Engineering Aspects of MAGNETOHYDRODYNAMICS

A conference report by **George W. Sutton**

THE progress, or lack of progress in some cases, which is being made toward the practical utilization of magnetohydrodynamics was the subject of an all-inclusive meeting with the rather lengthy title of "Symposium on the Engineering Aspects of Magnetohydrodynamics". The gathering, which was sponsored by the Basic Sciences Committee of the American Institute of Electrical Engineers, had the advantage of using the auditorium of the University Museum of the University of Pennsylvania. This auditorium was large, the seats were comfortable, free parking was available, and the acoustics and visibility were far superior to that of many recent meetings this writer has attended. The arrangements committee, under R. M. Showers, is to be congratulated. We hope this auditorium is used more often in the future.

As originally planned by C. Mannal, the general chairman, this was to be a symposium with ample time for discussion of each paper, and it was hoped that a good representation would be obtained of papers from research workers in the field of applied magnetohydrodynamics. Unfortunately, the response for papers was far greater than had been anticipated, and although most of the papers were excellent, only fourteen minutes was allotted to each paper, and very little time was allowed for discussion. The tremendous size of the audience, which turned out to be about 400, including those rugged individualists who did not respond to the seven-dollar registration fee, did not contribute to an informal atmosphere.

The resulting lack of discussion detracted somewhat, but considering the general high quality of the papers, Mr. Mannal deserves considerable praise. This writer was also impressed by the large number of familiar faces in the fields of fluid dynamics and plasma physics. One hopes that there were many more electrical engineers present for whom the symposium was primarily intended.

The highlight of this meeting was the excellent cocktail party given at the new Sheraton Hotel. A cold windy rain through which the attendees had to travel made the refreshments even more appetizing and the discussions more interesting; so interesting in fact, that some of us never got to the refreshment tables. Following the cocktail party, a tour was arranged of General Electric Company's Space Sciences Laboratory, where various plasma-producing devices were examined.

The technical program consisted of four sessions, on communications and diagnostics, power conversion, fusion, and flight applications. Each session began with an invited paper which attempted to summarize pertinent work in each area.

WE were privileged to hear not one but two invited papers on diagnostics at the first session, which was timed to the second by W. G. Dow (University of Michigan). The first paper, by M. Heald (Swarthmore), was an excellent summary of the use of microwave probes, together with the usual attenuation, Doppler, and phase-shift measurements. The difficulty of obtaining millimeter waves for large electron concentrations was reiterated, but the geometry and nonuniformities in the plasma were largely passed over, presumably because other problems are more important. These microwave techniques were elaborated upon later by H. L. Bunn (Livermore).

G. Bekefi (MIT), on the other hand, dismissed the microwave probe method as unnecessary, since bremsstrahlung and synchrotron radiation may be used directly. For this purpose, ingenious amplifying circuits

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Left, R. M. Showers of the University of Pennsylvania and, right, the general chairman of the symposium, C. Mannal of General Electric, discuss last-minute details before the meeting.

Left to right, H. Kurweg (NOL), A. Kantrowitz (AVCO) who gave an invited paper at the MHD power conversion session, and L. Steg (GE) who chaired that session.

have been devised, and analyses of the line shape yield information on the electron collision frequency. It was pointed out that, under certain circumstances, the line broadening of the harmonics can cause the emission to be continuous, and it was suggested that this could be a major cause of energy loss from fusion experiments.

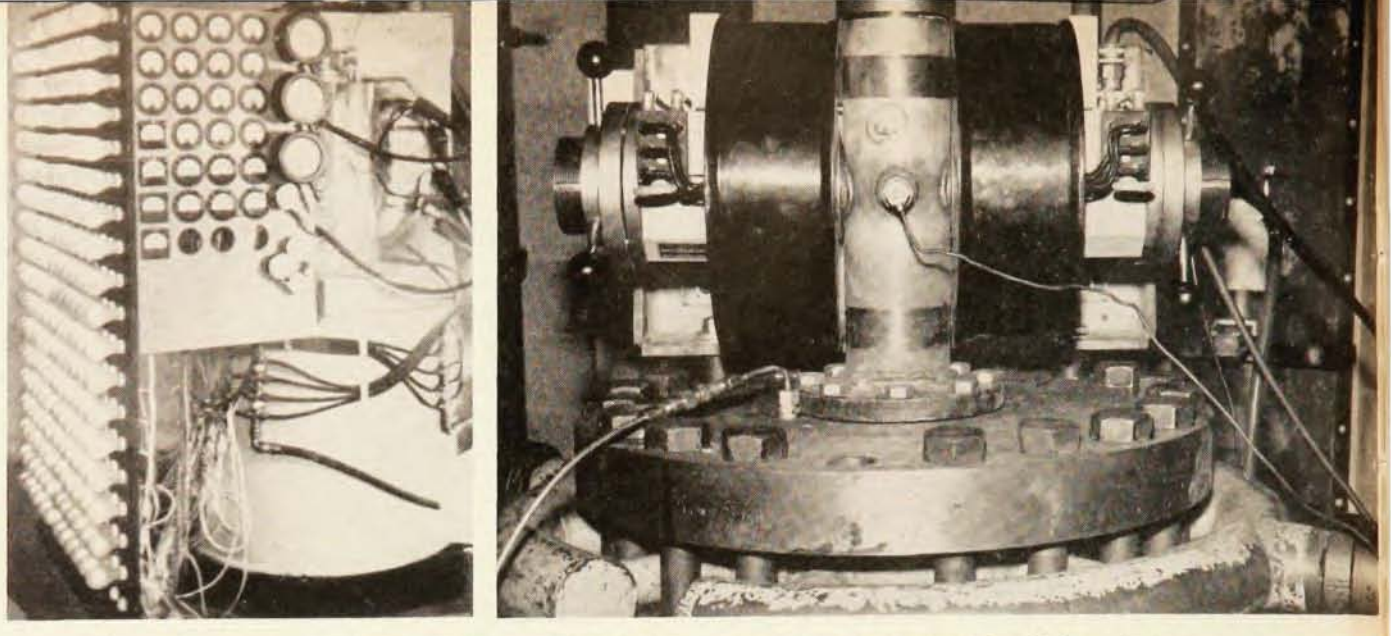
W. Hill spoke briefly on possible improvements in sodium *D*-line temperature measurements of moderately hot gases, and in two-color radiometric methods.

Two theoretical papers were presented on propagation of electromagnetic waves through plasmas. M. Sodha (Armour Research Foundation) considered the heating of the plasma and the resulting change in its properties, while M. Lessen (University of Pennsylvania) considered small-amplitude waves, but used the multifluid dynamical equations, with the assumption that the random motions of the heavy particles were negligible.

THE power conversion session, chaired by Leo Steg (General Electric Space Vehicle Department), contained papers by most of the research workers who are interested in generating electricity by means of magnetohydrodynamics from high-velocity ionized gases at energies less than one ev. There were several rather lively discussions, possibly because this was the first time that this group had been assembled—and, for most, the first time they had been heard in public. For this careful selection of papers, Hsuan Yeh deserves full credit.

In the invited paper of this session, A. Kantrowitz (AVCO Research Laboratories) reviewed once again the experimental verifications of the kinetic theory of low-temperature ionized gases, which he has directed since 1950. Briefly, his group has measured the conductivity and Hall effects in various shock-tube experiments, and has determined some new cross sections for atomic oxygen. They have also verified that conventional gas dynamics may be used to predict the flow of ionized gases in magnetic fields. For two possible flight applications, that of increasing the drag of hypersonic vehicles, and obtaining lift from the Hall effect, Dr. Kantrowitz expressed some doubt as to the eventual reduction to practice. He also reported on some new measurements of ionization times behind shocks which were performed at low density in a two-foot-diameter shock tube by S. C. Lin. The large diameter was considered necessary to reduce wall effects.

There followed five papers devoted to theoretical analyses of steady, dc magnetohydrodynamic generators, in which the quasi-one-dimensional gas dynamic equations, modified to include current flow and magnetic field, were integrated for constant area, constant pressure, constant velocity, constant density, and constant temperature flows. There were as many sets of assumptions as there were authors. For example, J. Huth (Rand Corporation) assumed that the current in the gas was due to the variation of magnetic field in the downstream direction; this was argued at some length from the floor by Dr. McCune (Aeronautical Research Associates of Princeton) who believed that it was due to the transverse variation. A. Sherman (GE Flight Propulsion Laboratory) assumed the isentropic relation between pressure and density. G. Sutton (GE Missile and Space Vehicle Department) pointed out that for a constant gas velocity flow, the effect of ohmic heating was to change the effective ratio of specific heats, and therefore this assumption was completely unnecessary. S. Way (Westinghouse) attempted to take into account the cathode and anode voltage drops in his analysis. G. Sutton (GE) assumed that the ratio of current to electric field remained con-



Two experiments proved the feasibility of MHD power conversion. Device on left which used argon and delivered 11.4 kw was discussed by R. Rosa of AVCO Everett Research Laboratory. Device on right which used air and delivered 0.9 kw was discussed by A. Were of GE. Both experiments used an electric arc to heat the working fluid and an easily ionizable element was added to the flow.

stant, and came to the conclusion that the constant gas velocity generator appeared to be superior. Mr. Coe (Republic Aviation) analyzed the constant cross-section generator in much detail, and concluded that the maximum conversion to electrical power was about twenty percent. Sutton then pointed out that this proves that constant area flows should not be considered. In any event, all of the analyses presented were based on constant electrical conductivity. Since an efficient MHD generator must change the gas state by a considerable amount, in the future we may expect more calculations in which the change in electrical conductivity is taken into account.

Two experimental papers were presented on magnetohydrodynamic power generation, by R. Rosa (AVCO Research Laboratory) and A. Were (GE Missile and Space Vehicle Department). Both experiments used arc-heated gases to which potassium carbonate was added, and the gas flowed through a channel with crossed magnetic and electric fields. In the AVCO experiments, the argon was heated to 3000°K, the magnetic field was about 45 cm long, and the electrodes were segmented. About 12 kw of power was extracted from the flow, and the Hall effects were measured. In the GE experiment, air and carbon were heated to 4800°K, and the magnetic field was 5 cm long. Using a field of 8600 gauss, one kw was extracted. Although both of these experiments indicate that MHD power generation is feasible in principle, direct conversion from chemical energy to power has not yet been accomplished.

An analysis of the electric wind machine for generating high voltages was presented by M. Gourdine (California Institute of Technology). This device is similar in principle to a Van de Graaff generator, except that the charges are carried by a stream of cold gas instead of on a moving belt. Thus, the current can be much greater, but the maximum voltage is limited by the mobility of the positive ions in the gas stream. In spite of the lack of analysis of the losses in this device such as heating the ionizing grid, this device may prove useful, especially if it is staged. Gourdine announced that he is constructing an experimental model, but did not mention similar work being done in England by W. E. Bennett (Atomic Weapons Research Establishment).

Electrical conductivities in acetylene-oxygen detonations seeded with potassium acetylide particles of 10-μ size were measured by J. Fay (MIT). Ionization was found to be almost immediate, and the conductivity agreed reasonably well with equilibrium theory. A. Fuhs described some tungsten arc experiments in which current densities of 7800 amp/cm^2 were measured.

The session concluded with a speculative paper by J. Grebe (Dow) who suggested that if coal is to be used as primary fuel for an MHD generator, then it is more economical to coke the coal first. From the coal gases, valuable chemicals could be extracted, while the waste gases could be burned. The ash in the coke would provide the required electrons in the MHD generator, which would then be extracted as potash and sold. Instead of burning the coke with compressed preheated air, Dr. Grebe suggested that liquid oxygen be used, eliminating expensive compressors and heat exchangers. No economic or technical data were presented, presumably because Dr. Grebe has not calculated them. We hope that the economic analysis of such a plant will be available in the near future to aid as a guideline for MHD power development.

IN the fusion session, chaired by N. W. Mather (Princeton), the invited paper by J. A. Phillips (Los Alamos) summarized the status of Project Sherwood, pointing out the low cost and abundant supply of fuel for controlled nuclear fusion. The presence of impurities which radiate is still somewhat of a problem,

but may be solved by new vacuum systems of 10^{-10} mm Hg capacity. Both the mirror and C-Stellerator machines were described, but the ideal heating method of either injecting preheated particles or heating cold particles has not been determined.

Additional details of the C-Stellerator were supplied by C. W. Little (C-Stellerator Associates) who emphasized the modular construction of the facility and associated flexibility, including the 0.1μ sec sequence timer. After the gas has been heated with rf, the gas will be heated further by ohmic heating, and finally ionic heating will be used to raise the temperature to the design point of 10^5 ev and 10^{-3} mm Hg pressure.

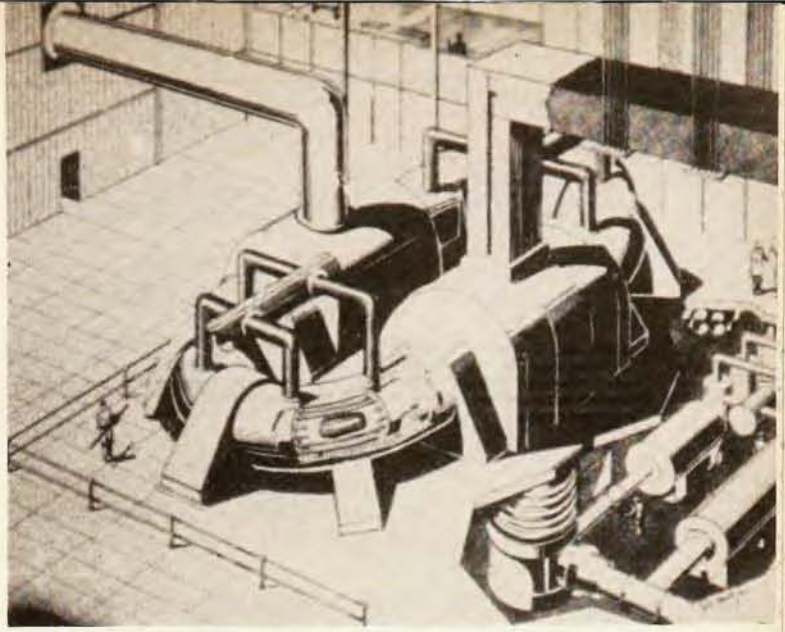
Two other methods of obtaining fusion power were described by John Grebe (Dow) and J. Slepian. The former involves underground explosion in limestone to create quicklime and steam. The quicklime would then release heat when combined with water, and the process could be repeated. The latter paper suggested the use of an older concept, the ionic centrifuge. This idea appears to be similar to the gaseous fission reactor. R. G. Mills (Princeton) devoted some time to performance calculations of fusion power plants, and determined methods of increasing the yield.

The last four papers dealt with specific component problems: W. F. Westendorp (GE Research Laboratory) described work on magnetic fields with fast rise times; E. L. Kemp (Los Alamos) described some spark gap switches; and A. E. Schofield (Los Alamos) designed some low-inductance and resistance capacitors. Finally, W. M. Wells, Jr. (Livermore) described some experimental measurements of the eddy-current pressure losses as liquid mercury passes into and out of a magnetic field.

AT the session on flight applications, chaired by E. Resler (Cornell), the invited paper was given by A. T. Forrester (Electro-Optical Systems) on the ion rocket motor. Most of the talk was concerned with the shaping of the porous tungsten emitter, and the electric fields. No experimental results were reported. S. Demetriades (Northrop) then made a plea for the so-called air-scooping vehicle, which is first propelled to satellite velocity at low altitude. It carries fuel, but collects oxygen to burn with the fuel to overcome drag, and stores part of the oxygen for later use in propelling the vehicle out of orbit. Although he claimed a drastic reduction in take-off weight for an interplanetary journey, little detail was given on the mechanism of collecting the oxygen or the requirements for dissipating its energy, except that it would require a refrigeration system at temperatures below the boiling point of oxygen.

Dr. Mostov (Republic) presented an analysis of a rail-type plasma accelerator, which caused an interesting and lively discussion of some of the assumptions concerning the nature of the plasma.

Some interesting experiments were reported by D. E. Cunningham (Thompson-Ramo-Wooldridge) in which a steady, cold plasma flow was accelerated by crossed electric and magnetic fields. With the electric field in the correct orientation it appears as if the flow was actually accelerated, but when reversed anomalous results were obtained. The cold plasma temperature was measured by thermocouples. The thermocouple details were not revealed, but little regard was given to the interactions between dissimilar metals, each at a different potential, with the plasma. Fortunately, these problems are recognized by the authors.



Artist's concept of the C-Stellerator, described in the fusion session by J. A. Phillips of Los Alamos and C. W. Little of C-Stellerator Associates. Device was constructed for flexible operation.
(*Courtesy Princeton Univ., Project Matterhorn*)

The heat transfer to the electrodes in such a device was analyzed theoretically by J. Kerrebrock (Caltech Jet Propulsion Laboratory) who found that a reduction of the electron density near the electrodes would radically increase the local joule heating of the gas, and hence the electrode. To my knowledge this is the first time this problem has been considered, and Dr. Kerrebrock's careful work resulted in one of the best of the theoretical papers given in this area.

W. Bush (Space Technology Laboratories) presented some design data for MHD heat protection for hypersonic re-entry vehicles. No advantage was demonstrated over the competing ablative method. F. D. Hains (Boeing Scientific Research Laboratories) described some effects of magnetic fields on redistributing the flow in a channel.

The remaining papers at this session were mainly devoted to theoretical analyses of the external aerodynamics of conducting gases in magnetic fields. Most of these papers were extensions of older papers which had not considered magnetogasdynamic effects. All of the authors found that the magnetic field affected the flow in some manner, but the ultimate utility of these effects was not clear.

The final impression one obtains from this meeting is that much work is in progress on magnetohydrodynamics and although many exciting results have been obtained, the engineering applications are still far away. One also senses a gap between the fundamental theoretical research in this area and experimental research, but perhaps this is to be expected.