

Figure 4. Integration of a 500 MW_T ETF with a Nominal 400 MW_e Utility Steam Power Plant.



LEGEND:

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

MHD IN SERVICE

NET POWER OUTPUT	447 MWe
NET POWER INPUT	1267 MWt
EFFICIENCY	35.2%
HEAT RATE	9683 BTU/KWH