Experiments in
Magneto-Fluid Dynamics

By R. A. Alpher

MAGNETO-FLUID dynamics deals with the motion of electrically conducting gases and liquids in the presence of magnetic fields. The macroscopic description of such motions involves the coupling of the equations of hydrodynamics and Maxwell's equations. For velocities small compared to that of light, and if one neglects displacement and charge convection currents, the coupling in the equations of motion occurs through a Lorentz body force term—a term involving the current density $\mathbf{j}$ and the magnetic induction, $\mathbf{B}$, viz., $\mathbf{j} \times \mathbf{B}/c$. The requirement of Lorentz invariance effects the introduction of the coupling into Maxwell's equations, so that one calculates $\mathbf{j}$ from the generalized Ohm's law $\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B}/c)$, where σ is the fluid conductivity, $\mathbf{E}$ the electric field intensity and $\mathbf{V}$ the fluid velocity. Both $\mathbf{j} \times \mathbf{B}$ and $\mathbf{V} \times \mathbf{B}$ are basically nonlinear terms, whence the already uncomfortable situation with nonlinearities in hydrodynamics is quite considerably aggravated. Linearization on the one hand and "simple" experiments on the other must be invoked to convey a physical feeling for the phenomena to be expected from this coupling.

Activity in magneto-fluid dynamics has exploded recently. (The reader is referred to employment advertisements in this magazine and in *The New York Times* and *New York Herald Tribune,* to papers listed in *Physics Abstracts,* and to the contents of such journals as *The Physics of Fluids.* Most striking is the listing of abstracts for meetings of the Divisions of Fluid Dynamics and Plasma Physics of the American Physical Society, and the plethora of special symposia held by various engineering societies and international organizations.) What has precipitated this new interest in a field which seriously engaged the attention of Michael Faraday and William Ritchie one hundred and thirty years ago?

Perhaps the greatest impetus to magneto-fluid dynamics has come from its application in astrophysics, for it is now generally recognized that the usual state of matter in the universe is the plasma state, highly conducting and pervaded by magnetic fields. Another rich and increasing source of activity in this field is research on controlled thermonuclear fusion where success appears to require at least confinement if not compression of conducting gases by magnetic fields. Other areas of much current activity include propulsion and pumping (the use of magnetic fields to set conducting gases and liquids in motion), power generation (the direct transformation of thermal and kinetic energy to electrical energy by passing a conducting fluid through a magnetic field), electrical switching devices, fluid velometry, and by a slight stretch of the imagination, biology, where the phenomenon of magnetotropism was recently demonstrated. What is most surprising with all this activity is that there has not been a larger number of simple laboratory experiments performed with a view toward merely demonstrating magneto-fluid dynamic phenomena, particularly in that domain in which a macroscopic theoretical picture is adequate. Perhaps it is because such experiments seem to be rather more educational than useful.

Historical Notes

THE subject of magneto-fluid dynamics has several historical highlights which merit recognition. In particular it is most interesting to find that the basis of the subject was known to Michael Faraday and his contemporaries. In 1832, Faraday [1] placed electrodes in the River Thames, separated by some 960 feet and connected with a wire looped over the parapet of Waterloo Bridge. Galvanometer signals were observed —he hoped to correlate these with tidal motions of the river in the earth's magnetic field, but he did not have a sufficiently clean experiment. Nevertheless, he suggested that large-scale motions of the conducting oceans are the source of changes in the earth's magnetic field. Again in 1832, W. Ritchie [2] pumped water (presumably not too clean) by passing through it a current transverse to an applied magnetic field. The phenomenon was proposed as an analogue to the driving force for ocean currents. Other 19th century scientists applied fluid magnetic principles to tidal motion monitors, fluid velometry, and other fluid dynamic measurements generally, as well as to instruments for measuring electrical currents. By the early 1900's patents were begin-

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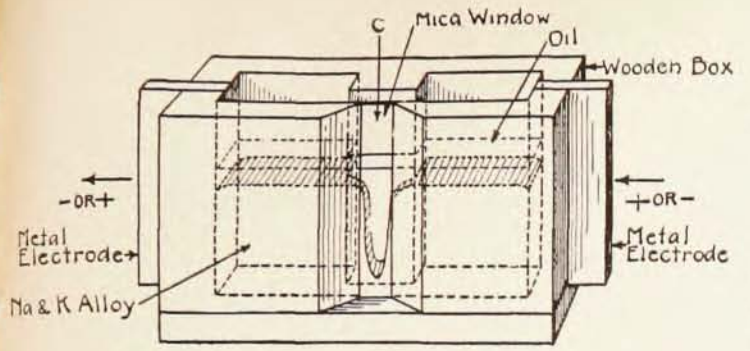


Fig. 1. Demonstration of pinch phenomenon by E. F. Northrop. (*Phys. Rev.*, 1907.)

ning to appear on such devices as magneto-fluid dynamic power generators and fluid velometers. It is rather interesting to note in how many of these patents it was assumed that if liquid mercury was a good conductor then mercury vapor should be superb.

In 1907, E. F. Northrop[3] reported on experiments in liquid metals, demonstrating a then new phenomenon which was suggested and "jocosely" named the pinch phenomenon by C. Hering. Among Northrop's reported experiments were the following. In one he observed a pinch effect when a sufficiently large current passed through a liquid metal in a narrow open trough between two reservoirs. The pinched conductor is shown in Fig. 1, taken from Northrop's paper. In another experiment Northrop confined the liquid metal in a vertical cylinder, in the top of which an opening led to a manometer or, alternately, to a reservoir feeding the liquid metal supply in the cylinder. By passing a sufficiently large current through electrodes in the cylinder ends, he produced a pinch pressure in a constricted region of the cylinder, which pressure could then be measured or used for pumping. By staging the cylinders he was able to develop pressures of the order of several atmospheres. The general arrangement for pumping is reproduced in Fig. 2.

A final historical sidelight, and one which forecast the widespread astrophysical application of the subject, was the suggestion by Joseph Larmor[4] in 1919 that magnetic fields in the earth and sun originated in a fluid-magnetic dynamo action.

Laboratory experiments in magneto-fluid dynamics are generally difficult in that the better the conductor, the larger the magnetic field, the more extensive the physical scale, the greater the effect. The situation becomes even worse if one insists that a true magneto-fluid dynamic experiment is one in which the effects are not merely small or marginal, but rather one in which the motion is determined by the freezing-in of the lines of force into the fluid. The experiments to be described later in this paper either do not in general satisfy the "purist" criterion, or do so just barely. It should be noted that the experiments described represent a personal selection. Someone else might well select a rather different group of experiments to illustrate laboratory demonstrations of magneto-fluid dynamic experiments. No slight is intended toward those whose work is not described.

Fluid Flow Studies

In 1930 E. Williams[5] published two papers dealing with basic magneto-fluid dynamic phenomena. The first of these was one of the earliest quantitative discussions of velometry. Williams described potential surveys from which he derived flow velocity distributions in the motion of $CuSO_4$ through straight and curved tubes in the presence of a transverse field of 10^4 gauss. With no current flow to an external circuit one has $E = VB/c$. It is interesting to note that open-circuit voltages as high as 1 mv were developed. In the second paper Williams discussed and explained earlier work by himself and T. J. Jones[6] on the specific resistance of mercury contained in a closed column in a magnetic field. These measurements had been obscured by the fact that fluid motions were induced in the mercury when current was passed through the column.

The modern era in laboratory experiments was ushered in by J. Hartmann and F. Lazarus.[7,8] As an outgrowth of work with liquid metal pumping, Hartmann calculated and with Lazarus measured the phenomena associated with the flow of mercury in a wide rectangular channel through a transverse magnetic field.

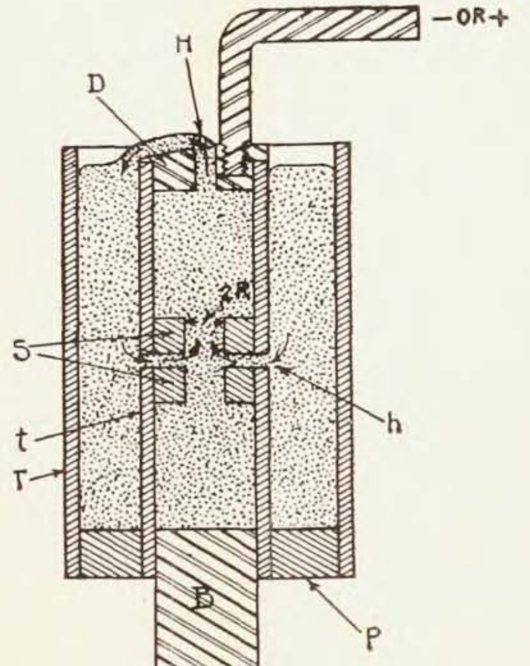


Fig. 2. Pumping liquid metals by pinch phenomenon. Cylinders *T* and *t* are insulators, *D* and *B* electrodes. Areas *S* are annuli to constrict the current and generate pressure. This forces the liquid through *H* whence it circulates through *h*. (*Phys. Rev.*, 1907.)

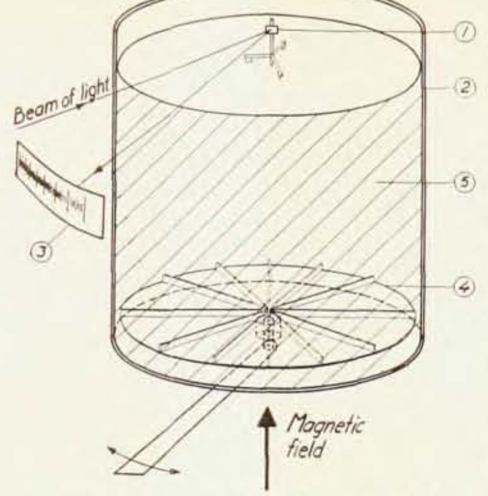


Fig. 3. Apparatus of S. Lundquist and B. Lehnert (who used two surface potential probes rather than a mirror) to demonstrate torsional cylindrical Alfvén waves. (*Phys. Rev.*, 1949.)

They confirmed that the velocity profile was altered by the field, changing with increasing field from the normal parabolic profile toward a more nearly uniform flow, the reason being that fluid viscosity became less important than induction drag with strong field. By the same token viscous shear was compressed into a very thin layer next to the wall. Moreover, the magnetic field moved the transition point from laminar to turbulent flow in the boundary layer toward higher Reynolds numbers. Because of practical applications of the Hartmann flow phenomena in such problems as liquid metal pumping and fluid velometry, as well as in magneto-fluid dynamic duct flows generally, there has been a considerable amount of added experimental and theoretical work since this pioneering investigation.

Alfvén Waves

It is often said that H. Alfvén is the father of modern magneto-fluid dynamics. He authored the basic notion of the freezing-together of fluid motion and field lines and predicted theoretically the existence of a new means of energy propagation [9]—wave motion along the magnetic field direction in highly conducting fluids. Naturally, the possibility that one could demonstrate such waves in the laboratory immediately became of considerable interest. Colleagues of Alfvén, S. Lundquist [10] and B. Lehnert,[11] subsequently carried out experiments to verify torsional cylindrical magnetohydrodynamic waves in mercury and in liquid sodium, respectively. Lundquist's apparatus is sketched in Fig. 3. Torsional waves were generated in the mercury cylinder by oscillating the disc-mounted vanes in the bottom. A resonance was sought by measuring phase and amplitude of the resultant surface wave motion by the motion of a floating mirror. Lehnert's sodium experiments differed in that measurements involved potential differences between two probes in the sodium surface. The former experiments gave a marginal result because the necessity of working at very low frequencies to minimize damping reduced the resultant resonance—because of the reduced damping with higher conductivity the sodium experiment was more definitive although some as yet unexplained discrepancies remain between theory and experiment. It is generally accepted that these experiments first verified the existence of Alfvén waves. Recent demonstrations with highly conductive plasmas in strong magnetic fields have been quite definitive.

Inhibition of Convective Instability

An area of magneto-fluid dynamics which has received very thorough examination is the inhibition by a magnetic field and/or Coriolis forces of convective instability in a layer of fluid heated from below—a problem of astrophysical and geophysical interest. The experiments of B. Lehnert and N. C. Little [12] illustrate the effect most graphically, while a series of experiments by Y. Nakagawa [13] has verified theoretical predictions by himself and particularly by S. Chandrasekhar in a most satisfactory manner. The Lehnert-Little experiment (see Fig. 4) consisted of so

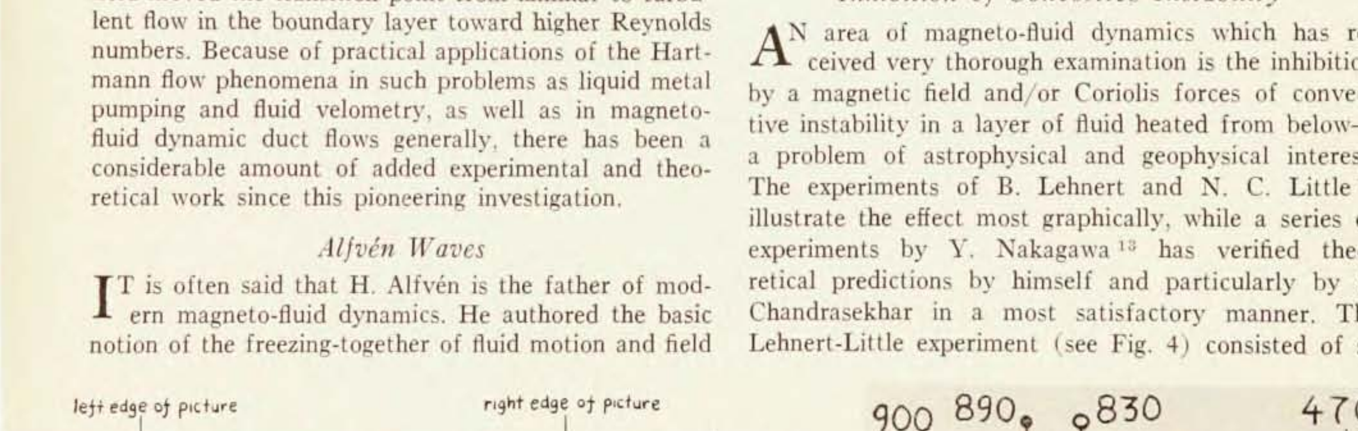


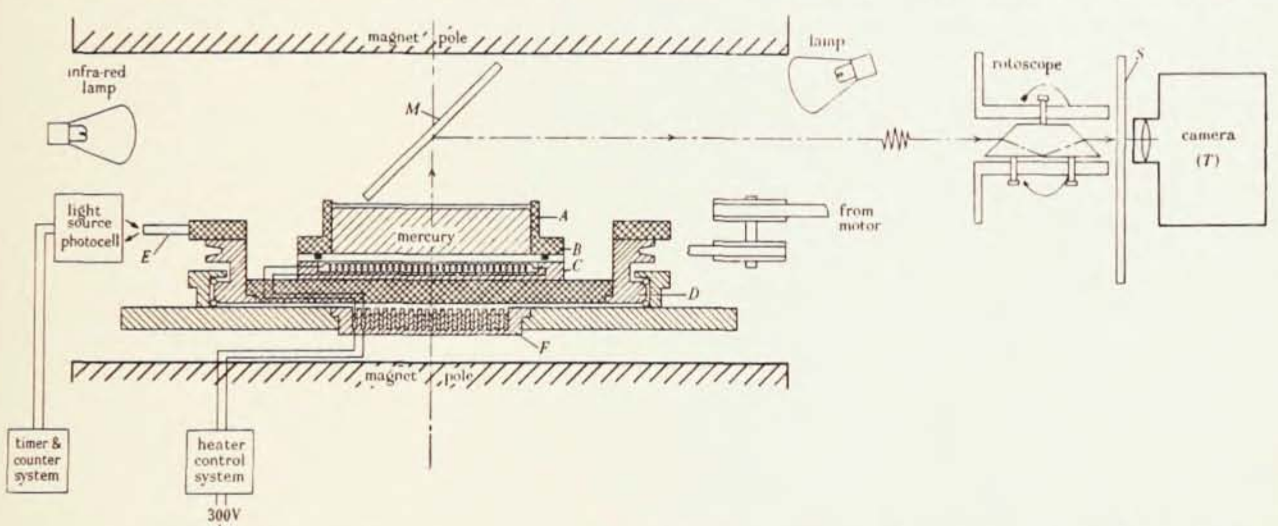
Fig. 4a (left). Apparatus used by B. Lehnert and N. C. Little to illustrate the inhibition of convective instability by a magnetic field. (*Tellus*, 1959.) *Fig. 4b*. Streak photograph of the motion of particles on the surface of mercury in Fig. 4a, showing regions of stability (left), instability (right), and transition (center). It was found that a normal component of 900 gauss inhibited convection at a temperature gradient of 0.5°C per cm. (*Tellus*, 1959.)

placing a container of mercury between magnet pole pieces that the field varied from uniform and normal near one edge of the container to a lesser and oblique field at the other edge. The container was heated uniformly from below and it was possible to adjust temperature gradient and field strength so that regions in which convection was and was not inhibited appeared in the same experiment.

An example of Nakagawa's experiments is given in Fig. 5. The arrangement in Fig. 5a enabled him to rotate a dish of mercury uniformly heated from below and observe the inhibiting effect of a uniform transverse field and of various rotational speeds. A sample streak photograph of the observed convective motion is shown in Fig. 5b. These experiments yielded a high degree of precision in verifying the detailed theory.

The Magneto-hydraulic Analogy

THE flow of a conducting fluid in a shallow layer with a free surface through a transverse magnetic field provides a convenient means of visualizing magneto-fluid dynamic phenomena. Moreover, quantitative data can be obtained not only for the flows per se but also because there exists a formal analogy, with certain restrictions, between the description of such flows and the flow of conducting gases. Flow patterns and depth changes in the fluid can be directly related to flow patterns and changes in such quantities as pressure, temperature, density, etc., in the flow of gases. The situation is similar to the more familiar water-table flows which involve the hydraulic analogy. A device for producing and studying shallow flows of conducting liquids has been developed by Alpher, Hurwitz, John-



A schematic diagram of experimental arrangement. *A*, Bakelite cylinder; *B*, stainless-steel plate; *C*, electric heater; *D*, non-magnetic ball-bearing; *E*, stainless-steel rod; *F*, mercury trough; *M*, front-surface mirror; *S*, rotary shutter; *T*, camera.

Fig. 5a. Apparatus used by Y. Nakagawa to verify the predicted behavior of a layer of conducting incompressible fluid heated from below and subject to the simultaneous action of a magnetic field and Coriolis forces. (*Proc. Roy. Soc.,* 1959.)

Fig. 5b. Streak photograph of surface of a mercury layer bearing a temperature gradient of about 1°C per cm, 3 cm deep, rotating at 5 rpm in an axial field of 1000 gauss. Note the large hexagonal convection cells. (*Proc. Roy. Soc.,* 1959.)

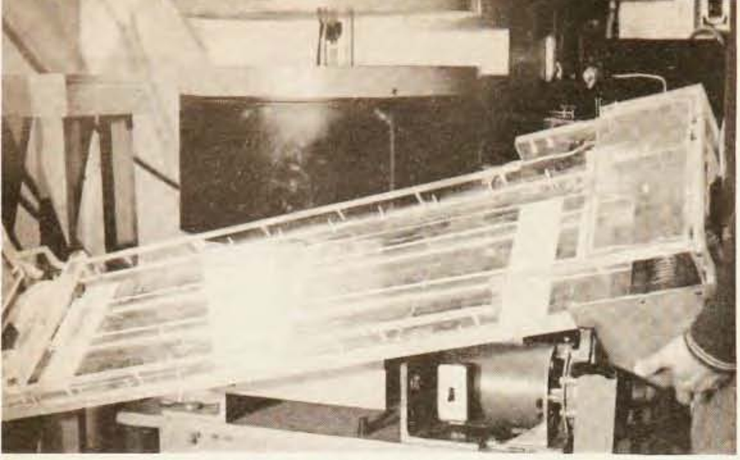


Fig. 6a. Photograph of free surface mercury channel for studies of magnetohydraulic analogy (*Rev. Mod. Phys.*, 1960). *Fig. 6b.* Bow shock wave and Kármán vortex street in wake of disturbance created by flush-mounted conducting disc in bottom of insulated channel with mercury flowing over it at about 1 cm depth, velocity about 40 cm/sec., field about 4000 gauss.

son, and White,[14] and is shown in Fig. 6. Mercury flows from a reservoir on the left through a nozzle into an insulated channel (slightly divergent and inclined to overcome friction), into a sump where it is cooled and recirculated to the reservoir. The channel flow can be adjusted to be "subsonic" or "supersonic" with respect to the velocity of gravity waves—this playing the role of the sound velocity in the analogy. An example of a particular study is shown in Fig. 6b. A copper disc was embedded flush in the bottom of the otherwise insulated channel. When mercury flowed over this disc through a transverse field, the disc acted as though it had anchored the field lines there—a consequence of the local reduction of induced emf. Thus at "supersonic" speeds the magneto-fluid dynamic disturbance took on the form of a "bow shock wave" analogous to that in supersonic flow about a cylinder, with a subsonic wake showing the shedding of alternating vortices—a Kármán vortex street.

The seemingly remarkable longevity of vortices in such flows led to the construction of a mercury motor [14] —a cylindrical insulated dish with a central electrode and a coaxial conducting wall. Application of a voltage across these electrodes with an axial magnetic field caused the mercury to rotate. After removal of the driving voltage and reestablishment of the flow to a no-net-current configuration, the decay of rotational flow could be measured readily. With a top cover on the device leaving no space for surface deformation, the device becomes an incompressible fluid analogue of the hydromagnetic capacitor.

The action of the bottom-embedded disc described above is illustrative of the fact that not always does a magnetic field so act as to stabilize the flow of a conducting fluid. Another and excellent example of this is an experiment by Lehnert,[15] in which he placed on the bottom of a shallow dish of mercury a center disc and two close-fitting concentric annuli of copper, the inner one narrow, the outer broad. The whole was immersed in an axial magnetic field. When the narrow annulus was rotated the fluid behaved as though the field lines were locked-in to the moving and stationary copper, so that there was no flow over the stationary disc and annulus, while the mercury tended to move as an annulus with the moving copper annulus. Strong shear developed between regions of moving and nonmoving fluid with a consequent double ring of vortices. This striking effect is illustrated in Fig. 7.

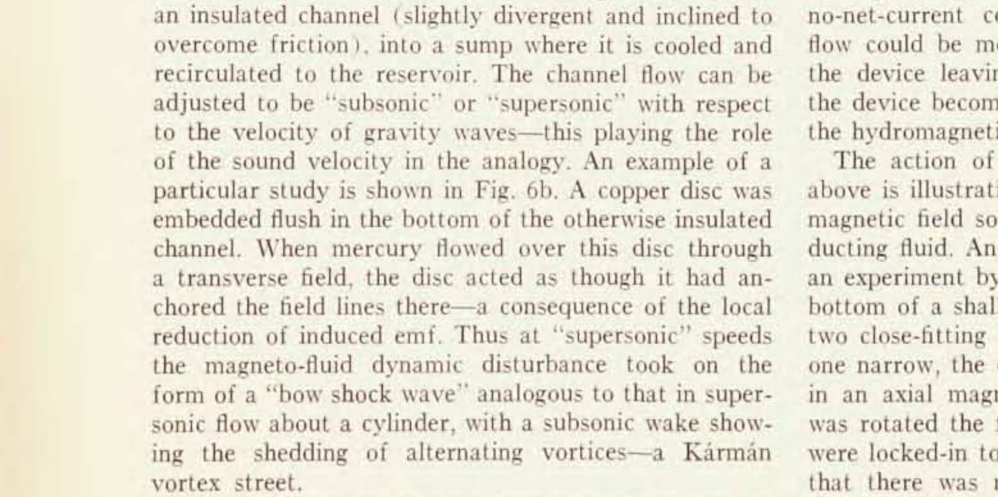


Fig. 7. In experiments by Lehnert an "instability" is caused by magnetic field in the flow of mercury over a copper bottom made up of a central disc and two concentric rings, the innermost ring turning and the whole in a field of 4300 gauss. These are surface photographs of a 6-mm layer of mercury; the left photograph is a 1/5 sec. exposure showing motion of floating sand grains, while that on the right shows the distortion of a grid image projected onto the surface. The moving ring, a cm wide and mean diameter about 7 cm, rotates at 1/5 rps. In the absence of field, there are in essence no surface disturbances due to ring motion. (*Proc. Roy. Soc.*, 1957.)

Models of Pinch Instabilities

IN recent years, considerable effort has gone into understanding various sorts of instabilities which arise in pinched plasma configurations. It has turned out to be possible to demonstrate some of these instabilities using liquid metal analogues—needless to say the experiments are much simpler to perform, the phenomena easier to visualize, and purely magneto-fluid dynamic effects separable from the great complexity of plasma problems. An example of such studies is the work of Dattner, Lehnert, and Lundquist.[16] They allowed mercury to flow through a hole in the bottom of one container into a reservoir beneath, whence it was recirculated to the upper container. In so doing they formed a free column of mercury 4 mm in diameter, 14 cm long. Passage of sufficiently large currents through this mercury column gave rise to sausage and kink instabilities easily observed and photographed. Lehnert[17] recently described a modification of this experiment to the hard-core or hollow pinch geometry in which the current-bearing mercury flows down the outside of a glass cylinder, inside of which a solid conductor isolated from the mercury created a trapped field.

Birdsall, Colgate, and Furth[18] and more recently Colgate, Furth, and Halliday[19] have reported on the use of liquid and solid sodium to study instabilities and equilibrium configurations in various pinch and mirror geometries. A most interesting feature of these experiments is the fact that one can examine the deformed liquid sodium at leisure afterward by allowing it to freeze-in with the configuration of interest. As an example of what can be done with solid sodium, Fig. 8 shows two views of a billet, initially a cylinder 2.5 cm by 2.5 cm, which was subject to four 200 μsec duration pulses in a 100 kilogauss mirror machine. The tensile strength of the sodium is sufficiently low that the sodium behaves as a liquid of high conductivity during field application. The longitudinal ridges and oval deformations are evidence of characteristic and expected instabilities.

Concluding Remarks

IT is clear from this all too brief survey and from the degree of selection that there is a significant amount of experimental results in magneto-fluid dynamics which is not complicated by the still more esoteric behavior of plasmas. The theoretical picture for such experiments generally is not so bright as it might be, for one is limited to fluids having quite finite conductivities. Unfortunately, it turns out to be considerably easier to construct theories with the assumption of infinite conductivity from which extrapolation to finite conductivity is not always made with safety. It therefore seems to be important that such experiments continue to be performed at least for the insight they provide into magneto-fluid dynamic phenomena involved in more complex experiments with plasmas.

References

1. M. Faraday, Phil. Trans. Roy. Soc. **15**, 125 (1832); or *Experimental Researches in Electricity* Vol. 1, p. 55, 1839.
2. W. Ritchie, Phil. Trans. Roy. Soc. **15**, 295 (1832).
3. E. F. Northrop, Phys. Rev. **24**, 474 (1907).
4. J. Larmor, Engineering (London) **108**, 461 (1919).
5. E. Williams, Proc. Phys. Soc. (London) **42**, 466, 479 (1930).
6. E. Williams, Phil. Mag. **50**, 27 (1925); T. J. Jones, Phil. Mag. **50**, 46 (1925).
7. J. Hartmann, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **15**, 6 (1937).
8. J. Hartmann and F. Lazarus, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **15**, 7 (1937).
9. H. Alfvén, Nature **150**, 405 (1942).
10. S. Lundquist, Phys. Rev. **76**, 1805 (1949).
11. B. Lehnert, Phys. Rev. **94**, 815 (1954).
12. B. Lehnert and N. C. Little, Tellus **9**, 97 (1957).
13. Y. Nakagawa, Proc. Roy. Soc. **A249**, 138 (1959).
14. R. A. Alpher, H. Hurwitz, Jr., R. H. Johnson, and D. R. White, Rev. Mod. Phys. **10**, 758 (1960).
15. B. Lehnert, Proc. Roy. Soc. **A233**, 299 (1955).
16. A. Dattner, B. Lehnert, and S. Lundquist, Proc. 2nd Int'l. Conf. on Peaceful Uses of Atomic Energy, Geneva, **31**, 325 (1958).
17. B. Lehnert, Rev. Mod. Phys. **10**, 1013 (1960); B. Lehnert and G. Sjögren, J. Nucl. Energy Pt. C, **1**, 121 (1960).
18. D. H. Birdsall, S. A. Colgate, and H. P. Furth, Proc. 4th Int'l. Conf. on Ionization Phenomena in Gases, Uppsala, 1959.
19. S. A. Colgate, H. P. Furth, and F. O. Halliday, Rev. Mod. Phys. **10**, 744 (1960).

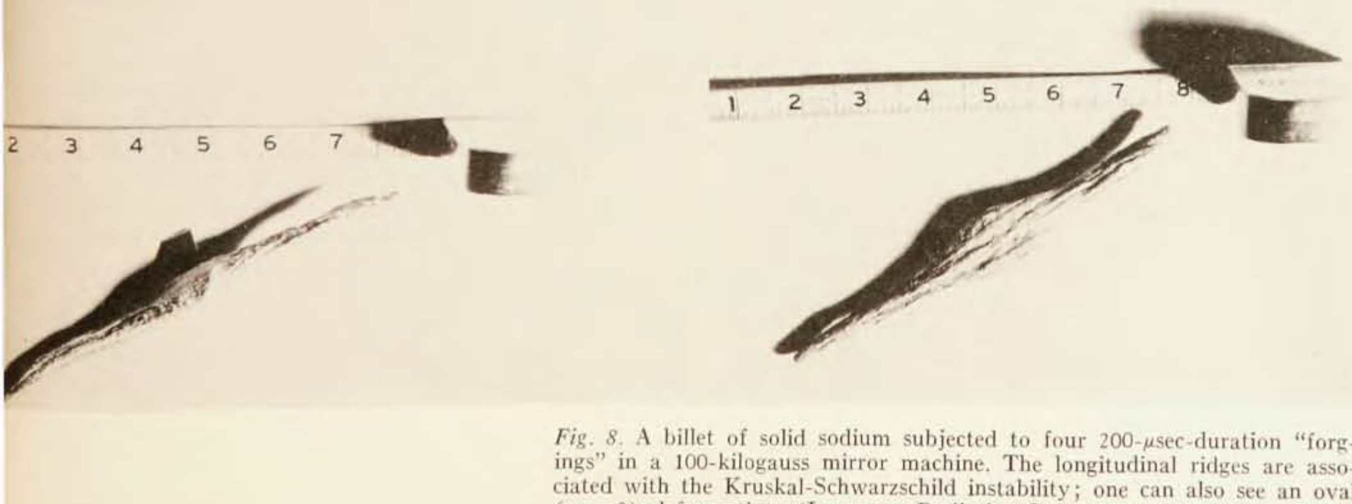


Fig. 8. A billet of solid sodium subjected to four 200-μsec-duration "forgings" in a 100-kilogauss mirror machine. The longitudinal ridges are associated with the Kruskal-Schwarzschild instability; one can also see an oval ($m = 2$) deformation. (Lawrence Radiation Laboratory, Livermore, Calif.)