

MAGNETOHYDRODYNAMICS

a symposium report



Above: delegates to the magnetohydrodynamics symposium held at the Lockheed Missile Systems Division laboratory in California.

Photos appearing on this month's cover (reading from the top down) show symposium speakers S. Colgate, E. Teller (the chairman of the meeting), M. Rosenbluth, E. N. Parker, and S. Chandrasekhar. The authors of this report are both physicists from the Stanford area. D. Bershader is at Stanford University and R. Landshoff is at the Lockheed Missile Systems Division.

By D. Bershader and R. Landshoff

THE week of December 16, 1957, was a busy one for physicists in the Stanford area, with no less than three major meetings taking place: a symposium on magnetohydrodynamics, a conference on nuclear sizes, and, finally, the regular west coast winter meeting of the American Physical Society. Of these, the first-mentioned was sponsored by the Lockheed Missile Systems Division and took place at its Palo Alto research laboratory adjacent to the Stanford campus. About 200 delegates, many of whom attended an initial symposium held there on the same subject in December 1956, participated in the more recent meeting. Considering the growing popularity of the field and the challenging nature of the material, an annual meeting dedicated to magnetohydrodynamics may be a worthwhile venture for several years to come.

Magnetohydrodynamics, as the name implies, deals with the dynamics of a fluid which interacts with a magnetic field. This requires the fluid to be a good electrical conductor. While some early work is concerned with liquid metals, the problems one now generally considers in this connection arise when the magnetic interaction involves ionized gases or plasmas. This implies relatively high temperatures, say from a few electron volts upwards. One can, in a somewhat artificial fashion, divide the subject matter into major subgroups consisting of astrophysical problems, thermonuclear phenomena (with emphasis on earthbound fea-

tures), high-temperature gas dynamics, and kinetic theory of the plasma, respectively. It will be evident from the discussion of the program which follows that all phases were included among the papers presented, with emphasis on basic physical problems rather than particular applications. Edward Teller, the conference chairman, stressed this point by admonishing the assemblage: "Please do not behave like alchemists; do not look for gold. There is plenty of amusement in the study of magnetohydrodynamics and it may turn out—as it often has—that the amusement will, in the end, lead to much more important things than we now believe to be the real purpose." These remarks were, in fact, directed to those whose attention may be too rigidly focused on the single question of applying magnetohydrodynamics to the production of controlled thermonuclear energy, though we can hardly deny the powerful motivation provided by this goal.

In the discussion which follows we begin with two papers which are directly related to the "Sherwood" effort. It has been known for some time that it is possible to produce neutrons by pinch discharges in deuterium. The first public report of such observations was made by I. V. Kurchatov at Harwell and this was followed by similar reports from American, British, and Swedish sources. Does this constitute a "breakthrough" in the field of thermonuclear energy? If the very careful observations made at the University of California

Radiation Laboratory which were discussed by S. Colgate can be considered as typical, the answer is no—at least up to the time of the meeting. These neutrons show an anisotropy from which one must conclude that they are not of thermonuclear origin. Colgate interpreted the D-D reactions which produce the observed neutrons as being due to an acceleration of a small number of ions. The voltage developed across the neck of a sausage-type instability could account for details of the observed neutron flux.

In order to obtain truly thermonuclear reactions, it appears necessary to eliminate or at least delay the disorganizing effect of plasma instabilities. H. J. Karr reported studies by the Los Alamos Sherwood team to gain a better understanding of instabilities and of the effect of corrective measures such as conducting walls and axial magnetic fields. In addition to visual observations and measurements of the current and voltage waveform of the discharges he described the current distribution in both space and time within the pinch, which is obtained by means of miniature shielded probe coils inserted clear into the discharge.

An entirely different plasma instability occurring in the interplanetary magnetic field was proposed by E. N. Parker. The charged particles of a plasma in a magnetic field tend to move in a manner so as to destroy the isotropy of the pressure tensor. Collisions between particles on the other hand tend to restore this isotropy. In the interplanetary gas this competition favors anisotropy as one moves beyond the orbit of the earth. This in turn leads to an instability which is enclosing part of the solar system in a shell of irregular magnetic fields. Such a shell had been inferred before, from observations of the slow decay of cosmic-ray activity following solar flares.

Two of the speakers discussed mathematical methods for treating the motion of a tenuous plasma. M. Rosenbluth derived an integral equation for the fields and from this obtained corrections to the ordinary magnetohydrodynamic equations which arise for fields where the charged particle orbits have turning points. He also applied the integral equation to show the origin of Landau damping of plasma oscillations.

S. Chandrasekhar presented a method to construct higher order adiabatic invariants which can still be used when the condition for validity of the well-known $W_{\perp}/B$ invariant breaks down and showed that this construction can in principle be used a great number of times to obtain a whole succession of invariants. In the case of periodic motion along a line of force one can consider a further invariant which is quite analogous to the action integral of the simple harmonic oscillator. Chandrasekhar discussed the limits of validity and applicability of these invariants.

Of particular interest to the fluid dynamicists was H. W. Liepmann's paper dealing with the interaction between familiar types of shear flow fields with external magnetic fields. The shear motion causes viscous heating which is presumed sufficient to produce ionization. Motion of the resulting plasma then interacts with

the magnetic field. The equations of motion can be solved with a minimum of simplifying assumptions for the case of pure shear flow, of which the most stringent is probably that of local thermal equilibrium. It turns out that the recovery temperature at an insulated wall is not affected by hydromagnetic effects whereas the ratio of drag to heat transfer increases with increasing field. Profile of physical variables such as velocity and temperature are field-dependent. Since the gas conductivity depends on temperature, the former is therefore field-dependent.

Liepmann also discussed the more difficult problem of Stokes flow of a sphere through a viscous, conducting, incompressible fluid in the presence of a magnetic field parallel to the motion. Here the expression for the drag contains a term linear in the field which means that the solution for small values of the field cannot be obtained from a perturbation procedure starting from the known solution for the flow with field zero. This can be verified by illuminating physical arguments. The change in drag to be expected by a small sphere in mercury should be easily detectable, and experiments of this sort are now under way.

The shock tube, now a well-known tool in gas dynamics research, has proven to be a convenient type of experimental arrangement for adaptation to magnetohydrodynamic studies. In the form employed by Fowler, Kolb, and others, a so-called T-tube is used. This is effectively a hybrid discharge and shock tube. A discharge between two electrodes increases the pressure of the gas, forming a strong shock wave together with an appreciable number of ions and electrons. In one type of experiment, interaction of the plasma with an externally produced magnetic field in the electrode area produces an effective increase in pressure, resulting in faster propulsion of the shock down the long arm of the T-tube. Wave front speeds corresponding to Mach numbers up to 200 have now been observed by several workers. Recent T-tube studies reported by S. Kash concerned observations of multiple shock pulses associated with the ringing of the discharge and of wave attenuation as a function of fundamental parameters such as pressures and tube diameter.

Kash also discussed experiments performed with a tube having an improved electrode geometry for purposes of magnetic driving. This is a conical or funnel arrangement with which it is possible to eliminate multiple shock interactions.

A variation of the technique, described by V. H. Blackman, utilizes an electrodeless breakdown of the gas in the shock tube by sending a current pulse through a single-turn copper coil. A high-velocity plasma was seen to move outward from the plane of the coil. Ionization kinetics were studied with an auxiliary rotating drum camera after some indication that the onset of luminosity behind the shock is coincident with the presence of free electrons and ions in the air. The delay in formation of the luminosity was a measure of the ionization lag time. Measurements were made in air and several noble gases. The results for argon

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compared well with those obtained in other shock-tube investigations.

The magnetohydrodynamic feature of the above-mentioned shock-tube experiments is limited to the initial propulsive phase. Other experiments have been performed, however, dealing with the subsequent interaction of shock and magnetic field. It must be remembered that a gas traversed by a sufficiently strong shock will become partially ionized. Blackman, for example, discussed attempts to give the traveling shock added "kicks" by pushing the plasma immediately behind the shock with flux changes in coils surrounding the tube at various downstream positions which are triggered at strategic instants.

F. R. Scott described experiments on the interaction of a strongly ionizing deuterium shock and a solenoidal magnetic field. By use of a special cylindrical experimental arrangement, it was found that the shock could be channeled along the axis with a radius dependent on field strength. Measurements of the effect were made with small magnetic probes, a smear camera, and by observation of the time-dependant behavior of the current which produced the field. It is evident that the approach in this experiment and those described above is largely an empirical one, a fact which stems from our inability to give accurate descriptions of the physical systems which are under investigation.

Turning from shock-tube experiments to the theoretical paper by E. S. Weibel, we learned that a standing electromagnetic wave in a plasma experiences forces which tend to concentrate it along the nodes of the electric field. In a treated example, an infinitely long cylindrical cavity is excited in the TM_{01} mode at cut-off. The radiation is capable of providing the confining pressure. The plasma and E-M field interpenetrate over a finite distance. The analysis showed further that charge separation was to be expected such that the ions are held primarily by the electrostatic field while the electrons are confined by the radiation. In the discussion which followed, Teller questioned whether such a confinement of a plasma, while of considerable interest for the sake of experimentation, would be useable for thermonuclear power production. Weibel estimated that the power level for economical operation would have to be 10 000 megawatts and declined to speculate further along these lines. Another interesting discussion arose when S. J. Buchsbaum of MIT showed a photo of a plasma which was confined in a cavity excited in a TE_{11} mode, and remarked that this confinement could be maintained for hours.

An impressive feature of the meeting was the relatively large percentage of the delegates who were actively working in this field. This was evidenced by the technical level of the discussion which followed the presentations and the animated conversations among small groups during the intermissions, the luncheon, and the cocktail party held that evening. A detailed account of the meeting is to be published in book form by the Stanford University Press. This follows a precedent set in connection with the 1956 meeting.