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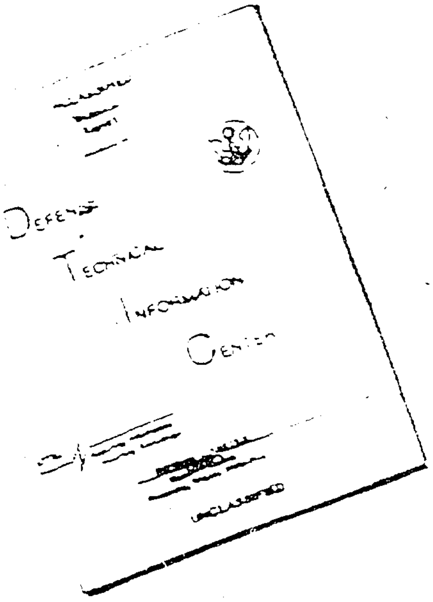
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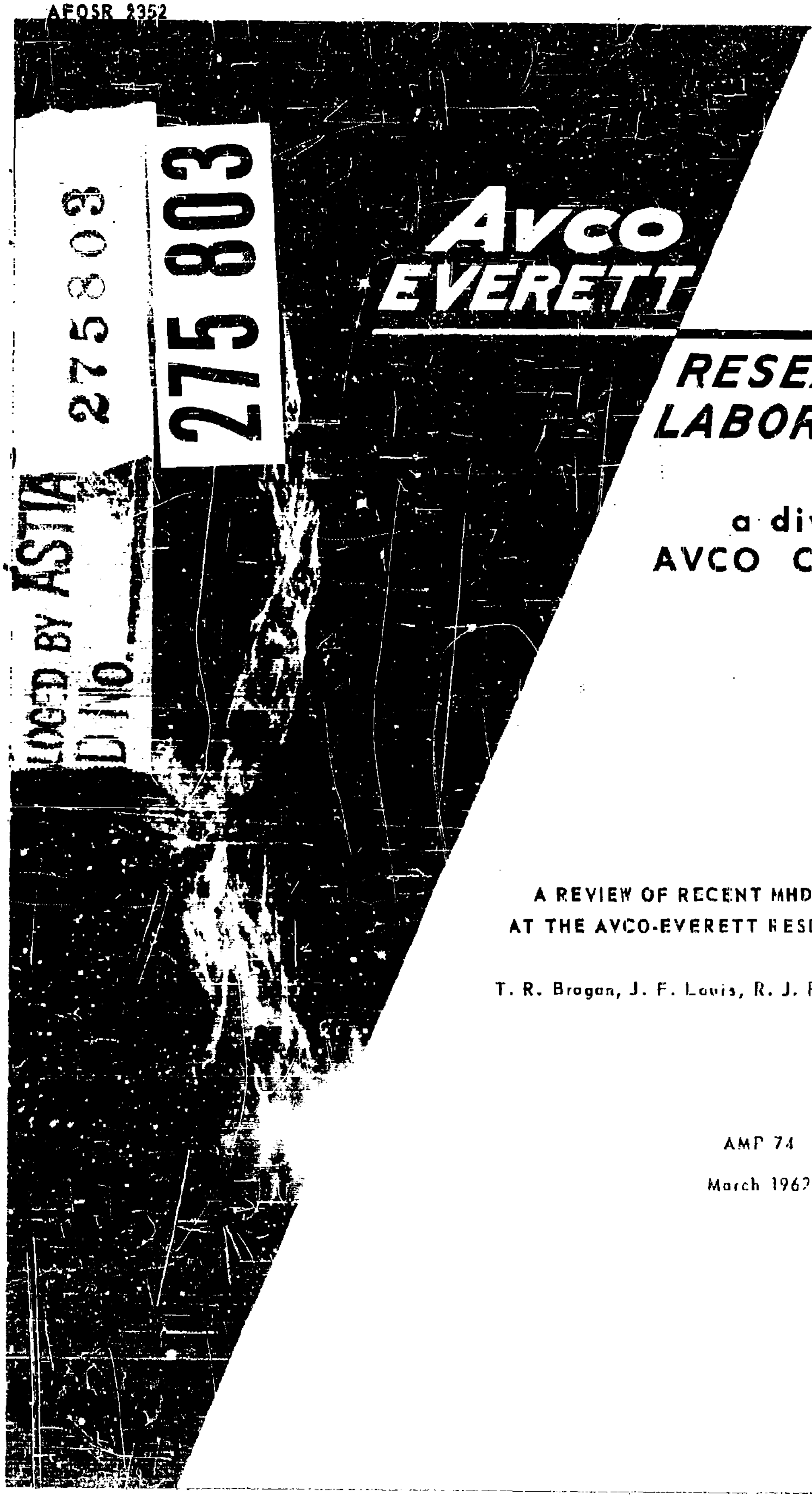

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A REVIEW OF RECENT MHD GENERATOR WORK AT THE AVCO-EVERETT RESEARCH LABORATORY

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T. R. Brogan, J. F. Louis, R. J. Rosa and Z. J. J. Stekly

AVCO-EVERETT RESEARCH LABORATORY
a division of
AVCO CORPORATION
Everett, Massachusetts

presented at

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Abstract

This paper presents a general review of work in the field of MHD power generation during the past year at the Avco-Everett Research Laboratory. The review includes the areas of conceptual plant design, electrical properties of gases, generator fluid mechanics and performance, field coil designs, and long duration testing.

In the area of gas properties, the experimentally determined conductivity of seeded combustion products is in good agreement with predicted values in the temperature range between 2300° K to 3000° K.

The study of generator fluid mechanics has continued during the past year using the Mark II combustion generator whose construction and initial operation was described at this meeting a year ago. Successful operation at Hall coefficients up to two has been achieved. Actual performance of the Mark II generator is discussed.

The discovery of high field strength superconducting alloys has important implications for MHD power generation, as well as for many other MHD devices. There is a brief description of these coils as applied to MHD generators, together with an assessment of the economic possibilities they present for use in a power plant.

The work reported here has been supported by the Avco Corporation and a group of eleven leading electric utilities*, and by the United States Air Force under Contract AF 49(638)1129.

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*The present utility group consists of American Electric Power Company and its subsidiaries - Appalachian Power Company, Indiana and Michigan Electric Company, and Ohio Power Company; The Dayton Power and Light Company, Illinois Power Company, Indianapolis Power and Light Company, Kansas City Power and Light Company, Louisville Gas and Electric Company, Boston Edison Company, Union Electric Company, and United Illuminating Company.

I. Introduction

One year ago at the second symposium on the Engineering Aspects of MHD, progress during the first sixteen months of the joint Avco-Utility Program for the development of the MHD Generator was reviewed[1]. The program has continued during the past year, and it is the purpose of this paper to review the work that has been carried out during that time. This work may be divided into five areas:

1. Conceptual Plant Design
2. Electrical Properties of Gases
3. MHD Generator Fluid Mechanics
4. Generator Component Development
5. Generator Field Coils

The status of each of these areas is summarized below, and compared to the situation as it existed a year ago. The body of the paper contains a more detailed discussion of each area.

The presentation last year included a description of the conceptual "oxygen" cycle which circumvented the problem of developing a high temperature preheater for the combustion air by reducing the required preheat temperature to a value compatible with conventional heat exchanger materials. Cycle analysis and heat balances have shown that the oxygen cycle retains the conceptual performance advantages of the MHD concept. A typical heat balance is presented in Section II.

The technique for the measurement of electrical conductivity of gases due to Rosa[2] has been adapted to combustion products, and last year the conductivity measurements at the adiabatic flame temperature were presented. These measurements have now been extended to lower temperatures, and the resulting experimental conductivities are in good agreement with predicted values. This work is described in Section III.

At the last sumposium the construction and initial operation of the Mark II Experimental MHD Power Generator was described. The initial runs were carried out using ablating wooden channels, and power outputs up to 100 KW were reported. A non-ablating channel of variable area ratio has been used for more recent operation, and power outputs up to 600 KW have been recorded with the mass flow essentially unchanged as compared to the original runs. Hall currents have been substantially eliminated. This work is described in Section IV.

The Mark II Generator's operating time is limited to about twenty seconds. This is more than adequate for studies of generator fluid mechanics, since equilibrium is reached after approximately five seconds.

However, the development of long duration generator components is necessary if the generator is to be considered for use in a central station power plant. A large portion of the effort during the past year has gone into the construction and initial operation of a Long Duration Test Facility for the development of MHD generator hot components. About 45 hrs. of test time have been accumulated on this facility, which is described in Section V.

Past calculations had indicated that with an MHD generator of a capacity compatible with a total plant output of 500 MW some 8% of the total plant output would be expended in providing the magnetic field for the MHD generator. This large power dissipation was expensive, both from the view of thermal performance and capital cost of plant. There are two possibilities for reduction or elimination of this dissipation: first, the sodium cryogenic coil, and second, the superconducting coil. Work in these areas is discussed in Section VI. The work on the superconducting coil has been supported by the U. S. Air Force under Contract AF49(638)1129 in connection with the Aerospace applications, but evaluation of the economics of the superconductor as applied to the MHD Generator is included in Section VI.

II. The Oxygen Cycle

The oxygen cycle eliminates the need for exotic preheater materials by bringing the requiring preheat temperatures into line with the capability of conventional heat exchanger materials. This is done by enriching the oxygen content of the combustion air. High combustion temperatures are necessary because of the very strong dependence of the electrical conductivity of seeded combustion gases on temperature (see Section III). Using the oxygen cycle, there is a slight reduction in thermal performance because of the fact that less regeneration is used as compared with the air cycle. This reduction in performance has been made good to a large extent by the advent of high field strength superconducting magnets with consequent elimination of field coil dissipation.

In order to keep the capital cost of the plant as low as possible it is desirable that the oxygen enrichment be minimized. Our calculations have indicated that, using conventional preheater materials, the N_2/O_2 molar ratio may be as high as 2, as compared with the value 3.76 for air. At this N_2/O_2 ratio, about 47% of the total combustion oxygen must be delivered by the air separation apparatus. For a plant of nominal output of 500 MW, about 3300 tons per day of oxygen are required.

A typical heat balance for a plant of nominal 500 MW output is given in Fig. 1, and the compressor cycle for the plant, in Fig. 2. Referring to Fig. 1, the mixture of air and oxygen with a N_2/O_2 molar ratio of 2 is supplied to the preheater in the boiler at a pressure of 236 psi and is preheated to 1600° F. It is then introduced into the combustion chamber where it is burned with a mixture of fuel and seed (potassium carbonate or hydroxide). The DC output of the MHD generator through which the combustion gases expand is 352,000 KW, and the net AC after inversion is 338,000 KW. A total power of 265,000 KW is generated by the turbines with the steam provided by the heat in the exhaust of the MHD generator. After deduction of the compressor and auxiliary power the turbines produce a net electrical output of 152,000 KW. The total plant output of 490,000 net KW represent a heat rate of 6,380 Btu/kwh for a cycle efficiency of 53.5%. As compared with the original air cycle, the distribution of output between MHD and steam shifts slightly to the steam side due to the reduction in preheat temperature. A superconducting coil has been assumed; were this not so, about 40 MW would be dissipated in a copper coil.

Compressors are required, both for air separation and for compression of the N_2/O_2 mixture to the cycle operating pressure. Because of the fact that there is less gas to compress to the cycle pressure as the N_2/O_2 ratio is reduced, the total compressor power is relatively insensitive to the N_2/O_2 ratio. In Fig. 2 the main air compressor and the HP No. 1 and HP No. 2 compressors supply air at low and high pressure to the air separator. The power requirements are typical of the Linde-Frankel Air Separation Cycle[3]. Upon leaving the air separator, the oxygen is mixed with air and compressed to cycle pressure in a two-stage unit. The intercoolers and aftercoolers for the compressors are cooled by boiler feedwater from the condenser; thus a portion of the compressor work is recovered as heat into the steam cycle.

The indicated fuel and seed costs for such a plant at full load are 1.63 mils/kwh with fuel at $\$0.23/10^6$ Btu, and assuming 90% recovery of the seed.

III. Electrical Properties of Combustion Gases

The MHD principle is based on the fact that gases delivered by conventional heat sources can be made adequate conductors of electricity if a small amount of easily ionizable impurity called seed is added to the gas. The conductivity attained by this technique can be predicted approximately using elementary kinetic theory principles, and the approximate results do not differ appreciably from those using more exact methods. From several experimental methods for measuring electrical conductivity we have chosen the one due to Rosa[2]. This method as adapted to combustion products was described at the last Engineering Symposium[1], and the results of the conductivity measured at the adiabatic flame temperature of seeded JP4-O_2 flames were presented. Also discussed was the influence of electronegatives on the conductivity with the conclusion that halogens could not be present in the flame.

During the past year the conductivity measurements in the seeded JP4-O_2 flame have been extended to temperatures below the adiabatic ture by adding cold products of combustion (CO_2 and H_2O) to the flame. The actual flame temperature then is determined by the ratio of the mass flow of cold products to the mass flow of combustibles.

The actual gas temperature at the entrance of the test section was measured using the sodium line reversal technique. Further temperature reduction in the test section up to the point where the data was taken was determined by measuring the heat loss from the flame gases to the test section. Thus the temperature at the point of measurement is accurately determined.

The measurement technique is simply the determination of the voltage-current characteristics of a direct current discharge in the seeded gas between two electrodes. Guard electrodes reduce the effects of fringing. The electrical conductivity of the gas between the electrodes may be obtained from the slope of the voltage-current characteristic and the geometry of the test section. Typical discharge data for several temperatures is shown in Fig. 3. The intercept at zero current indicates an electrode voltage drop of some 60 volts. For these experiments, water cooled graphite electrodes were used, and the high electrode drop with cold electrodes is not unexpected.

The measured and predicted values of conductivity are compared on Fig. 4, where it is seen that good agreement exists. Thus there is every reason to believe that the conductivity of seeded combustion products can be predicted with good accuracy.

IV. MHD Generator Fluid Mechanics

A non-ablating channel for the Mark II MHD Generator was designed and built. The channel was constructed with an area ratio (outlet to inlet) variable between 1.0 and 1.22. Subsequent modifications increased the maximum area ratio to 1.45, and modifications now in progress will further increase the area ratio to about 2.5.

A mixture of gaseous oxygen and a fuel consisting of methylcyclohexane, in which is dissolved a solution of KOH and ethyl alcohol, is burned in the combustion chamber of the Mark II Generator. This fuel provides a convenient method of introducing the seed into the flame in a uniform manner. The flame conductivities approach those of the kerosene-oxygen flame. Total mass flows up to 6 lbs/sec can be accommodated in the burner. Some attempts were made to photograph the flame in the burner through windows in the burner back plate, using the high speed camera. Although fine definition photography was not possible, it was concluded that the combustion was relatively uniform and stable.

As originally constructed, triple pointed graphite electrodes were used on each electrode segment of the non-ablating channel in a manner similar to that described for the wooden channels[1]. The idea behind such electrodes is that they will protrude into the gas stream through the boundary layer and be heated to the point where they make a good contact with the gas. Early runs with the non-ablating channel however demonstrated two difficulties with these electrodes. First, they made the generator wall rough with the result that a large pressure drop was incurred. This in turn made it difficult to maintain the gas velocity at a high value throughout the generator. Second, at the values of $\omega\tau$ obtainable in this generator the current concentration at the tip of the pointed electrodes caused an intense local Hall effect and consequent deteriorated generator performance. Accordingly the pointed electrodes were replaced by flat graphite electrodes which provided much cleaner aerodynamics and reduced the possibility of intense local Hall effect. The electrodes are replaceable.

The MHD generator magnet was designed for peak field strength of 33,000 gauss. From the beginning of the program, trouble was encountered due to inadequate electrical contact and strength at the joints between the copper plates of which the magnet is fabricated[1]. We were finally forced to abandon efforts to fix the assembled magnet, and the magnet was disassembled and reassembled with stronger joints of better electrical properties. In addition, bracing on the sides of the magnet was added to improve the structural characteristics. With these modifications the magnet has been regularly operating at the peak design field strength.

The experimental program with the generator has been devoted to the study of heat transfer rates, pressure distribution, electrodes, and the electrical characteristics of a generator for different values of the magnetic field. A typical heat transfer distribution is shown in Fig. 5, where the heat transfer rate is plotted vs. the axial distance along the channel.

Figure 6 gives the generator voltage distribution plotted against channel length for the short circuit, open circuit, and a load of 10.7 ohms on each electrode. The mass flow is 5 lbs/sec, and the magnetic field, 33,000 gauss. The channel area ratio is 1.45. The open circuit voltage across the channel increases with this distance, with the exception of the extreme downstream end, where circulating end currents cause the voltage to drop off. The maximum voltage is 1400 volts, corresponding to a field of 4 kilovolts per field. The distribution is not symmetric about the ground level, because the increasing electric field with distance causes eddy currents, which give rise to a second order Hall current at open circuit with consequent assymetry of the voltage distribution about ground. The large increase in voltage developed as the distance along the axis increases is due to the large velocity increase at open circuit. A maximum velocity of 1600 meters per second is estimated.

In the short circuit case the voltage across the channel is zero, and the only potential developed is the Hall potential, which reached a value of 1800 volts, corresponding to 1200 volts per meter. The total short circuit current is roughly 3500 amperes. The value of Hall potential developed indicates that first order Hall current has been largely eliminated. Under a 10.7 ohm load there is both the voltage across the channel due to the induced field and along the channel due to Hall effect. Again the magnitude of the Hall voltage indicates an absence of first order Hall currents. The power output in this particular run is 600 KW.

The pressure distribution for the three cases described in Fig. 6 is shown in Fig. 7. At open circuit the pressure drop due to the MHD effects is minimum, and most of the pressure drop is due to the fact that the gas velocity increases above the speed of sound. The channel inlet is at sonic speed corresponding to a pressure ratio of about 0. 6. Under a load of 10. 7 ohms and at short circuit the magnetic forces dominate the pressure distribution. With the channel area ratio of 1. 45 the inlet velocity is reduced from a value of about 930 meters per second at open circuit to a value of 500 meters per second under load, and is further reduced to about 400 meters per second at short circuit. Since the power output is proportional to the square of the velocity, the generator is presently limited in power output to little more than the 600 KW already attained by the present channel area ratio of 1. 45. Modifications presently in progress are expected to remove this limitation.

In the operations to date we have been successful in largely eliminating Hall currents and have succeeded in producing a flow which is dominated by the MHD effect and in which the pressure ratio due to these MHD effects is considerable. The progress during the past year has been achieved with essentially no change in generator mass flow from that reported a year ago.

V. Generator Component Development

A considerable part of the effort during the past year has been devoted to the construction and initial operation of a Long Duration Test Facility, in which the hot components of an MHD generator can be subjected to tests of extended duration at appropriate gas conditions. A schematic drawing of the facility is shown in Fig. 8. Air in amounts up to 2. 2 lbs/sec is inducted into a two-stage gasoline engine driven compressor and delivered at pressures up to 150 psia. It is then mixed with oxygen evaporated from the liquid state and preheated to 1500° F in a preheater fired with natural gas. The air-oxygen mixture is then introduced into a combustion chamber where it is burned with a commercial fuel and seed to provide a source of hot combustion products for extended testing of hot generator components. A photograph of the test section of this facility is shown in Fig. 9.

About 45 hrs. of test time has been accumulated to date with the Long Duration Test Facility.

VI. MHD Generator Field Coil Development

As mentioned in the Introduction, in a plant of 500 MW output the MHD generator field coil will consume about 8% of the total output if it is made of water cooled copper. There are two possibilities to reduce or eliminate this power dissipation: first, the sodium cryogenic coil operating at 10° K, and second, the high field strength superconducting magnet.

The principle of the sodium cryogenic coil is illustrated in Fig. 10, where is shown the ratio of the coil dissipation plus refrigeration power for sodium to that of a copper coil at room temperature vs. the temperature. A refrigerator efficiency of 0.25 has been assumed, as well as equivalent geometries and packing factors. It is seen that at a temperature of 10° K the total energy required to maintain the field of a cryogenic coil (dissipation plus refrigerator power) is a factor of 10 less than for a copper coil at room temperature. This improvement is obtained at the expense of investment in a large helium refrigerator.

Work on a sodium cryogenic coil was begun at the Avco-Everett Research Laboratory in late 1960, and had reached the point where fabrication of a model coil was about to begin when it was disclosed that high field strength superconductors were becoming available.[4]

Before this disclosure any consideration of the use of a superconducting field coil for an MHD generator was stymied by the fact that such coils could not operate in field strength exceeding about 10,000 gauss. This is far below the field strength desired for an MHD generator where the peak field may reach perhaps 100,000 gauss eventually. With the discovery of high field strength superconductors, however, this difficulty was removed, and work on the sodium cryogenic coil was halted.

Several materials have been shown to exhibit superconducting properties at high field strengths. Because MHD generator field coils are comparatively large and of a somewhat unusual shape, it is most desirable that the coil material be ductile and easily worked. At this date the most suitable material for such coils appears to be the solid solution alloy, Niobium-Zirconium. The critical characteristics of a typical Niobium-Zirconium alloy as determined in our laboratory are shown in Fig. 11. It is seen that this wire of .010" diameter will carry a current of 20 amperes at field strengths up to 50,000 gauss. The current density here is about one hundred times that which we might expect would be practical in a copper magnet for a large MHD generator. Thus the weight of coil material for a superconducting magnet would be much less than for a comparable copper magnet.

The reduction in weight and elimination of power dissipation in a superconducting magnet must be balanced against the relatively high cost for the superconducting material, in order to obtain an economic evaluation of the superconducting field coil for an MHD generator. Such a comparison is shown in the table below, which has been computed for the case where a 15% return on capital is required.

COST COMPARISON OF MAGNET MATERIALS

COST OF COPPER INSTALLED	\$1.00
CURRENT DENSITY	500 a/cm^2
POWER COST /YEAR	\$0.94
OTHER COST (.15 OF CAPITAL)/YEAR	\$0.15
RUNNING COST/YEAR	\$1.09

IF IN A SUPERCONDUCTING MAGNET THE MATERIALS ACCOUNT FOR HALF OF THE TOTAL COST, THE SUPERCONDUCTORS MUST COST LESS THAN

\$3.64/LB AT 500 a/cm^2
\$36.40/LB AT 5,000 a/cm^2
\$364. /LB AT 50,000 a/cm^2
\$3,640. /LB AT 500,000 a/cm^2

Presently available superconducting materials will operate at appropriate field strength with current densities in the neighborhood of 30,000 amperes per square centimeter, and the very small quantities available are priced at about \$350 per lb. Thus, even with the presently limited availability of these materials they are very close to being economically feasible now, and we would expect the picture to shift decisively in their favor as more sizable amounts of material are made available.

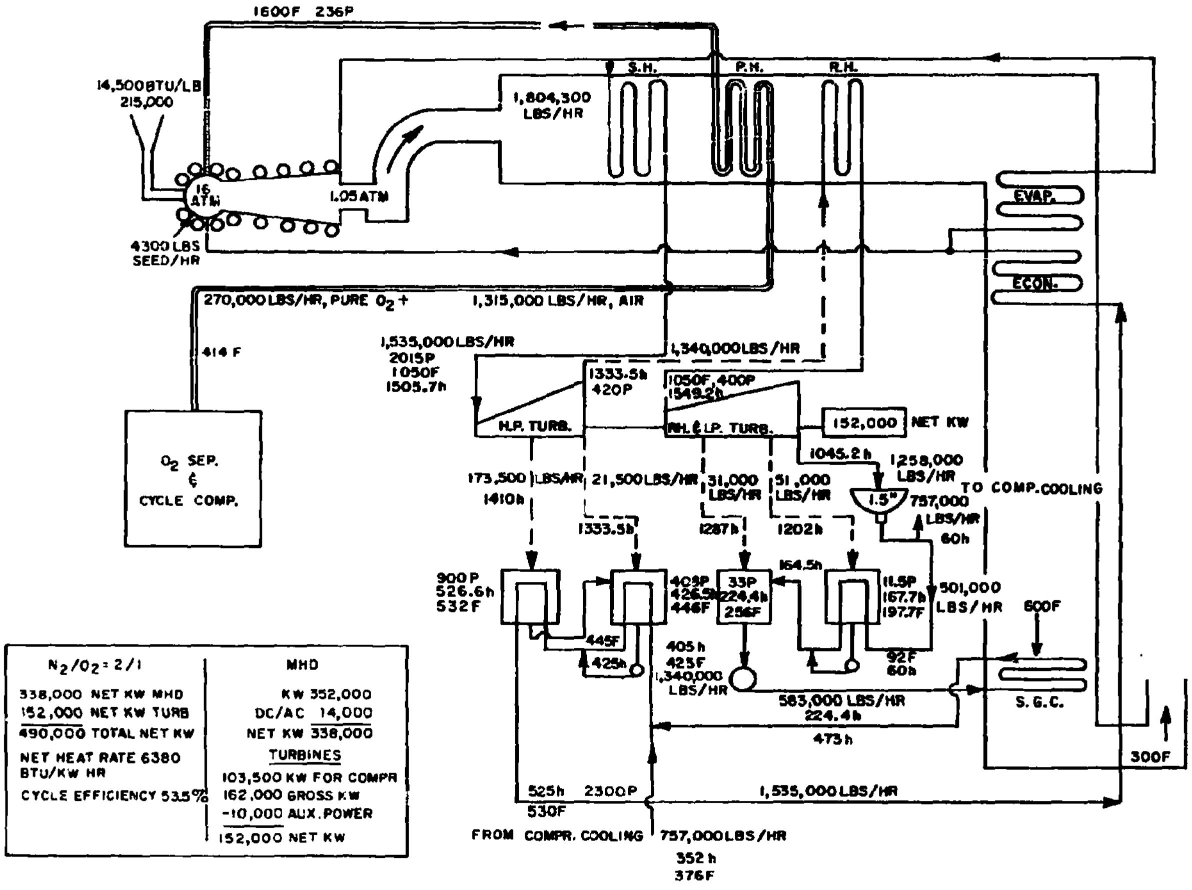

Fig. 1 Typical Oxygen Cycle Heat Balance for N_2/O_2 = 2

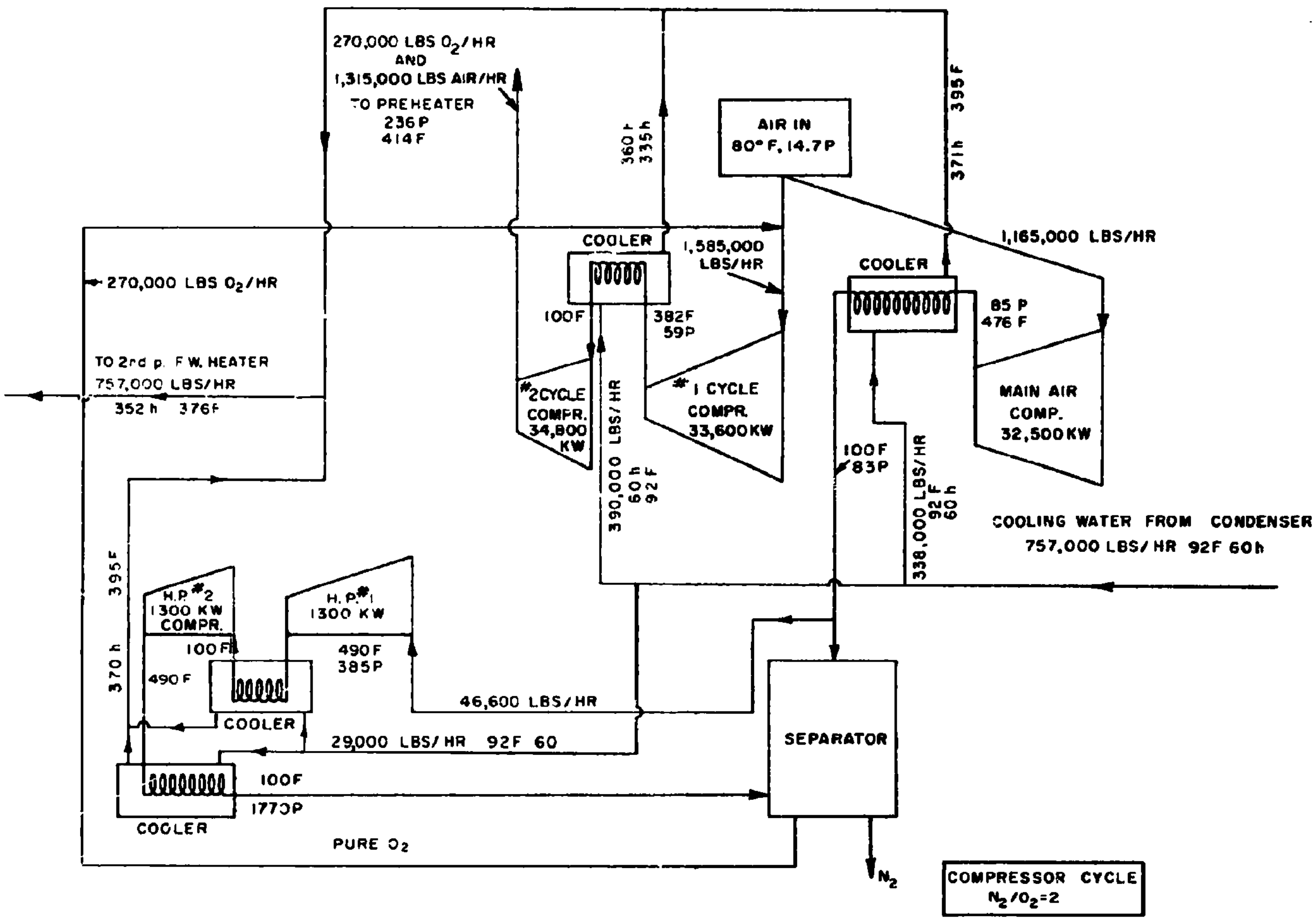

Fig. 2 Compressor System for Cycle Shown in Fig. 1

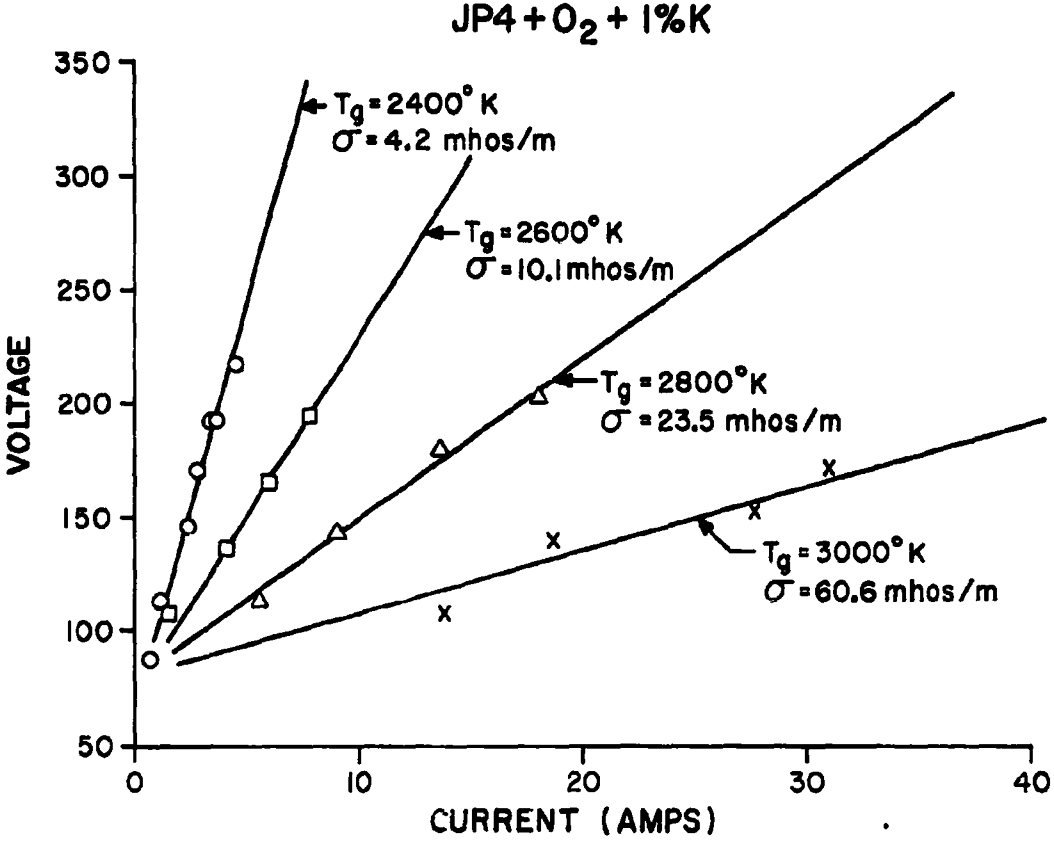

Fig. 3 DC Voltage-Current Characteristics of Seeded $JP4-O_2$ Combustion Products

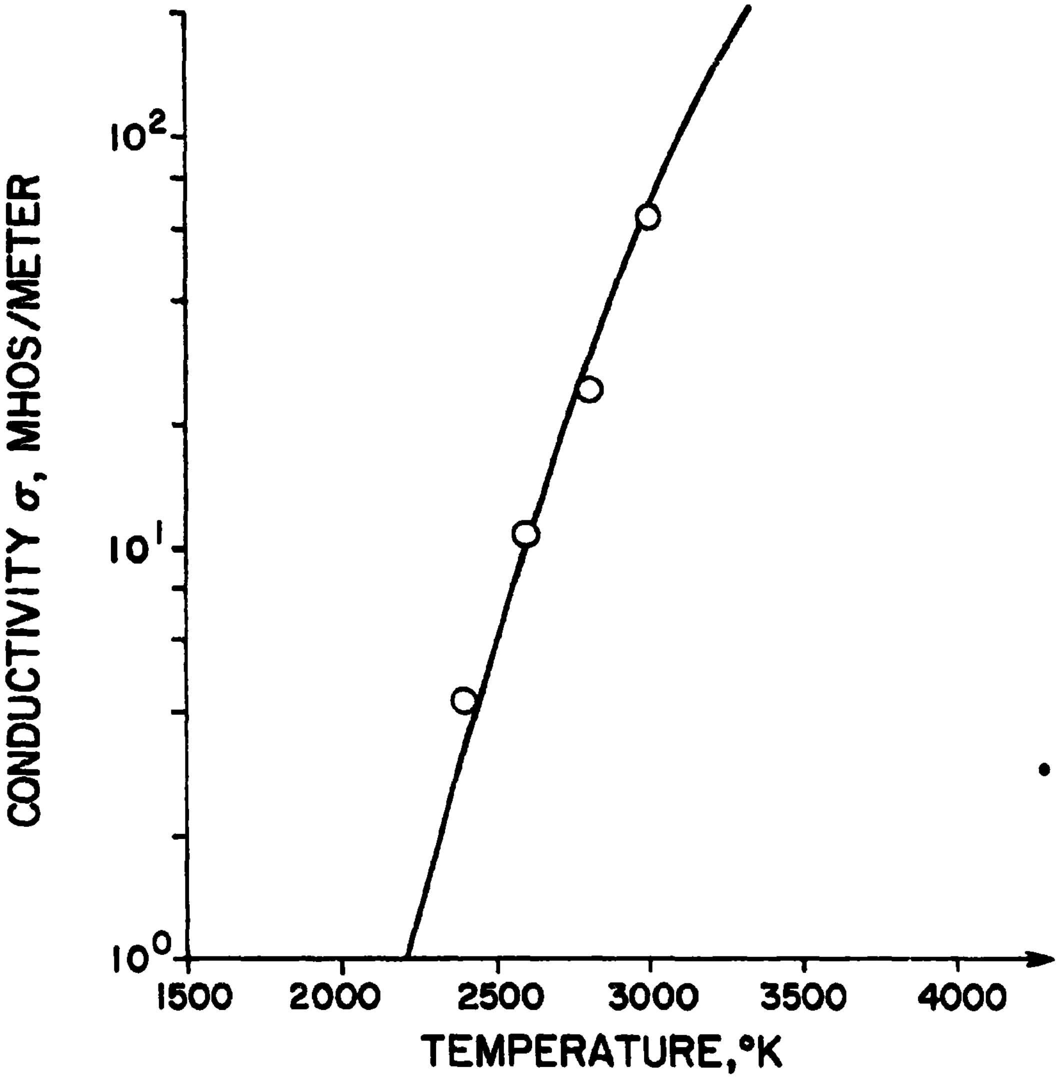

Fig. 4 A Comparison of Measured and Predicted Conductivity vs. Temperature for Seeded Combustion Products of JP4 and O_2

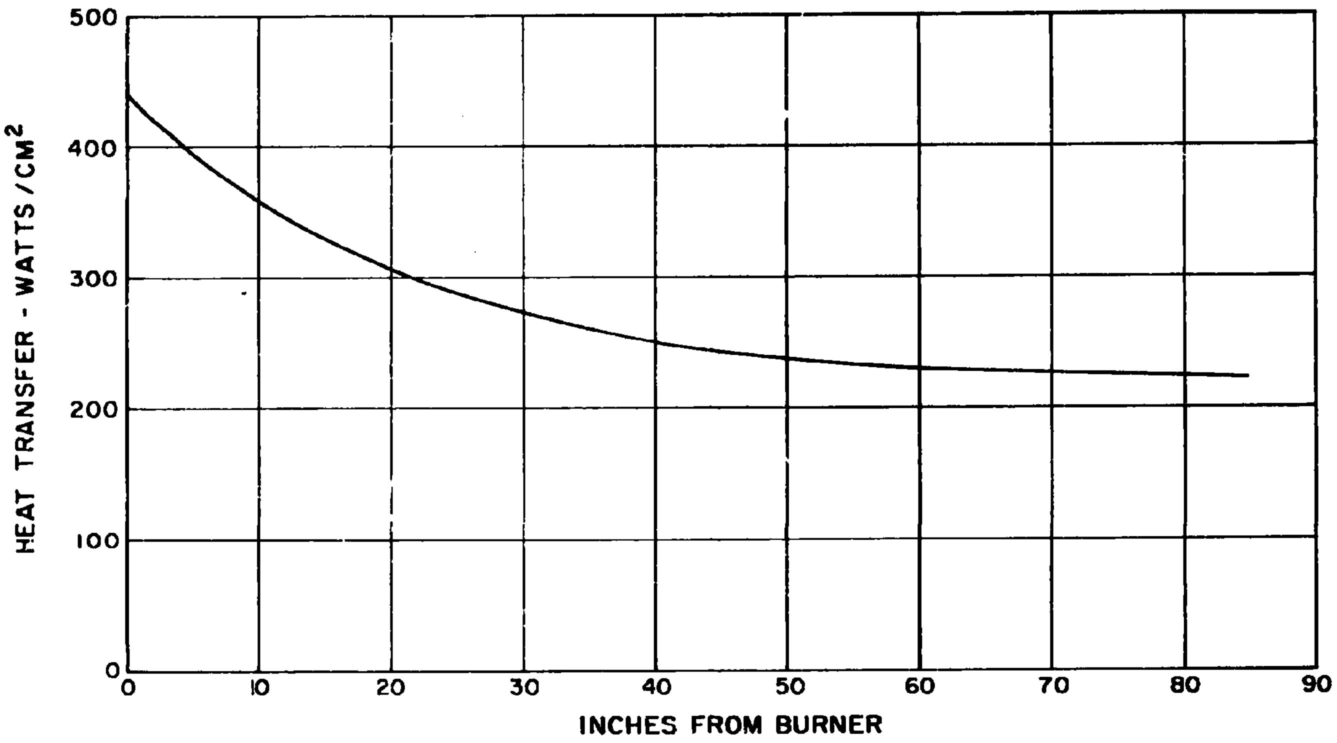

Fig. 5 Heat Transfer Rate vs. Distance along Channel, Mark II

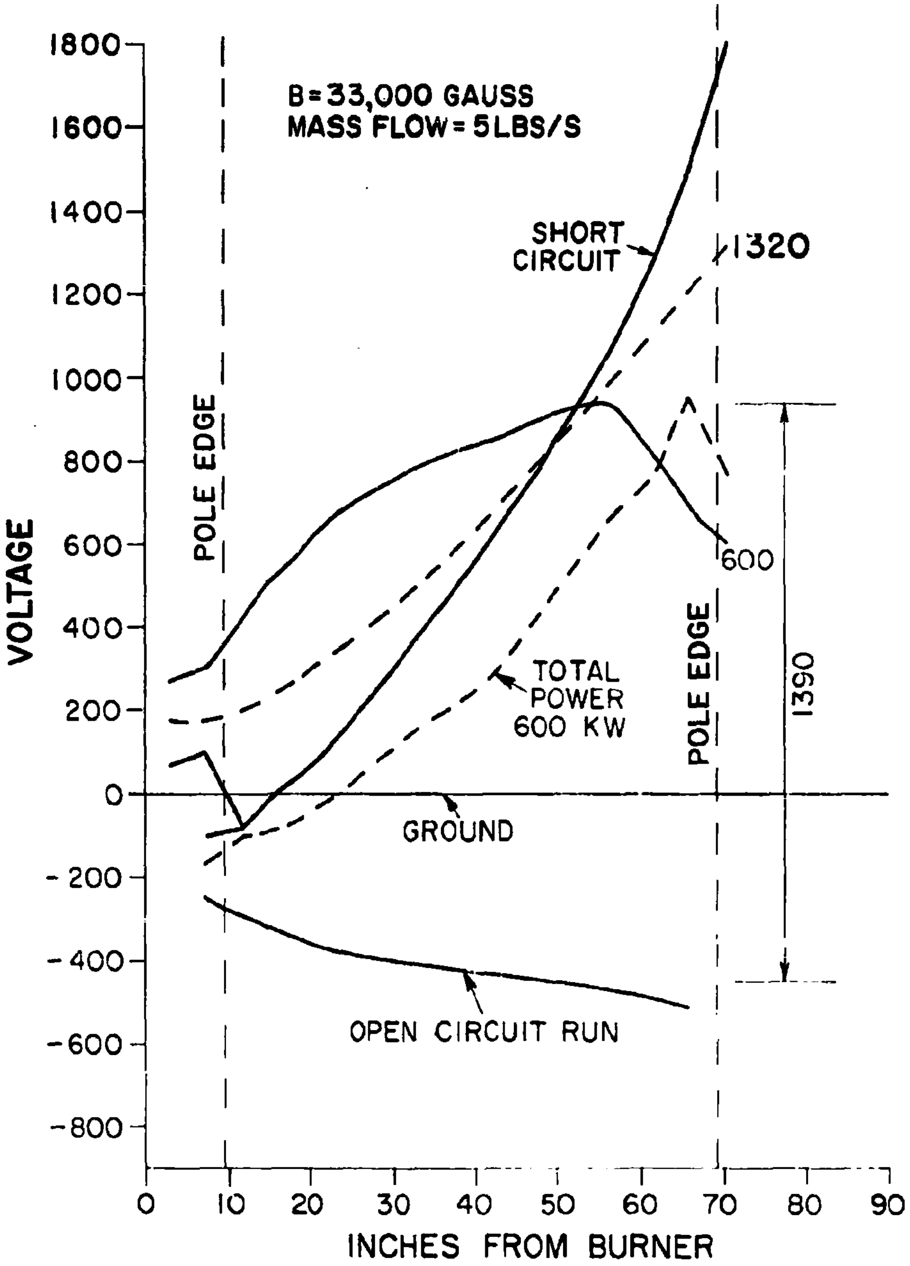

Fig. 6 Typical Voltage Distributions for Mark II Generator

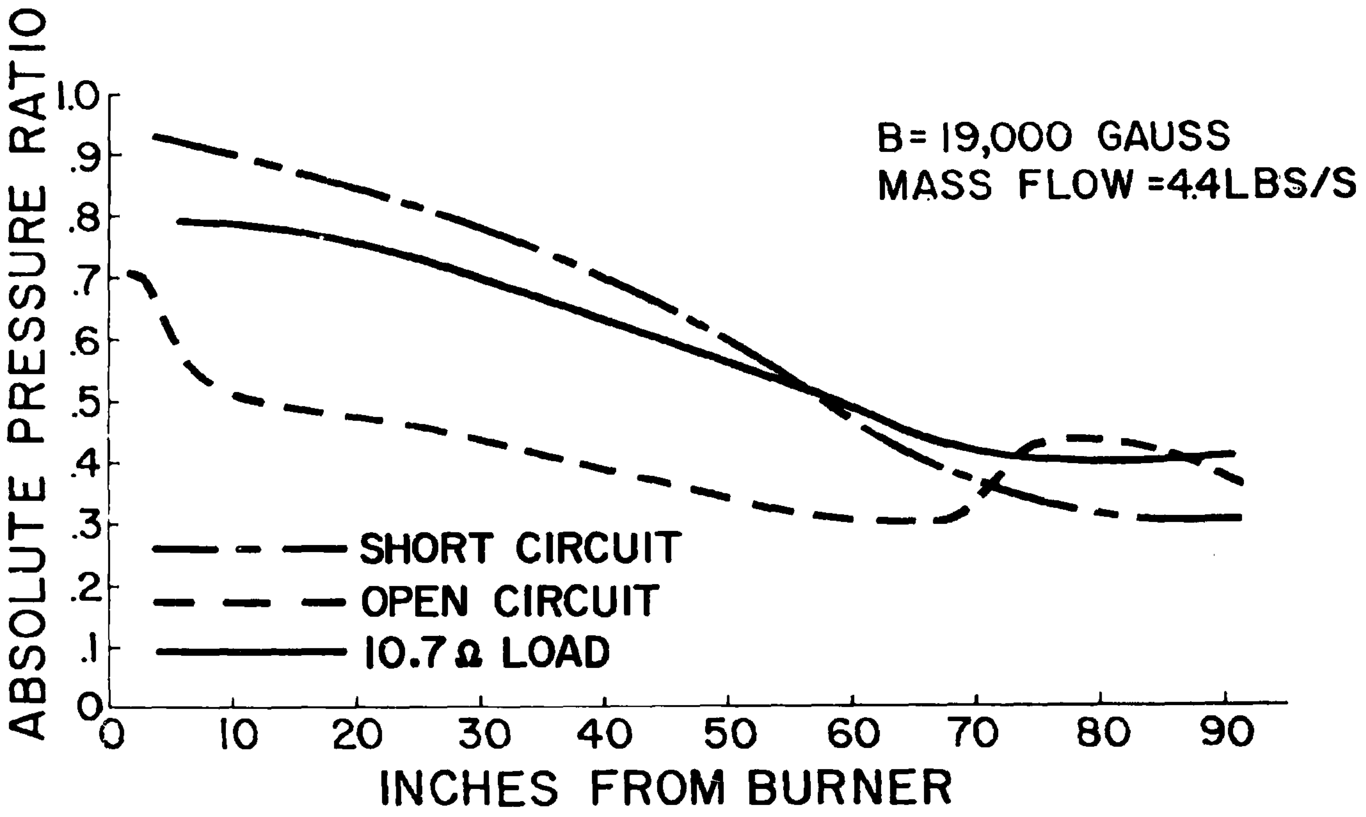

Fig. 7 Pressure Distribution for Mark II Generator

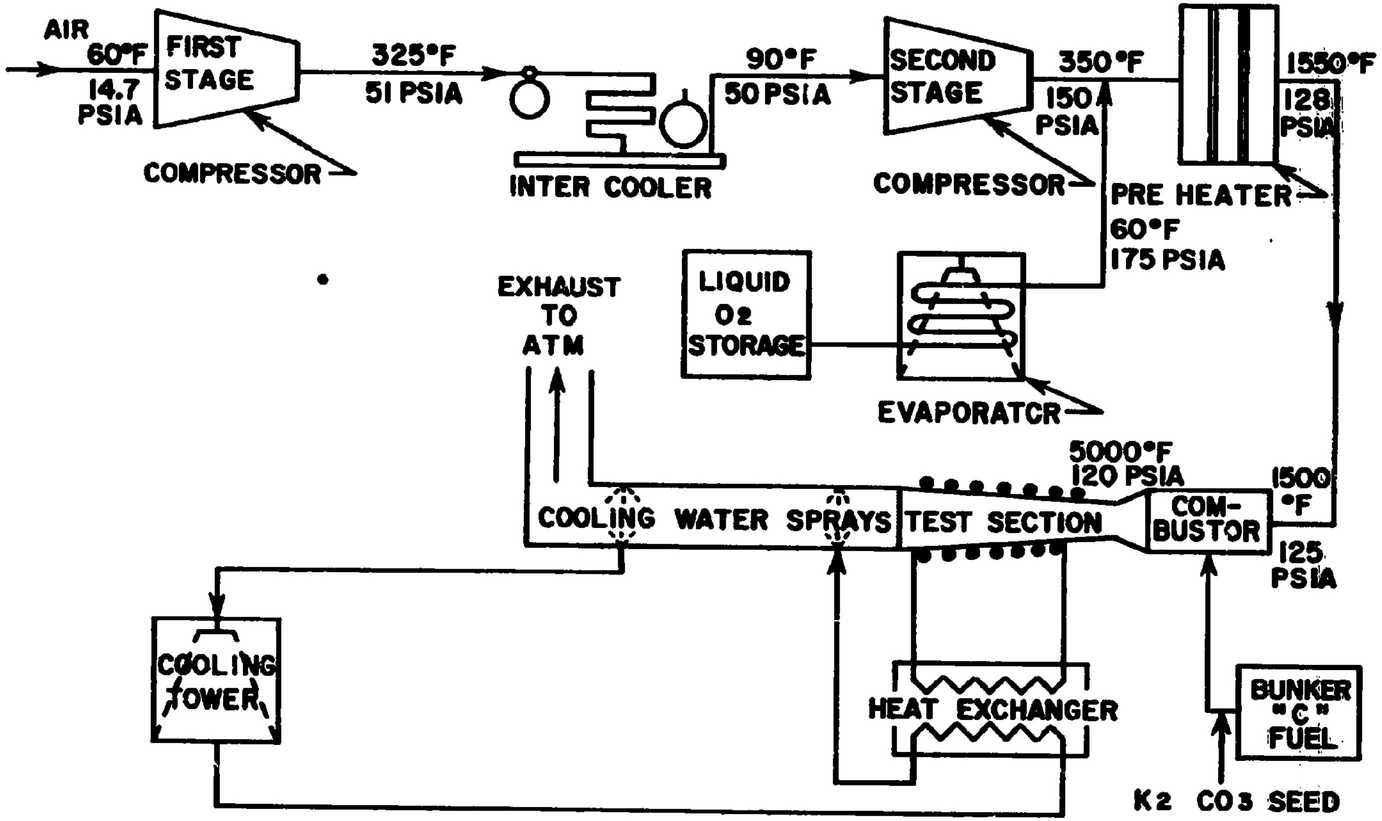

Fig. 8 Long Duration Test Facility Schematic

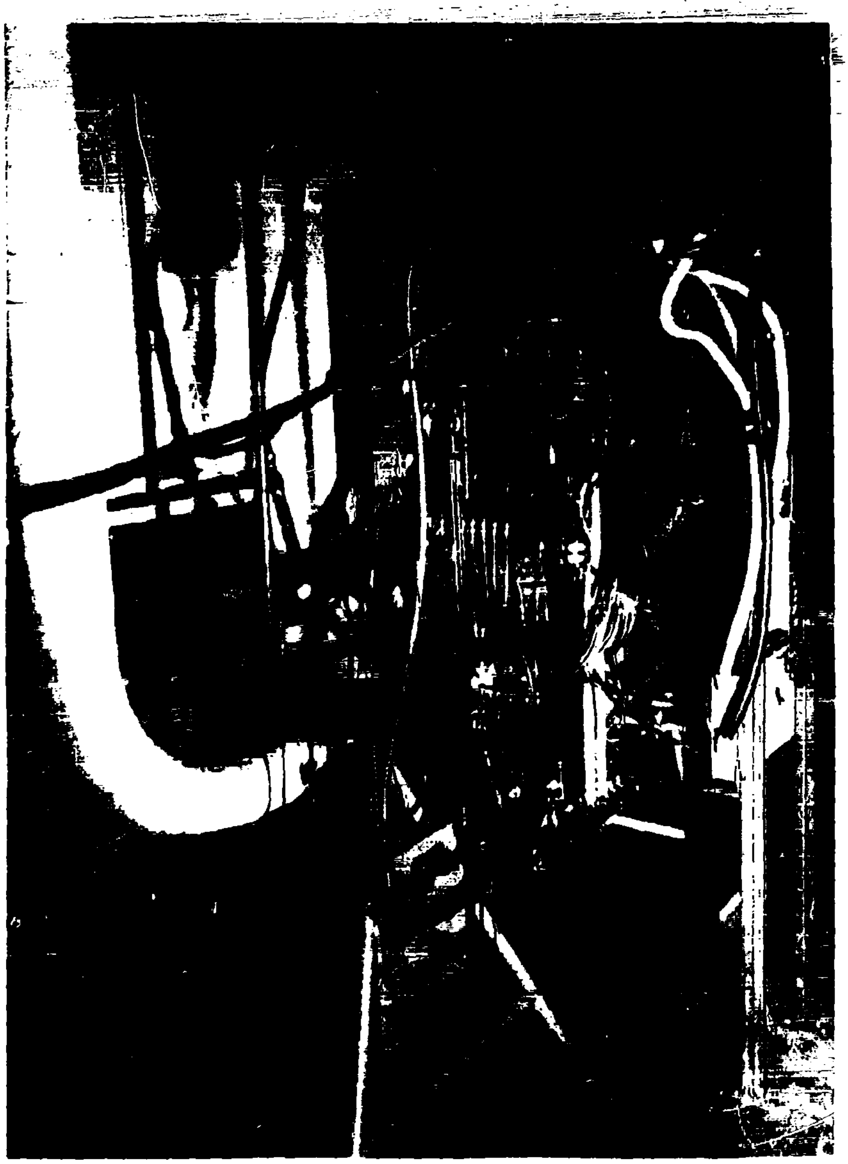

Fig. 9   Test Section of Long Duration Test Facility

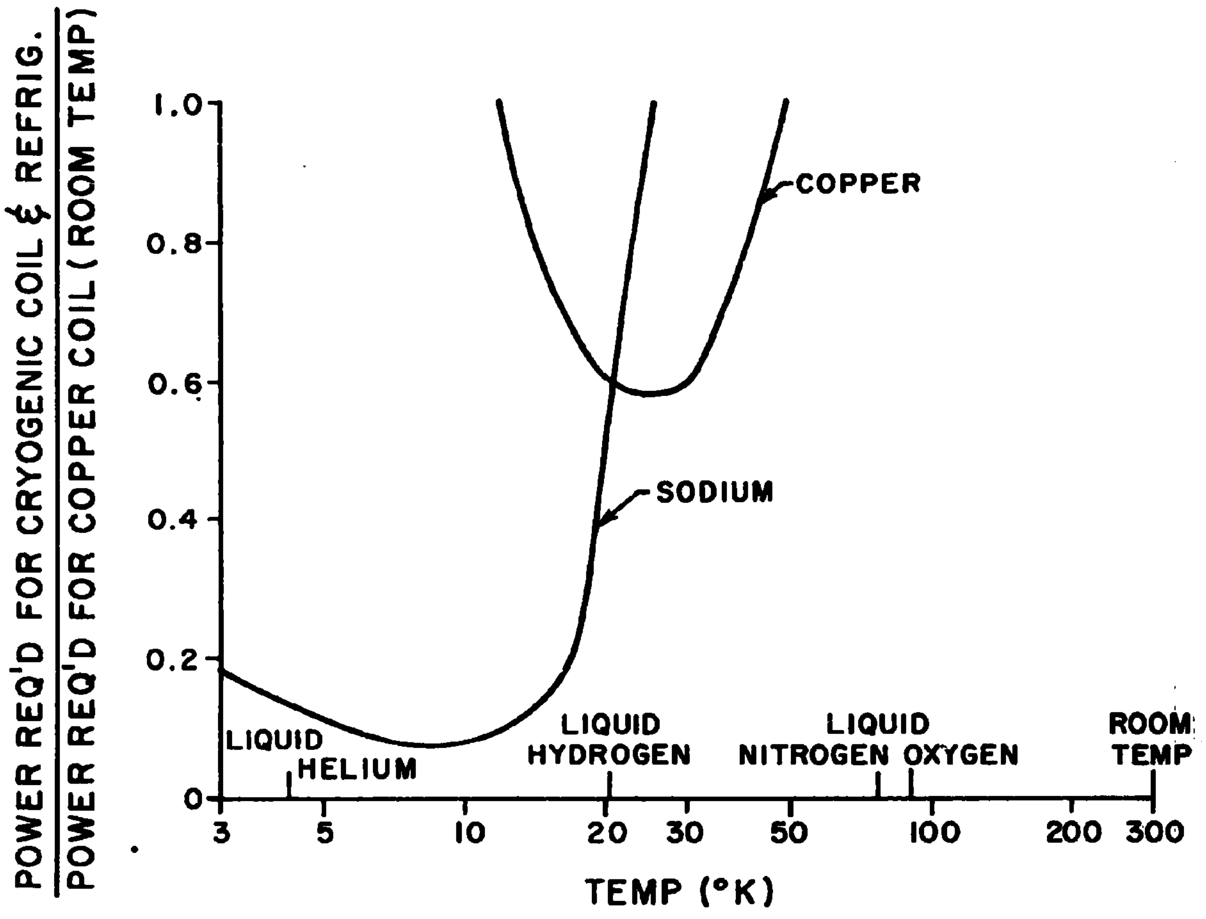

Fig. 10 Performance of a Sodium Cryogenic Coil

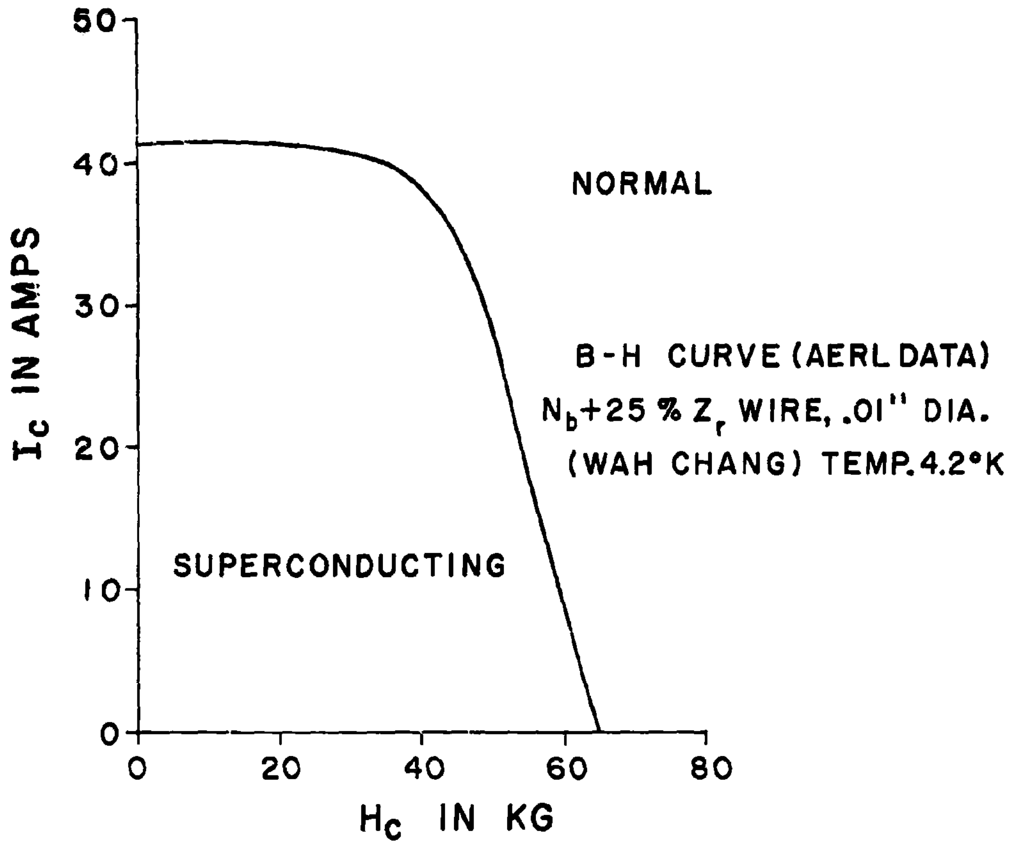

Fig. 11 Critical Current-Critical Field Characteristics of Nb-Zr

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A REVIEW OF RECENT MHD GENERATOR WORK AT THE AVCO-EVERETT RESEARCH LABORATORY, by T. R. Brogan, J. F. Louis, R. J. Rosa and Z. J. J. Stekly. March 1962. 20 p. incl. illus. (Avco-Everett AMP 74; AFOSR 2352)
(Contract AF 49(638)1129
co-sponsored by Avco-Corporation and 11 utility companies)
Unclassified report

This paper presents a general review of work in the field of MHD power generation during the past year at the Avco-Everett Research Laboratory. The review includes the areas of conceptual plant design, electrical properties of gases, generator fluid mechanics and performance, field coil designs, and long duration testing. In the area of gas properties, the experimentally determined conductivity of seeded combustion products is in good agreement with predicted values in the temperature range between 2300°K to 3000°K. The study of generator fluid mechanics has continued during the past year using the Mark II combustion generator whose construction and initial operation was described at this meeting a year ago. Successful operation at Hall coefficients up to two has been achieved. Actual performance of the Mark II generator

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2. Generators, Magnetohydrodynamic.
3. Mark II MHD Generator.
4. Fluid mechanics.

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