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A PROBE FOR ELECTRICAL CONDUCTIVITY MEASUREMENTS IN IONIZED GASES

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A PROBE FOR ELECTRICAL CONDUCTIVITY MEASUREMENTS IN IONIZED GASES

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ABSTRACT: A probe technique for measuring the electrical conductivity in a small region of an ionized flow field is described. The technique involves observing the interaction between an ionized gas and a small perturbing R.F. magnetic field. The probes are basically small coils. Several probes have been dynamically calibrated in a shocktube. A few preliminary measurements were made in the wake of a 4-inch sphere which was subjected to high-speed flight conditions.

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IN IONIZED GASES

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The authors wish to express their appreciation to Messrs. Paul Leath, Robert Gastrock, and Michael Plummer for their valuable contributions to this program. In addition, the authors would like to acknowledge Mr. Joseph J. Lentz for his indispensable aid with the experimental facilities.

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Captain, USN
Commander

A. E. Seigel
A. E. SEIGEL
By direction

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INTRODUCTION

During the past few years the U. S. Naval Ordnance Laboratory has become engaged in conducting ionized wake studies in its Hypersonic Shock Tunnel Facilities. The procedure, ideally, was to make a point measurement of the electrical conductivity in the wake of a model which was subjected to high-speed flight conditions. The technique which the authors chose to develop was that of monitoring the interaction between the moving ionized gas and a high-frequency perturbing magnetic field. Since the details of the probing technique have been described in two previous reports (refs. (1) and (2)), only a brief outline will be given below. Although there will be a few minor changes in the probe design and the operating circuitry, this report is of a final nature since the authors feel that the validity of the technique has been adequately demonstrated.

THEORY AND APPARATUS

The probes consist, basically, of small coils embedded in, or wound upon ferrite cores. The ferrite is used primarily to restrict the magnetic field to a particular geometry. Figures 1 and 2 illustrate two probe configurations which are being used.

Figure 3 is a diagram of the probe coil and the associated circuitry. The probe is excited by a one-megacycle, crystal-controlled oscillator which is used in series with a relatively large resistor to obtain a constant current signal. The presence of an ionized gas passing over (or through) the probe coil will cause a change in the impedance of the coil. The potential change across the coil will be equal to the impedance change, since the current is held constant. In this fashion it is easily seen that the effect of the ionized gas is to produce an amplitude modulation of the one-megacycle "carrier." The remainder of the circuit is used to extract the modulation from the carrier. The circuit has an over-all response of 100 kilocycles which means that the change in impedance of the coil due to fluctuations in the ionized flow can be followed with a 10-microsecond response time.

A general theoretical model for the cylindrical probe is presented in reference (1). A more primitive model is presented in reference (2), and for the purpose of continuity is also included as Appendix A of this paper. Both treatments yield a relation between the potential across the probe coil and the electrical conductivity of the ionized gas.

In order that the probing technique not be limited by one's ability to solve accurately the mathematical problem associated with a particular field geometry, it was decided that a dynamic calibration of the probes was necessary. This calibration is accomplished in a specially designed shocktube. This shocktube (described more completely in ref. (2)) was constructed of stainless steel in order to minimize the impurity level. To reduce the boundary layer in the test section, an annular dump region is provided just upstream of the testing region (see figs. 4 and 5). The probe is mounted on a sting just downstream of a 70 Kmc microwave interferometer which is used to obtain the electron density of the ionized air (see fig. 6). A range of conditions for the shock-heated air was obtained by varying the initial pressure and shock velocity.

CALIBRATION RESULTS

Several of the wedge-type probes have been calibrated in the manner described above. Due to an oversite on the authors' part the wedge angle was too large and a detached shock was incurred. Since the microwave interferometer measures the electron density in the free stream, it is difficult to use this value to determine conditions behind the standing shock. The authors thus chose to calculate the electrical conductivity, in a fashion used by Dr. Lin in reference (3), using initial pressure and shock velocity as a starting point. The temperature and density ratios across the standing shock were obtained from reference (4), the particle densities from reference (5), and the collision cross sections from reference (6). Figure 7 is a typical calibration curve for one of the wedge-type probes. The vertical scale (probe signal) is the amplitude of the signal as displayed on the oscilloscope. Some of the scatter of the data points is attributed to fluctuations in the standing shockwave which will amplify any flow irregularities.

The new generation of probes will have a wedge angle sufficiently small to insure an attached shock below the probe. Since the probe will then be sensing the free-stream region, a direct comparison with the interferometer will be possible. Figure 8 is a selection of traces from the calibration run on one of the probes. The oscilloscope is triggered about 100 microseconds before the shock arrives at the probe position. There is an anomalous spike, which occurs during this 100 microseconds, which the authors are unable to explain. The extra marks on the photographs were made by the authors when reading the data. A large percent of the irregularities and over-all slantedness of the traces is attributed to noise.

SHOCK-TUNNEL TEST

Several test shots were made in the 1.5-in. Hypersonic Shock Tunnel No. 1 to see whether a measurement could be performed with the conductivity probe. The probe was placed in the wake of a 4-inch sphere (see fig. 9). Since only qualitative results were sought from these initial tests, no attempt was made to align the probe with the flow streamlines.

Figure 9 is a probe trace and a schlieren photograph of a typical shot. The fact that the probe is not aligned with a streamline is confirmed by an attached shockwave on top of the wedge. The sphere was flying at simulated conditions of Mach 8 at an altitude of 125,000 feet.

Figure 10 displays two probe traces from two different shots. The flight conditions for the sphere were Mach 8 at an altitude of 50,000 feet for both shots. Repeatability is indicated. The excessive noise on the upper trace was due to a loose cable cover plate inside the tunnel which was discovered after the shot.

The flow duration indicated on the probe traces in figures 9 and 10 checks very closely with those predicted from aerodynamic calculations.

DISCUSSION

The lower limit of sensitivity of the probes described above is about 10^{-4} mhos/cm. This limit is set, basically, by the signal-to-noise ratio (i.e., a signal representing 10^{-4} mhos/cm represents a modulation of only about .02 percent). There is no upper limit of sensitivity. It is, however, very difficult to distinguish between 10^5 and 10^6 mhos/cm since both yield about 100 percent modulation on the carrier.

As soon as the new generation of probes has been calibrated, the probes will be used to determine the radial and axial variation of the electrical conductivity in the wake of various models at various flight conditions. It is also anticipated that coils will be embedded in the models themselves so that the conductivity of the ionized gas surrounding the model can be determined.

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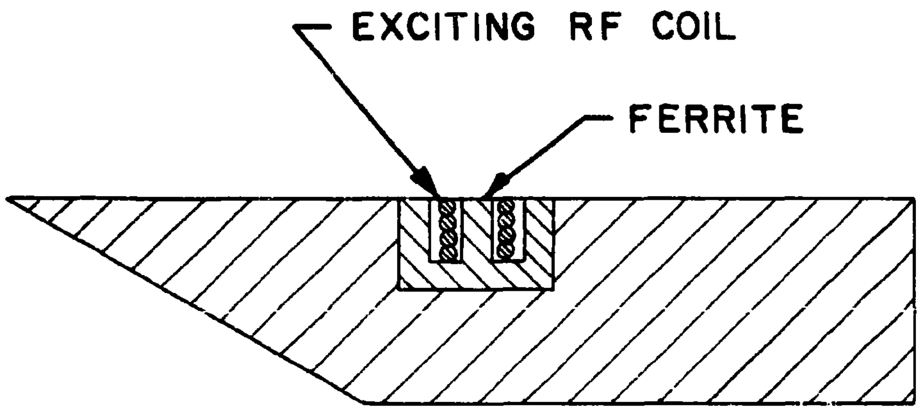
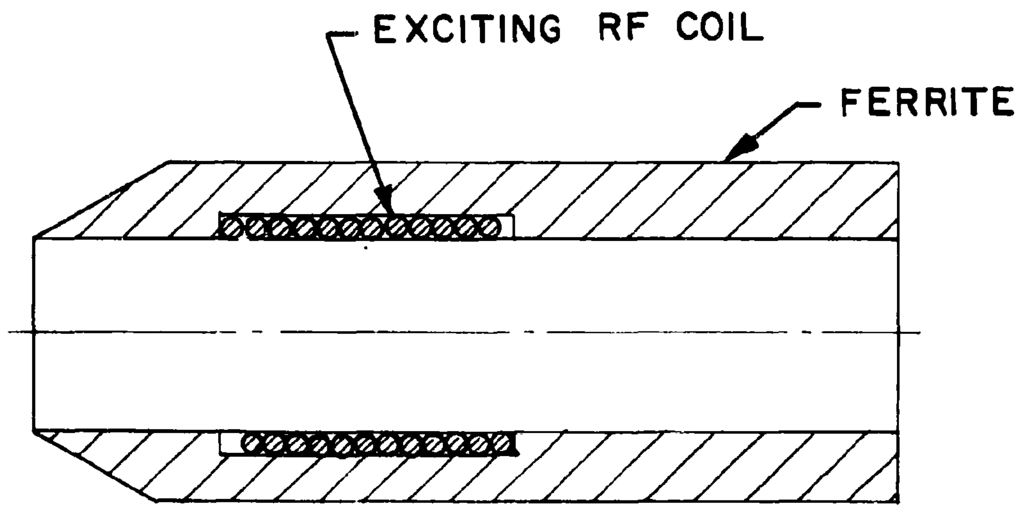
6. Massey, H. S. W. and Burhop, E. H. S., Electronic and Ionic Impact Phenomena (Oxford University Press, New York, 1952)



FLAT PLATE RF-PROBE



CYLINDRICAL RF-PROBE

FIG. 1 CROSS-SECTIONAL VIEW OF CONDUCTIVITY PROBES

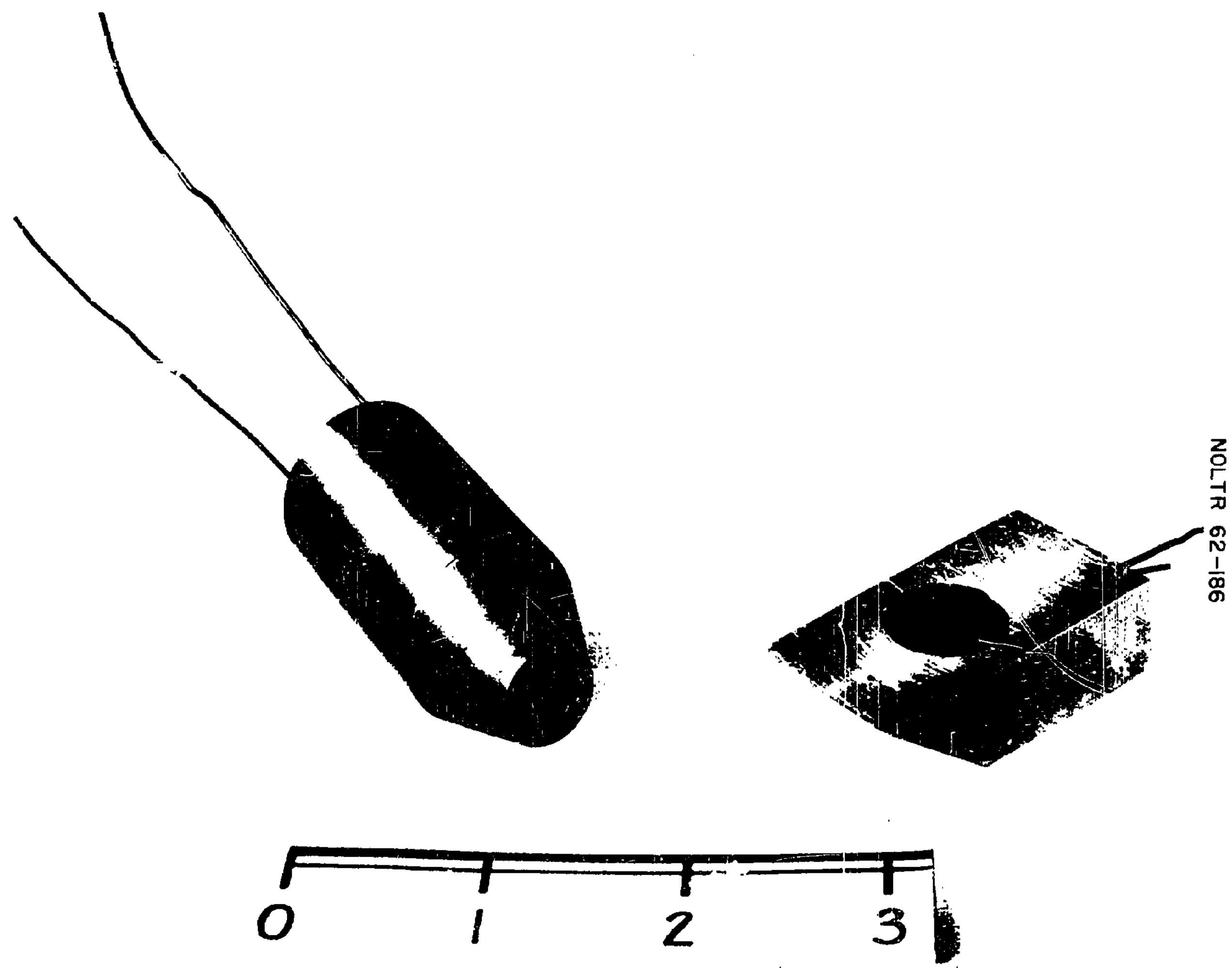


FIG. 2 CONDUCTIVITY PROBES (SCALE IN INCHES)

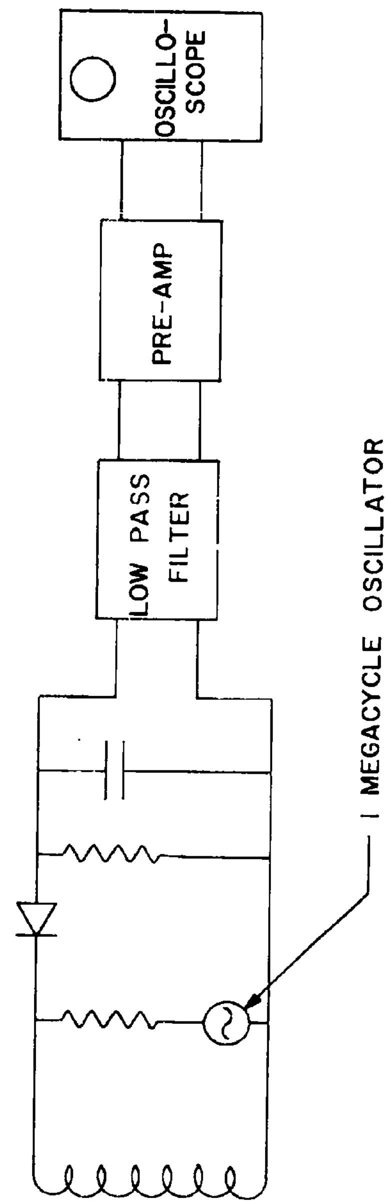


FIG. 3 CONDUCTIVITY PROBE CIRCUIT.

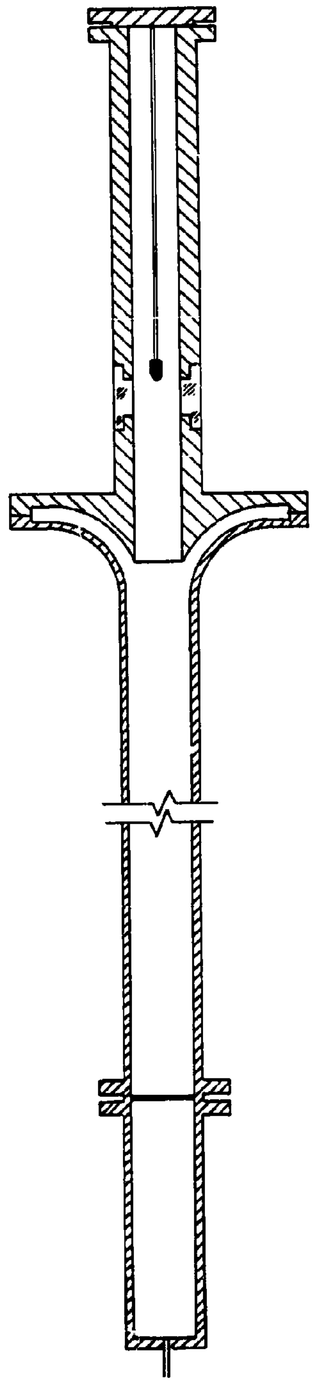


FIG. 4 SCHEMATIC DRAWING OF THE 5-IN. SHOCKTUBE.

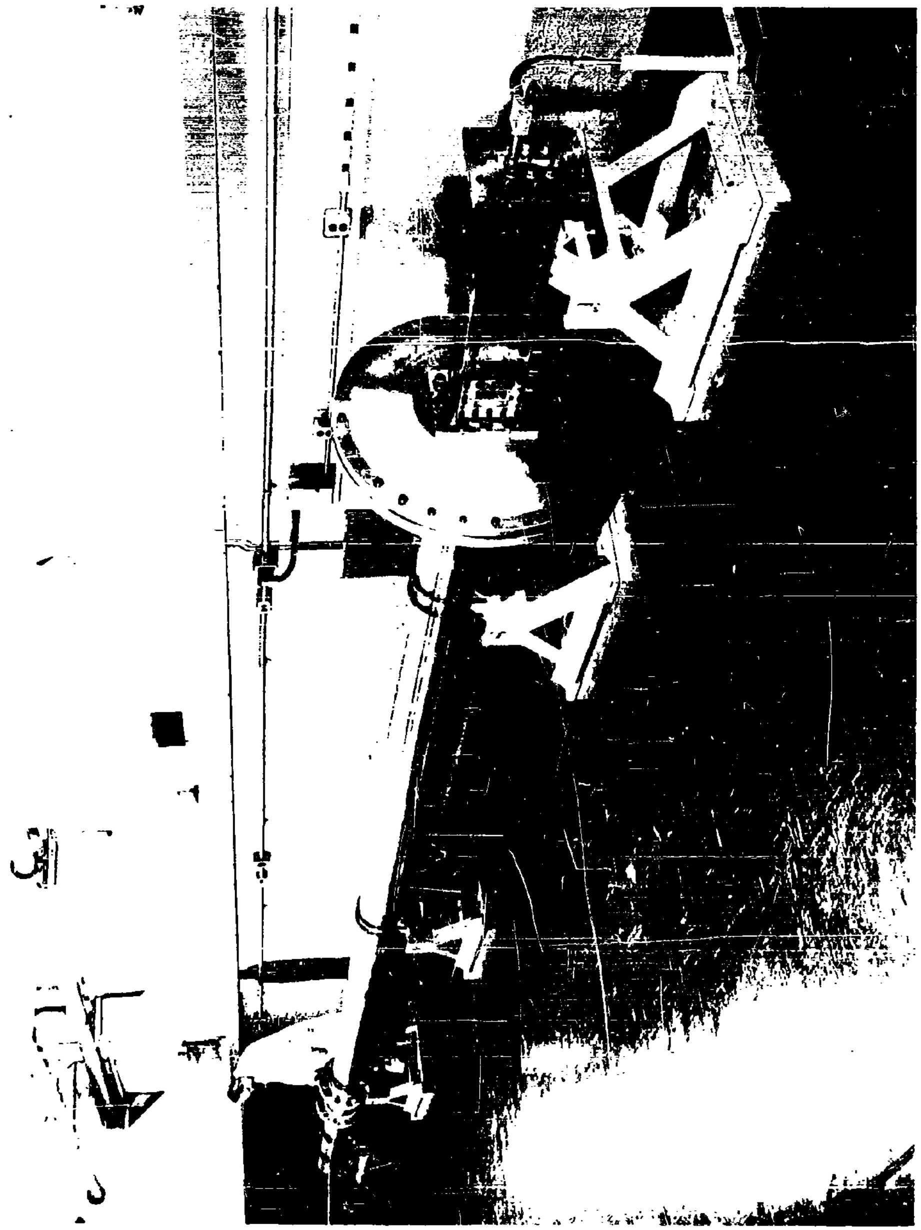


FIG. 5 THE 5-IN. SHOCKTUBE

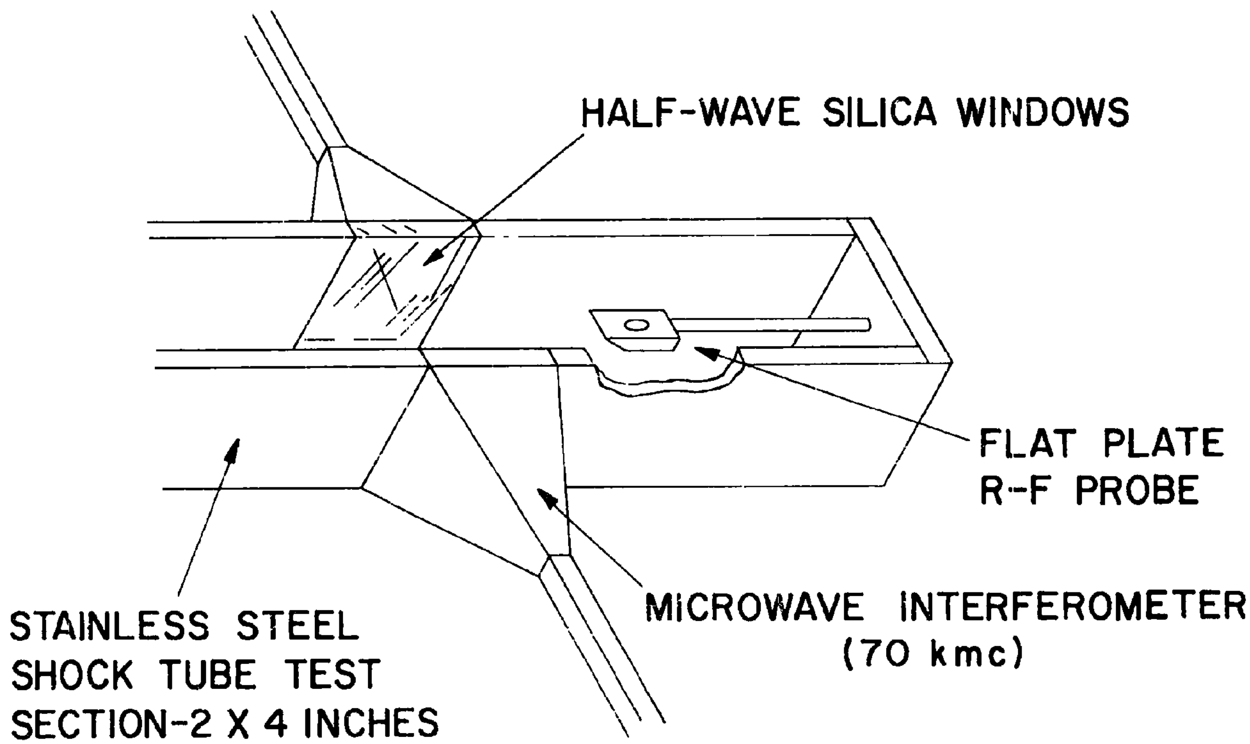


FIG. 6 INTERFEROMETER AND PROBE POSITION.

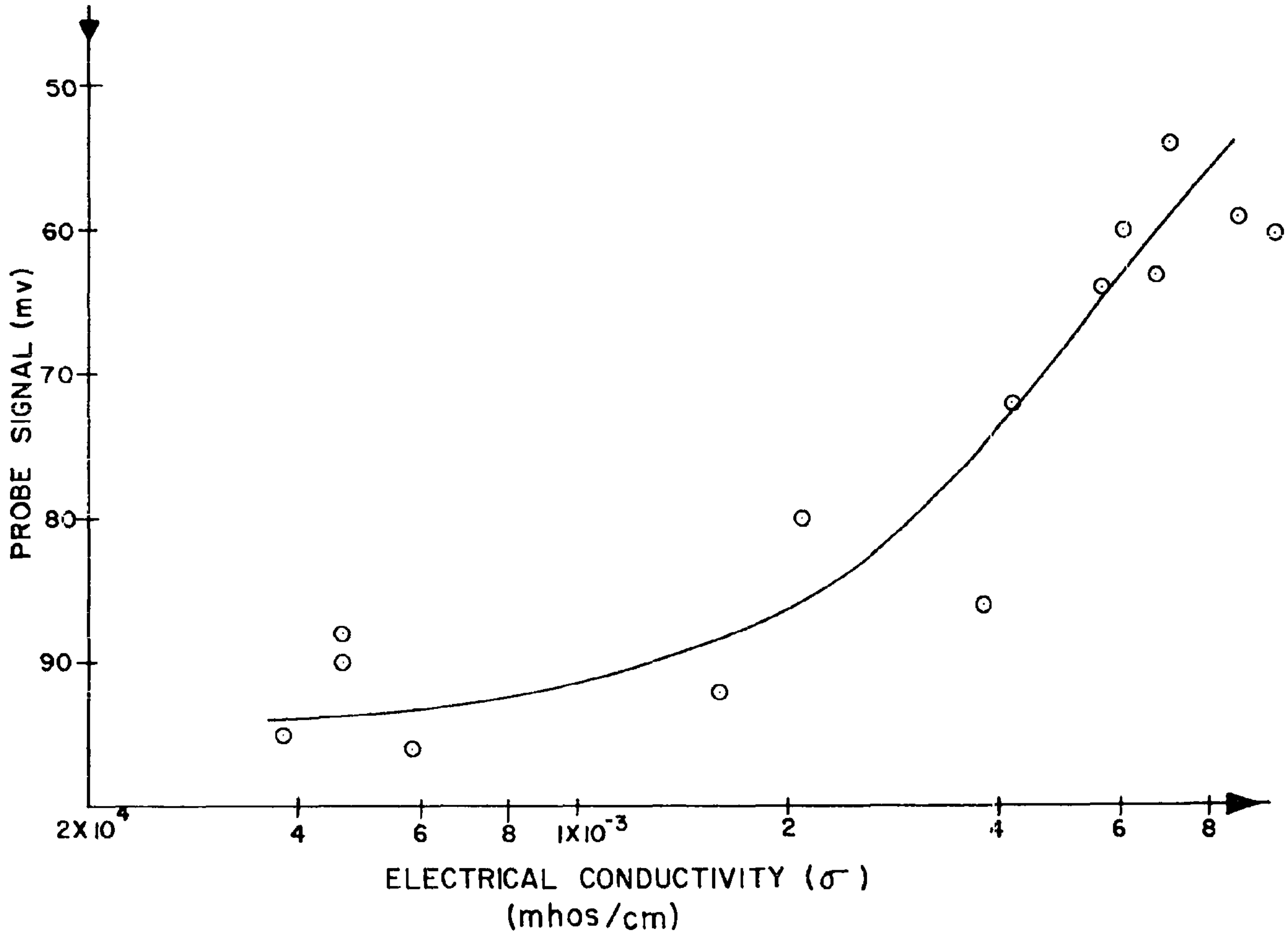


FIG. 7 CALIBRATION CURVE FOR CONDUCTIVITY PROBE NUMBER 1

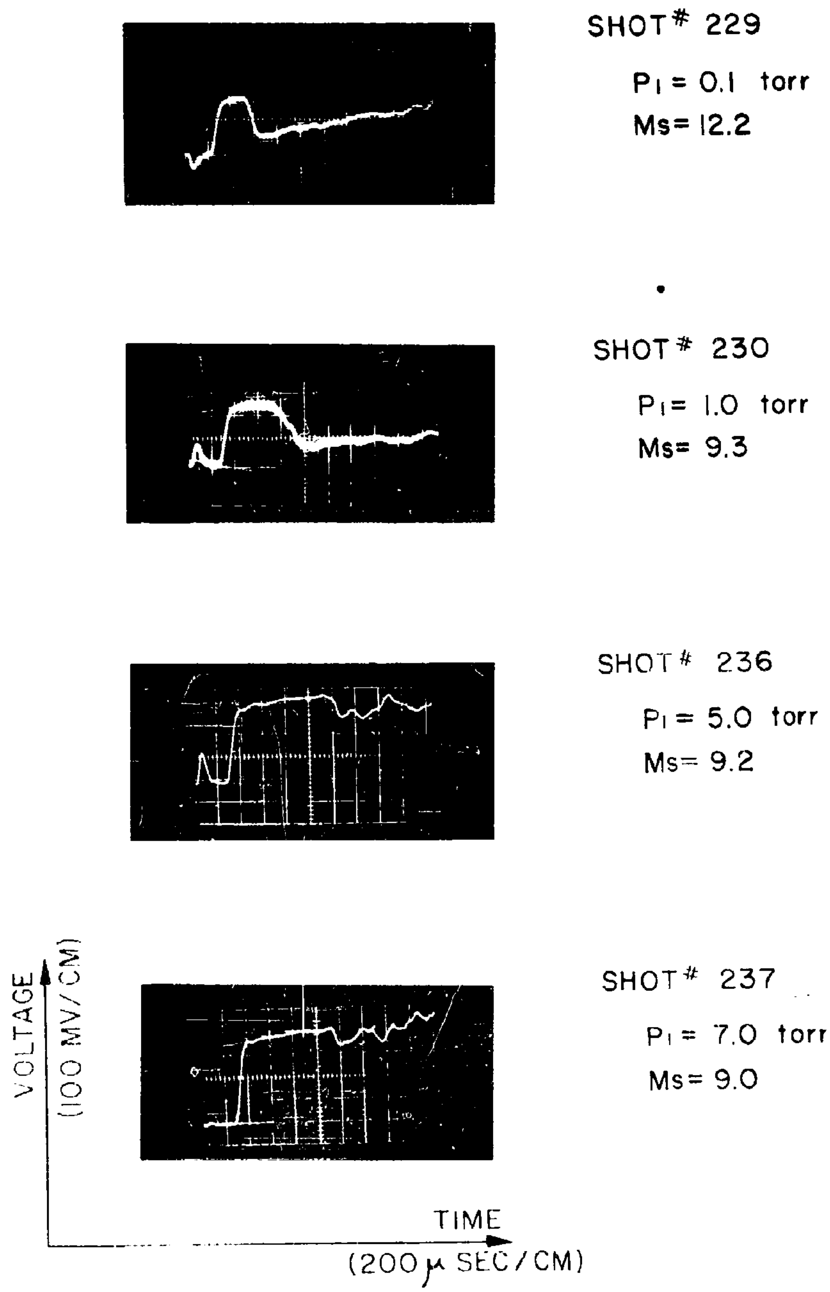
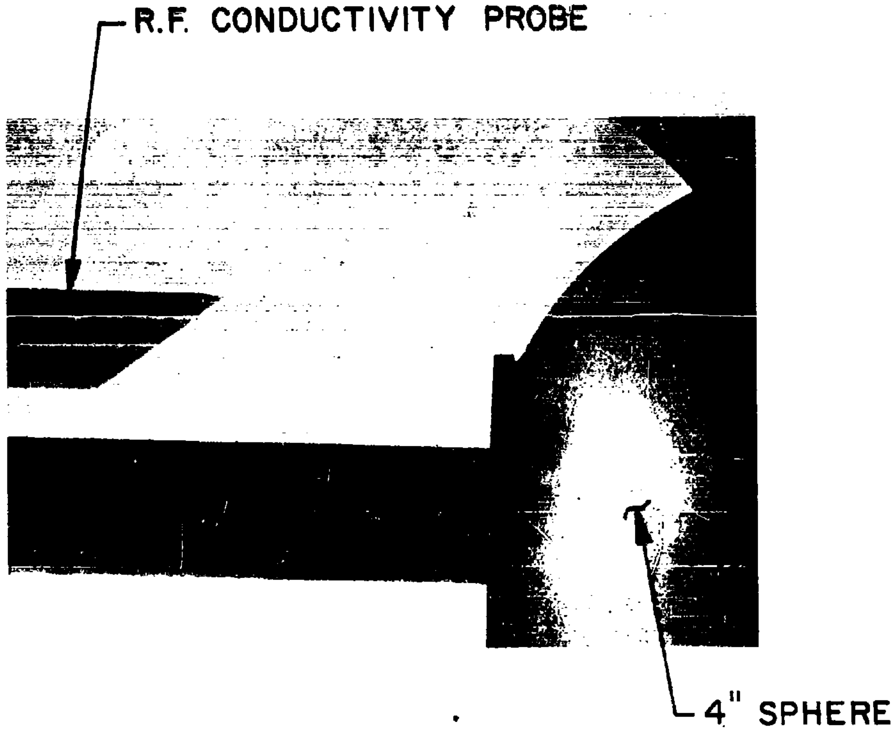


FIG. 8 PROBE TRACES TAKEN DURING A CALIBRATION RUN.



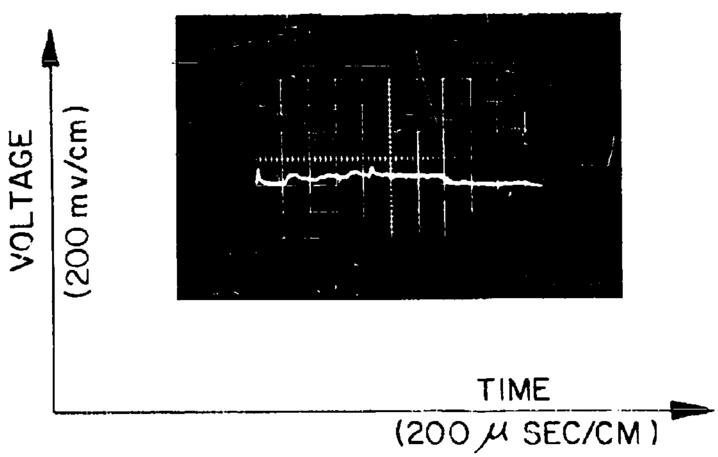


FIG. 9 SCHLIEREN PHOTOGRAPH AND PROBE TRACE OF A WAKE CONDUCTIVITY TEST

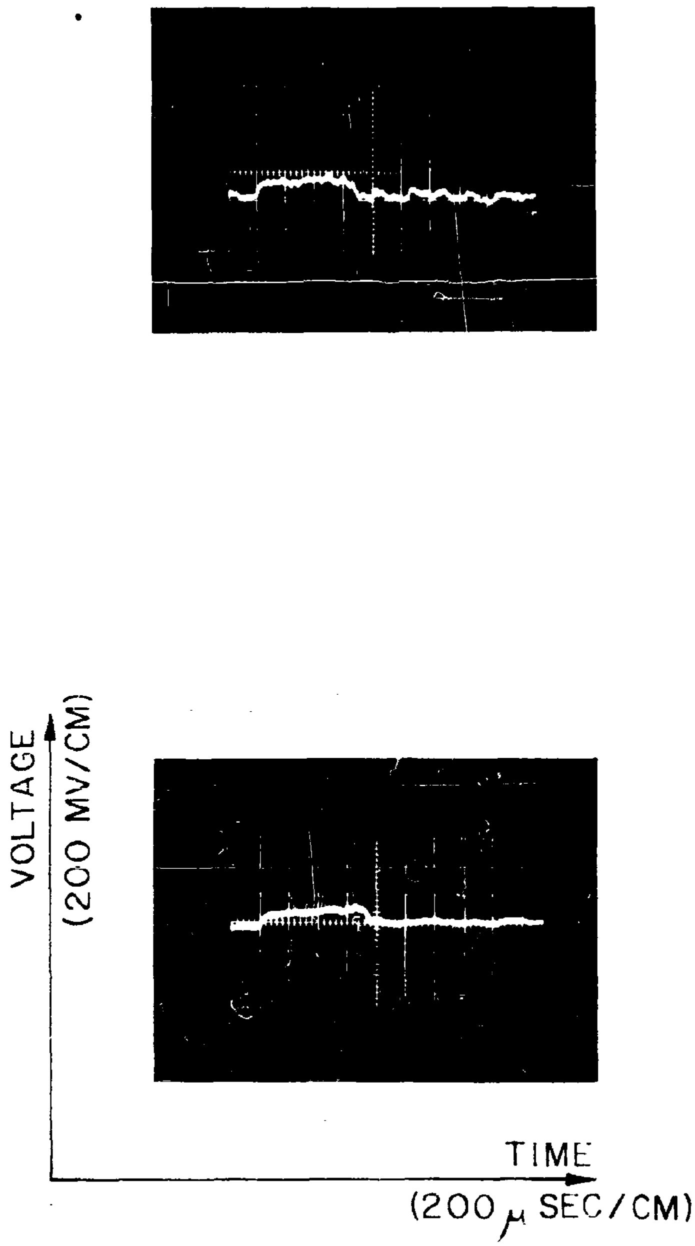


FIG. 10 PROBE TRACES OF TWO WAKE CONDUCTIVITY TESTS, REPEATABILITY IS INDICATED.

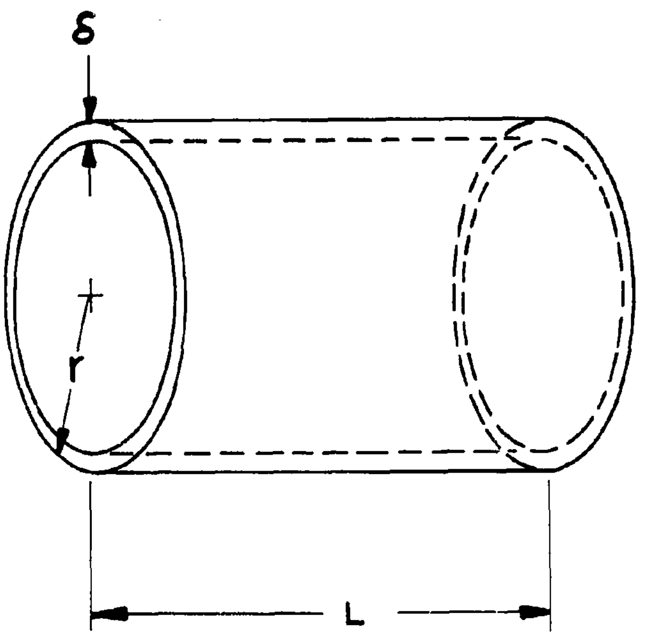


FIG. 11 CORE GEOMETRY

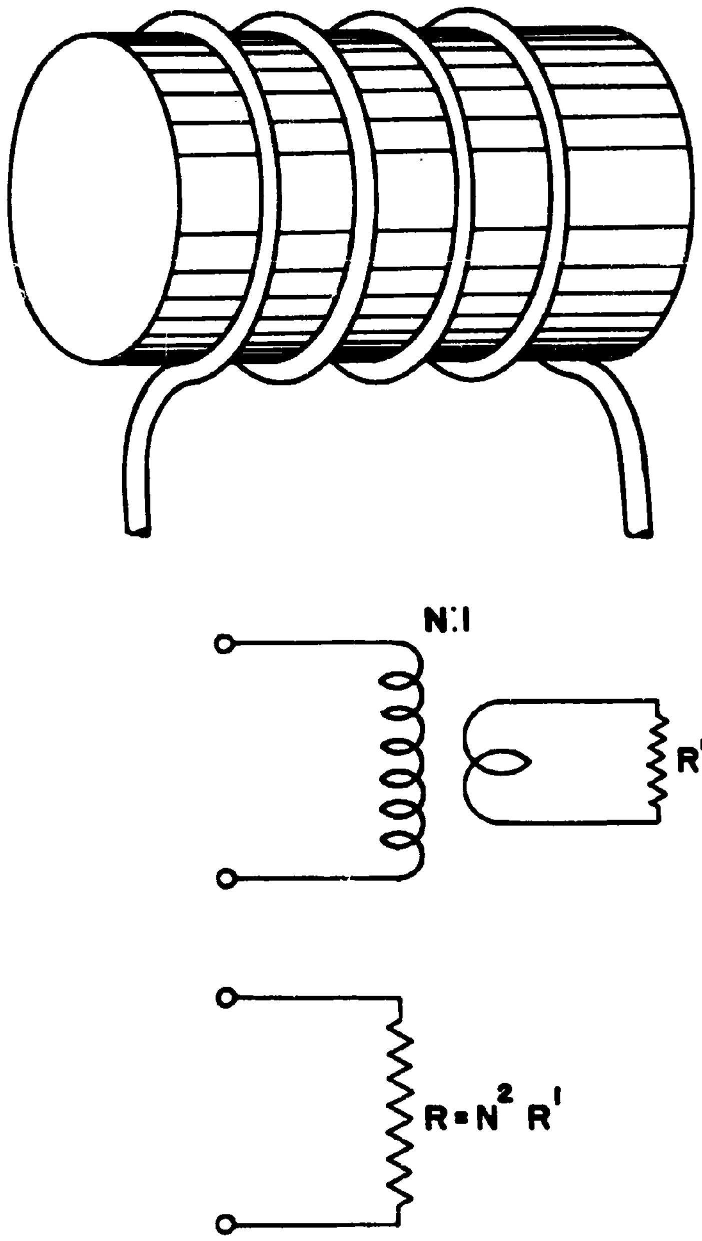


FIG. 12 PROBE COIL AND EQUIVALENT CIRCUIT FOR THE CONDITION.

APPENDIX A

A detailed calculation relating the impedance of a solenoid as a function of the excitation frequency f and the electrical conductivity σ of the core is given in reference (2). Rather than repeating this information, it is instructive to consider the special case when the product f σ is sufficiently large that the skin depth of field penetration δ is small compared to the core radius r (see fig. 9). It is further assumed that although the gas is in motion, the frequency is high enough to effectively stop this motion. Since the field penetration is small compared to the radius, one can consider that the induced current flows in the thin cylindrical shell of width δ. The resistance R' of this shell is given by

$$R' = \frac{2\pi r}{\sigma L \delta} \qquad \text{(A1)}$$

where $2\pi r$ is the length of the current path, L δ is the cross-sectional area, and σ is the electrical conductivity. Since the skin depth is given by

$$\delta = (\pi f \mu \sigma)^{-1/2} \qquad \text{(A2)}$$

equation (A1) becomes

$$R' = \frac{2\pi r}{L}\left(\frac{\pi f}{\sigma}\right)^{1/2} \qquad \text{(A3)}$$

The geometry of this shell in relation to the excitation coil suggests that one can make use of a transformer analog, where the ionized gas is represented by a one-turn secondary with a load impedance R' (see fig. 10). A convenient equivalent circuit for the transformer is simply an impedance equal to the load impedance times the turns ratio squared. The probe impedance is thus

$$R = N^2 \frac{2\pi r}{L}\left(\frac{\pi f}{\sigma}\right)^{1/2} \qquad \text{(A4)}$$

Since the current I is held constant the magnitude of the potential across the coil V is given by

$$|V| = I N^2 \frac{2\pi r}{L} \left(\frac{\pi f}{\sigma} \right)^{1/2} \tag{A5}$$

Equation (A4) is found to be fairly accurate for skin depths as large as 0.3 r . The more general result derived in reference (1) makes no assumptions of f or σ .

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Measuring	MEAU	Interferometer	INFM		
Electrical	ELEC	Radiofrequency	RADF		
Conductivity	COND	Magnetic field	MAGI		
Ionized	IONI				
Gases	GASE				
Flow	FLOW				
Fields	FIEL				
Wake	WAKE				
Probe (Design)	PROBD				
Dynamic	DYNA				
Calibration	CALB				

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4. Probes - Flow
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A PROBE FOR ELECTRICAL CONDUCTIVITY MEASUREMENTS IN IONIZED GASES (U), by Lemmuel L. Hill and others. 31 Dec. 1962. v.p. illus., diagr. (Ballistics research report 83)
UNCLASSIFIED

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2. Flow fields
3. Gases, Ionized
4. Probes - Flow
I. Title
II. Hill, Lemmuel L.
III. Series

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