THE DEVELOPMENT OF DIRECT AND ALTERNATING CURRENT GLOW DISCHARGE ANEMOMETERS FOR THE STUDY OF TURBULENCE PHENOMENA IN SUPERSONIC FLOW

Thesis by

Thomas Vrebalovich

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ABSTRACT

A direct current glow discharge anemometer (D.C. glow) was designed and constructed. This instrument was calibrated in low speed flow. Shock tube experiments with the D.C. glow indicated that its frequency response was greater than 50 kc. However, the shortcomings of the D.C. glow such as sputtering and asymmetric burning properties of the discharge became apparent. Therefore, a 700 kc. alternating current (A.C.) glow was designed and constructed. The time stability properties of this instrument were found to be much better than those of the D.C. glow. Since no frequency compensation circuits were used with the A.C. glow, the signal to noise ratio was much higher than that of a hot wire. This A.C. glow was used to survey the profile of the fluctuations in a turbulent boundary layer in supersonic flow at Mach numbers between 1.3 and 4. Power spectrum measurements of the fluctuations in this boundary layer were also made with the A.C. glow. These measurements indicated that there was energy in the spectrum above 100 kc. Finally, measurements of frequencies in excess of 100 kc. were made by the A.C. glow in a sound field produced by a source of single frequency ultrasonic sound waves in supersonic flow.

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I. INTRODUCTION

In recent years the turbulence problem in supersonic flows has gained considerable attention. The most characteristic feature of this problem, in contrast with turbulence in incompressible flow fields, appears to be the strong interaction that may exist between the various types of disturbances found in supersonic flows such as vorticity, pressure, and temperature fluctuations. Very little experimental work has been done so far to explore this interaction, mainly because of the lack of adequate instrumentation.

There are three important criteria for instruments to be used as turbulence detecting devices in supersonic flow. Firstly, since there is more than one flow parameter, the various fluctuating quantities to which the instrument responds must be known and separable if possible. Second, the frequency response of the instrument should be above 100 kilocycles for high speed flows. Lastly, the physical size of the instrument which is in the flow field must be small enough in order that it does not alter the flow field prohibitively and has an adequate spatial resolving power. Of course, there are other factors, such as the time stability of the instrument, which must also be considered.

There have been many attempts to develop instruments that might meet the above criteria. Among those instruments which have been considered are the hot-wire, electric discharges, optical methods, and electromagnetic methods. The most used and most successful instrument in turbulence research is the hot-wire. It has been used mainly in low speed flow. The inertia of the hot-wire to rapid changes in the flow parameters limits its frequency response and requires frequency compensation circuits. The frequency response is limited by the noise introduced by the compensation circuits. Furthermore, due to strength requirements in high speed flows, large diameter hot wires, having lower frequency response than those used in low speed research, must be used. The compromise between strength of the wire and noise level due to the compensation limits the frequency response of a hot wire in supersonic flow. In supersonic flows Kovasznay (Ref. 1) recorded disturbances on his hot wire as high as 70 kc. and found the noise level at 70 kc. to be of the same order of magnitude as the signal level.

In low speed subsonic flows the hot-wire adequately meets the criteria of sufficient frequency response, separability of disturbances of the flow parameters, and small physical size of the instrument. This is not the case in high speed flows. The noise level of the compensated hot wire limits the frequency response greatly, and it is very difficult to interpret the measurements in terms of the flow parameters.

It is thus clear that attempts to develop other instruments for measuring turbulence in high speed flows are warranted. Optical methods have been used by Kovasznay (Ref. 2) in high speed flows but give only integrated effects such as the correlation function of the density fluctuations. Electromagnetic methods, which depend upon the voltage that can be obtained when a conductor or dielectric moves through a magnetic field, have been used successfully in the case of the flow of a conducting liquid (Ref. 3). An extension of these techniques to either air, which is a dielectric, or ionized air has not been developed at this time. Electric discharge techniques, which rely essentially on the influence of a moving air stream upon the discharge, have been given much consideration in regard to their possible use as turbulence detecting devices in recent years. The types of electric discharges which have received the most attention by investigators are the glow and corona discharges. These and other types of electric discharges in gases will be discussed in detail in the next section.

Lindvall (Ref. 4) in 1934 was the first to suggest the use of an electric discharge in an anemometric application. He used a direct current glow discharge to measure both mean air velocities and turbulent motion in the wake of a cylinder. His direct current glow was operated at constant current and the voltage across the glow was recorded. Lindvall's experiments showed that it was possible to use an electric discharge to study turbulence in a moving air stream.

In 1941 a group of investigators in Germany became interested in Lindvall's works and, under the sponsorship of Deutsche Versuchsanstalt fuer Luftfahrt, began studying the use of electric discharges techniques to measure turbulence in air. They devoted their attention to dark current, corona and glow discharges. Their work is currently available in a series of microfilms (Ref. 5) and in an NACA publication (Ref. 6). Fucks' "Tests of a Glow-Discharge Anemometer" (Ref. 7) is among the microfilms and is the best review of the work on glow discharges by the German group. They found that the direct current glow discharge was not suitable for measuring turbulence due to the high noise level of their instrument, excessive electrode sputtering, and instability of the instrument at velocities in excess of 70 meters per second.

The German group abandoned research on the D.C. glow and tried to eliminate the asymmetric burning and sputtering effects of the D.C. glow by using an A.C. glow discharge. Fucks and Schumaker (Ref. 8) used a 500 cycle A.C. glow at low speeds and found that this tended to eliminate sputtering, electrode erosion, and the asymmetric burning effects present in the D.C. glow. They made some mean velocity calibrations with the 500 cycle glow. Their instrument was not suitable for measuring turbulence since it would be extremely difficult to separate the turbulence from the 500 cycle driving voltage. Fucks suggested the use of a high frequency carrier of at least 300,000 kilocycles to remove the difficulty encountered with the 500 cycle carrier and eliminate the effects of asymmetric burning and sputtering. This suggestion in fact is the basis for much of the work of the present writer.

Having abandoned the D.C. glow, and 500 cycle A.C. glow, the German group never attempted to develop the high frequency A.C. glow but instead turned their energies toward the development of corona and dark current types of anemometers. They made some mean velocity measurements and turbulence measurements with the corona and dark current anemometers. They also tested the electrical characteristics, such as the effect of different types of radiation on the sensitivity of a dark current anemometer. Several of the references to this work have been listed. Reference 9 contains an excellent bibliography of the work of Fucks on corona and dark current discharges and their anemometric applications. The German group did much of the ground work in the development of dark current, corona, and glow discharge (A.C. and D.C.) anemometers but never really developed an instrument which could be successfully used to detect turbulence in high speed flows.

While discussing corona discharges, it is well to mention the work of Werner and a group of investigators at the University of Minnesota (Ref. 10). They have done some extensive work in trying to develop a corona discharge anemometer and have met with some success in measuring mean velocities and rms values of fluctuations in the wake of a cylinder. They have operated a corona discharge up to a Mach number of .8 and claim an uncompensated frequency response of 100 kilocycles or more. The recent work of this group indicated that they are in the process of developing an instrument which might meet the criteria of a turbulence detecting device in high speed flows.

In 1948 Mettler (Ref. 11) succeeded in developing a D.C. glow discharge which, contrary to the results of the German group, had a low noise level and was successfully operated in a supersonic wind tunnel up to a free stream velocity of 520 meters per second with no indication that this velocity represented an upper limit. Mettler made some subsonic and supersonic calibrations. He compared the response of the D.C. glow and hot wire to turbulence in low speed flow behind a grid. He tried to overcome the asymmetric burning and sputtering of the glow by using a suitable electrode configuration and electrode material. He also developed a qualitative theory of the response of both glow and dark current discharges to air flow which aids in understanding the effect of the flow parameters on electric discharges.

Little work has been done concerning the frequency response of electric discharges to disturbances in flow parameters. Werner estimates the frequency response of the corona to be at least 100 kc. In 1923 Phillips Thomas (Ref. 12) used a glow discharge for a diaphragmless microphone and estimated its response to be greater than 5000 cycles. Glow discharges have been used with marked success in shock tubes to measure the velocity of the shock wave (Ref. 13), and this indicates that the frequency response must be high. Observation of the voltage rise on the glow in a shock tube in the above tests would have given the frequency response of the glow. This is done in this paper.

Initially, the purpose of this investigation was to continue the work of Mettler on the applicability of the D.C. glow for turburlence investigations in high speed flow. The instrument was to be refined, calibrated, and used for high speed turbulence work. The shortcomings of the D.C. glow (asymmetric burning, electrode erosion, and sputtering) became again apparent and presented an obstacle to this program (Ref. 14). A high frequency A.C. glow, which seemed to offer the possibility of eliminating both sputtering and the asymmetric burning properties of the D.C. glow, was considered. The main object of this paper was then to discover whether a glow discharge, D.C. or A.C., could meet the severe criteria of a turbulence detecting instrument in high speed flow.

To summarize, from the preceding paragraphs it is clear that there is a need to develop an instrument which will meet the criteria established above. The field of electric discharges, especially the glow discharge, offers the possibility of new types of inertialess instruments for turbulence detection in high speed flows.

II. ELECTRIC DISCHARGES IN AIR

The main purpose in this section is to present an elementary discussion of electric discharges in gases with emphasis on the glow discharge and their applicability to fluid mechanics research. The superposition of a transverse airstream on an electric discharge such as the glow at static pressures found in wind tunnels greatly complicates the already complex phenomenon. This problem of the superposition will also be discussed.

A. Types of Electric Discharges

There are four types of electric discharges, any of which might be considered for an anemometric application. These can be illustrated rather generally by the various regions of a typical breakdown curve of voltage vs current between two electrodes (Fig. 1). The electrode spacing and shape, gas pressure and the characteristics of the external circuits determine which type of discharge will result. The different regions indicated on the curve in Figure 1 are not sharply divided and in fact blend one into another in a gradual manner. They are distinguished from each other because, in general, they correspond to different physical mechanisms of producing and maintaining electrical discharges.

1. Dark Current or Townsend Discharge. This region corresponds to voltages of 6 to 12 kv and currents from 10^{-12} to 10^{-9} amperes. In this case, a continuous source of external radiation, such as cosmic rays or x-rays, is required to provide a constant flow of current. A strong electric field is required to transport the ionized molecules of the gas within the electrode gap to the cathode.

2. Corona Discharge. The corona discharge, under atmospheric pressure, is a self-sustaining, high voltage (8 to 15 kv) and low current (10^{-7} to 10^{-6} amp) electrical discharge. In a negative point corona (i.e., the negative electrode is a point) light is emitted near the negative point. For similar configurations and external parameters (pressure, temperature, electrode material, etc.) the corona discharge operates at both higher voltage and current than the "dark current" or Townsend discharge, as is illustrated in Figure 1.

Although sputtering, defined in the section on the glow discharge, is not a problem in the dark current and corona discharge as it is for the glow, the operating voltages for the dark current and corona discharges are so high that insulation difficulties require that a large probe be built to hold the electrodes. This, of course, is unsuitable for aerodynamic measurements, especially in the high speed range.

3. Arc Discharge. The electric arc is a self-sustained discharge having a low voltage drop and capable of sustaining large currents. The electrodes are usually at the boiling temperature of the materials used. The mechanism by which the arc is sustained is also quite different from that of the glow, the difference being the role which thermionic emission plays in the production of ions and electrons. The arc discharge has such a high noise level and high electrode erosion rate that it is probably not suitable for use in turbulence measurements.

4. Glow Discharge. The mechanism of a glow discharge is much more complex than that of a dark current discharge. As opposed to the dark current discharge, a glow discharge sustains itself without any external readiation; furthermore, the field distortion caused by the space charge is an inherent part of the sustained operation of the glow. The essential characteristic of the glow discharge is that the voltage remains very nearly constant with changing current. The voltage and current ranges are from 300 to 700 volts and 2 to 25 ma. These depend on the electrode spacing, configuration, the gas and the gas pressure.

The glow discharge has the advantage of a conveniently and easily managed voltage range. The voltage fluctuations caused by a fluctuating air velocity are sufficient in magnitude to eliminate the need for any additional amplification (Ref. 11). Of major importance (in so far as the aerodynamic applications of the glow are concerned) is the fact that the low operating voltage allows the probe, into which the electrodes are built, to be small.

A definite disadvantage of the direct current glow discharge anemometer is electrode sputtering. The self-sustaining property of the glow discharge is due to the liberation of electrons by bombardment of the cathode with positive ions; this bombardment causes a continual disintegration of the cathode surface. This disintegration process is known assputtering. The process of sputtering causes the loss of material at the cathode and this material is deposited on nearby surfaces. Some of the sputtered material lands on the anode. The amount of sputtering depends on the current in the discharge, the gas pressure, electrode spacing and cathode material. The presence of electrode sputtering seriously complicates the calibration and operating techniques of the glow in an anemometric application.

The above definitions are by no means exhaustive but are sufficient for our present purposes. Detailed discussions of the different types of electric discharge described above are given by Cobine (Ref. 15) and Loeb (Ref. 16).

B. Details of the Low Pressure Glow Discharge

Most of the experimental work on glow discharges has been done at pressures of less than a millimeter. A low pressure glow discharge is easy to observe in a large discharge tube and measurements may be made in the different regions of the discharge. Loeb (Ref. 16) and Cobine (Ref. 15) show the details of voltage, ion, electron, and light distribution in a typical low pressure glow discharge. The distribution of voltage and the appearance and nomenclature of the main parts of a low pressure glow discharge are illustrated in Figure 2. The negative glow region glows brightly and has a high concentration of positive ions which distort the field to cause most of the potential drop to lie between the cathode and the negative glow region. This region of the discharge between the cathode and negative glow region which has the high electric field gradient is referred to as the cathode, or Crookes, dark space, and the voltage change across this region is called the cathode fall or cathode drop. The cathode fall is practically independent of pressure and is nearly equal to the minimum sparking potential. The sparking potential, E, is that voltage necessary to cause a breakdown to an electrical discharge between two electrodes at a given pressure, p, configuration, spacing, d, and cathode material. The minimum sparking potential is the minimum voltage in the curve of pd vs E. The positive ions are accelerated by the cathode fall, bombard the cathode and thereby release electrons. These electrons then create new ions by colliding with air molecules and the process continues.

The Faraday dark space lies between the negative glow region and the positive column which extends almost to the anode (Fig. 2). The voltage gradient in the positive column is very small and the number of positive ions and electrons is nearly equal. The positive column is independent of the conditions at the cathode. When the anode is moved toward the cathode the positive column disappears without any change in the remainder of the discharge. Even the voltage remains fairly constant until the anode reaches the negative glow and dark space regions.

There are certain similarity relations which hold for the glow discharge. If the pressure, p, and spacing, d, are varied such that pd is constant, then the discharges are similar. As long as the cathode is not covered by the discharge, the discharge is a normal glow and the appearance and potential distribution are similar (Fig. 2). These similarity relations hold for different regions of the discharge such as the dark space. At constant spacing then, the positive column disappears at the anode as the pressure is decreased.

The area of the cathode which is covered by the discharge is proportional to the current and inversely proportional to the square of the pressure for flat electrodes. When the entire area of the cathode is covered, an abnormal glow discharge (Fig. 1) results and the laws of similitude no longer hold. Due to the excess current which causes the abnormal glow, the cathode fall is greater, the dark space is thinner, and the voltage across the discharge is higher than in the normal glow.

The preceding discussion of the mechanism and character of the low pressure discharge will aid in the understanding of the high pressure glow and the effect of a transverse airstream on the glow.

C. High Pressure Glow

Although one may contend that a high pressure (atmospheric) glow is more nearly an arc than a glow, due to the fact that the mechanism of electron emission for the glow and arc might not be different at high pressures, the voltage, current and microscopic details of the high pressure discharge are believed to be similar to the low pressure glow. Except for the fact that the positive column seems to have definite boundaries, the high and low pressure discharges look similar and one would expect the similarity relations to be valid for the high pressure glow. Measurements of voltages and charge concentrations in the high pressure glow discharge are difficult since the length of the discharge has changed from say one meter to one millimeter with the increase in pressure. With the very small electrode spacing, one would expect that the electrode shape will be very important in the determination of the voltage distribution and current density in the discharge. Even in the low pressure glow, the cathode shape affects the current density.

D. Superposition of Transverse Air Stream on the Glow

In the following discussion interest will be centered on the observable features of a glow discharge between two electrodes in a transverse airstream and will refer to observations made during experiments which were performed. When the glow was placed in an airstream, a number of effects were observed. The glow tended to burn on the downstream side of the electrodes and the burning position seemed to be a function of electrode shape, spacing and air velocity. Increases in air velocity or electrode spacing moved the glow downstream between the electrodes. According to Mettler (Ref. 11), the change in voltage with changing air velocity is due, in part, to the loss of positive ions. It was also noted that the discharge tended to lengthen with increasing air speed, and from the similarity relations discussed above, one would expect most of the lengthening to occur in the positive column. At constant current in the discharge then, the voltage would increase due to the lengthening of the discharge. With very small spacing, the positive column tends to disappear and the problem of what happens to the dark space in an airstream presents itself.

The previous discussion was mainly concerned with the effects of the airstream on a direct current glow, but would probably apply to a high frequency A.C. glow also. In the A.C. glow, two negative glow regions were visible. At small spacings or diminishing pressure they were very difficult to distinguish. The positive column was not noticeable except at large spacings. The A.C. glow acted just like the D.C. glow in the airstream. The A.C. glow tends to go out on each voltage reversal. It does not completely deionize on each reversal so that the peak in voltage necessary to start the glow is lower than that which would be necessary to strike the glow if there were no ionized material in the gap. This process does not seem to affect the character of the visible discharge.

The A.C. glow responds in the same manner as the D.C. glow to the airstream. As will be found in succeeding sections, the voltage across the D.C. glow increases with velocity and this holds true for the A.C. glow also.

E. Temperature and Density Effects on the Glow

The preceding discussion indicated that the velocity of the airstream affected the glow. Besides velocity fluctuations, there are fluctuations in density, pressure, and temperature in high speed flow fields. If the glow is to be used effectively, it is of primary importance then to determine in what manner the glow responds to these other fluctuating quantities. Therefore, some experiments have to be devised for this purpose.

The D.C. glow was placed in a pressure tank and the pressure was varied from 100 to 1500 mm Hg. absolute. Figure 3 shows the results of this experiment. As has been discussed before, the discharge lengthens as the pressure is decreased. In the case of the smallest gap, .002", the anode got into the negative glow and dark space regions as the pressure was decreased. The cathode also tended to become covered by the negative glow and perhaps produced an abnormal glow as the pressure was decreased. For the .005" gap the anode probably remained in the Faraday dark space region (Fig. 2) as the pressure was decreased, and this would account for the small voltage change with pressure. With the largest gap, the anode is clearly in the positive column. From Figure 2 and the similarity relations discussed, one can see that decreasing the pressure has the same effect as moving the anode toward the cathode.

An attempt was made to determine the effect of density on the glow in a moving media. Opportunity to do this presented itself during some supersonic wind tunnel experiments with the A.C. glow (Section V). The pressure level of the wind tunnel was changed and the A.C. voltage and current changed in the A.C. glow at a given supersonic Mach number. Unfortunately, the current in the discharge could not be controlled. Therefore, the data was not conclusive in so far as determining which flow parameters affect the discharge.

Mettler found that the effects of temperature on the glow were not appreciable. Ion mobility, which is the ratio of the average ion velocity in the discharge to the electrostatic field strength and is inversely proportional to gas density, should give an indication of the effect of temperature on a discharge. In fact, from positive ion mobility data in Cobine (Ref. 15) and Loeb (Ref. 16), one would not expect any voltage change with temperature at constant density, since mobility is not affected very much by temperature changes.

In low speed subsonic flow, both the D.C. and A.C. glow discharges respond to velocity, since there are no other parameters which vary. It seems then that the D.C. and A.C. glow respond to both velocity and density in supersonic flow. There is hope that the parameters can be separated, but as will be discussed, experiments will have to be devised to make this separation practicable.

III. ELECTRODES

A. Electrode Material

There are many criteria to be considered in choosing a proper electrode material. It is important that materials be chosen which give maximum time stability to the glow discharge, that is, minimum sputtering and noise level in the discharge. In order that calibrations change little while the glow is burning, it is essential that the material be fully resistant to oxidation. The material should have high thermal conductivity, specific heat and electrical conductivity. This would help to keep the electrode temperature near the ambient temperature of the airstream and eliminate the problem of melting the electrodes for a given glow current. These physical properties would also minimize the transient cooling effects of a turbulent (fluctuating) airstream which might show up as a voltage fluctuation across the two electrodes in a manner similar to that found in a hot wire. The material must also be one that can be formed or machined into given geometry and one which can be given a good surface finish.

Mettler and Fucks tested many materials to find which ones would meet the criteria established above. Among the materials tested were aluminum, copper, iron, tungsten, platinum, platinum-rhodium, Duralumin, and elkonite. Lindvall, Mettler, Fucks and this writer found platinum to be the best material to use as electrode material. Fucks and Schumacher had some success with palladium and iridium electrodes. It was also found that tungsten and tantalum could be used satisfactorily for the anode when platinum was used for the cathode in the direct current glow. Almost all of the materials considered were tested in air at atmospheric pressure, and experience with low pressure discharges indicates that some of these materials might work very well at the low static pressures encountered in supersonic wind tunnels. For example aluminum and tantalum electrodes operate with much less sputtering than platinum at low pressures. Platinum with a purity of 99.8 percent was used exclusively in the present research.

B. Electrode Shape

For the experiments in subsonic flow, platinum wire was attached to steel drill rod. The platinum tipped ends of the electrodes were made into several distinct shapes. Flat ended electrodes were made by holding the electrodes in a special jig (Fig. 4) in a vertical position and then rubbing them across fine oilstones and polishing compounds. Hemispherically shaped electrodes were cold forged on the tip of an electrode by holding the electrode in a special jig (Fig. 5) and striking a die. These electrodes were then polished in a jewelers lathe. By the above two methods, geometrically similar electrodes were easily produced. Partially rounded electrodes were made in a jewelers lathe using fine sandpaper and polishing compounds. Another method of making spherical points is to strike an arc between two electrodes. The arc melts the platinum, and surface tension causes a sphere to form on the end of the platinum wire. This technique was used successfully by Fucks. Geometrically similar electrodes were more easily produced by forging and sanding than by this latter method. Platinum proved to be workable and, as stated above, fairly reproducible electrode shapes could be made.

The electrodes used in supersonic flow were more difficult to fabricate. They were a part of the probe, whereas the electrodes described above could easily be replaced, adjusted, polished and shape changed.

The details of the electrodes used in supersonic flow will be described in the succeeding sections on the direct current glow and alternating current glow.

C. Electrode Surface Conditions

From experiments performed by Mettler and others involving electrical discharges in gases, it seemed advisable to make the electrodes as smooth as possible. Irregularities in the electrode surface induce local effects in the burning of the glow which may affect the stability of the glow. Bumps or pits, undetectable except under a microscope, in the surface of the electrode cause discontinuities in the electrical field gradient which, in the case of a point, cause a concentration of electron flow in this region. Such an effect will raise the local temperature, melt the metal, and cause material transport from the point -- this is one of the factors that causes sputtering.

In order to reduce the above mentioned effects, several polishing techniques were tried. Flat electrode surfaces were polished on oilstone, on glass with a levigated alumina compound, on glass with jewler's rouge, and on hard silk covered glass with levigated alumina. Examination of the electrode surface under a microscope indicated that polishing on silk-covered glass with levigated alumina gave the best surface.

After cold forging, the hemispherical electrodes were very smooth, and, in order to insure the best possible surface, they were polished in a jeweler's lathe by holding levigated alumina impregnated silk against the rotating electrodes. The surface obtained in this way was as good as that obtained on the flat electrode surfaces. For the A.C. glow it was found that even with poorly polished electrodes, the burning of the A.C. glow tended to polish the electrodes after a very short time. In order to make sure that no impurities were left on the electrode surfaces, they were cleaned with carbon tetrachloride and dilute nitric acid. A careful polishing procedure as outlined above produced electrodes which resulted in an easy starting and stable glow discharge.

IV. D.C. GLOW

A. Equipment

1. Wind Tunnel. An eight inch open jet wind tunnel was used for all of the low velocity calibrations with the D.C. glow. The tunnel had a velocity range of five to thirty meters per second. The D.C. glow probe was mounted on a traversing stand by means of which the probe could move both along the axis of the jet and normal to this axis. A pitot tube and a Zahm type micromanometer, capable of measuring pressure differences to 0.01 millimeters of alcohol, were used to measure the free stream air velocity in the jet. The pitot tube was mounted on the traversing stand near the glow probe. The glow probe and pitot tube are shown mounted on the traversing stand in front of the jet in Figure 6.

2. Electronic Equipment. A block diagram of the basic components used in the D.C. glow circuits is shown in Figure 7. A power supply and current regulator (Fig. 8 and 9) provided the source of voltage for the D.C. glow. The power supply provided the high voltage necessary to start a glow discharge between two electrodes, and the current regulator maintained a constant current through the glow. The D.C. voltage source could supply 2000 volts for starting the glow and then maintain constant current between 5 and 25 milliamps. as the voltage across the glow varied from 300 to 600 volts. The noise level of the regulator was .0018 volts with the glow operating. In order that small differences in the D.C. voltage across the glow might be measured accurately for calibration, a bucking system was used (Fig. 8). To observe the fluctuations in the voltage across the glow while

it was in a turbulent air stream, it was necessary to isolate the measuring circuits from the glow by use of a capacitor. The mean square of the fluctuations and other simultaneous measurements could be taken with no further amplification of the fluctuating voltage. Figure 10 shows the D.C. equipment as it was used for low speed tests.

The circuit employed by Mettler (Ref. 11) is similar to the one described above.

3. Probes. Two probes (Fig. 11) were used in the direct current glow experiments. One was used for high velocity and the other for low velocity. The high velocity probe had platinum tipped steel electrodes and the gap between the electrodes could only be adjusted by bending the steel wires. The high velocity probe was designed for minimum flow interference. The low velocity probe also had platinum tipped electrodes which could easily be adjusted by using a gap-spacing jig and a microscope comparator (Fig. 12). The distance between the electrodes (gap) can be set to one ten-thousandth of an inch (.0001") by using a Bausch and Lomb optical microscope comparator. The structural rigidity of both probes seemed sufficient to hold the gaps constant while the probes were in an air stream.

B. Experimental Results

1. Calibration. Some of the descriptions of the methods of calibrating a D.C. glow probe in low speed flow which can be found in Mettler's thesis (Ref. 11) and in a preliminary report on the glow anemometer by Morgan and Vrebalovich (Ref. 14) will be repeated here for the sake of completeness. A typical low velocity calibration

curve (Fig. 13) was obtained once the glow had been established in the air stream by varying the velocity of the jet (Fig. 5) in small steps and observing the change in the D.C. voltage across the glow. This procedure gave a calibration curve of voltage across the glow vs free stream velocity. This calibration could then be applied to any turbulence measurements which might be made with this glow configuration. Due to the time stability of the glow which will be discussed later and the impossibility of exactly duplicating a given glow configuration, a calibration curve has to be made with each set of electrodes just before turbulence measurements are to be made.

The calibration curves are easily used to determine velocity fluctuations in turbulent measurements. For example, in the calibration curves given in Figure 13, one must operate the glow at a mean velocity where the calibration curve is both fairly linear and steep. Then, in order to convert voltage fluctuations to velocity fluctuations, one must multiply the rms fluctuating voltage, ΔE, by the inverse of the slope of the calibration curve, $\Delta U/\Delta E$, at the mean velocity U, at which the turbulent measurements are being made. Of course, the above procedure assumes that at the fluctuation frequencies under consideration, the dynamic response of the D.C. glow to velocity fluctuations is the same as the equilibrium response, i.e. the calibration curve. From the above it is clear that the calibration curve enables one to convert fluctuating voltages to fluctuating velocities.

In practice, the process is not as complex as the preceding paragraph might indicate. One decides at what mean velocities measurements are to be made. A configuration, gap, and current are chosen such that the glow will be operating in a linear region of its calibration curve and in a region of high sensitivity. A complete calibration curve need not be made since our interest is only in one region of the curve. Therefore, the calibration need be made only in the region of interest and this would involve plotting only several points of the calibration curve to determine the slope of the curve.

2. Glow Sensitivity and Electrode Shape. In low velocity flow there are several parameters which may be changed to increase the sensitivity to velocity disturbances. The electrode spacing may be increased and this tends to steepen the calibration curve slope (Fig. 13). Decreasing the current in the glow also tends to increase the sensitivity (Ref. 11). The shape of the electrodes may also be varied to take advantage of the asymmetry in the D.C. glow discharge. The electrodes may be shaped so that they cause the anode part of the discharge to be focused on one spot (Figs. 13 and 14 - asymmetric electrodes) or they may be shaped in order to lengthen the discharge as the air velocity is increased. The effect of electrode shape on the sensitivity of the glow to velocity disturbances is shown in the calibration curves of Figure 14. These curves are plots of E-Eo vs U, where E is the voltage across the glow at the air stream velocity U, and Eo is the voltage across the glow at U = 5m/sec. The curves were plotted in this manner for ease of comparison. It will be noted that the calibration curves for the hemispherical and asymmetric points show equal sensitivity to velocity disturbances but over a different mean velocity range. That is, the asymmetric electrodes could be

used in a higher velocity range than the hemispherical electrodes in this case. The velocity sensitivity and the air velocity at which measurements are to be made is determined by electrode spacing, glow current, and electrode shape.

3. Frequency Response from Shock Tube. A standard technique for determining the frequency response of an instrument is to find its transient response to a step function on its input. A shock tube provides an excellent step function in velocity and pressure which may be used to determine the frequency response of an instrument placed in the shock tube. A shock tube was built and fitted with electronic instrumentation. The D.C. glow probe was placed at the mouth of the shock tube. The diaphragm was broken and as the shock passed the glow probe, the voltage across the glow changed as is illustrated in Figure 15. The rise time of the shock wave was less than a microsecond and took approximately two microseconds to pass over the glow. The velocity behind the shock was 60 feet per second and the pressure rise was about one-half psi. A single sweep of one-hundred microsecond duration on a Tetronix 512 was recorded on linagraph ortho film as the shock passed the probe. The rise time of the voltage across the glow was approximately seven microseconds (Fig. 15) and this indicates a frequency response in excess of 50,000 cycles. It was felt that the limit in the frequency response observed was due in part to the pickup circuit response rather than the glow discharge itself. From ion mobility data one would expect the frequency response to be higher than this. An average positive ion velocity of approximately 1000 meters per second is attained at atmospheric pressure in a .003" gap.

This corresponds to 10^{-8} seconds for an ion to cross the gap.

The glow probably reacts differently to disturbances which are superimposed on a mean flow than to disturbances with no mean flow as is the case in the shock tube. A method of obtaining single frequency high frequency disturbances in high speed flow will be discussed in the A.C. glow results.

C. Shortcomings of the D.C. Glow

The effects of sputtering and the asymmetric burning properties of the D.C. glow introduced anomalies in the calibration curves that made it very difficult to use the glow for turbulence measurements. Material sputtered from the cathode tended to introduce instabilities which would cause the glow voltage to change markedly during a calibration run. Some of the sputtered material would stick to the anode and form small bumps on it. With no air flow a large bump was formed on the anode and eventually shorted out the discharge. The cathode developed a shiny circular depression in the area where the glow tended to burn. The magnified surfaces of a pair of electrodes with flattened ends is shown in Figure 16. These electrodes were used for one and a half hours at 10 ma. in an air stream.

The portion of the cathode which has the circular depression and the portion of the anode which has the concentration of small pits and bumps are in the downstream portions of the electrodes. High current densities in the glow accentuated the pits and bumps on the electrodes and higher air velocities tended to reduce the bumps by blowing out the sputtered material. The electrodes show the effects of the asymmetric burning property of the glow (Fig. 16). The erosion of the cathode tended to change the gap between the electrodes. The combination of sputtering and asymmetric burning of the electrodes caused instabilities, scatter, and voltage steps in the calibration curves as is shown in Curve 1, Figure 17. Curve 2, which was obtained with the same configuration as curve 1, shows only the scatter in contrast to the voltage steps of curve 1.

Calibration curves tended to have some hysteresis (Ref. 11 and 14) with respect to time when the calibration curves were repeated. Even though there was scatter and discontinuities in the calibration curves, the slopes of the calibration curves do not change appreciably at a given mean velocity. Rapid calibration in the mean velocity range of interest and rechecks of calibrations, after turbulence measurements have been made, provided a check of the stability of the D.C. glow.

Turbulence measurements made by Mettler and this writer were not always reliable due to the burning properties of the D.C. glow described in the preceding paragraphs. It was felt by Morgan and this writer (Ref. 14) that the best solution would be to make the glow burn in a symmetrical manner. This will be discussed in the next section.

Supersonic measurements with the D.C. glow were attempted by both Mettler (Ref. 11), and this writer. Mettler's results indicated that it was possible to maintain a glow discharge in supersonic flow. Again because of the shortcomings described in the preceding sections, it was felt that effort should be expended in perfecting the nature of the discharge rather than make further attempts to utilize the D.C. glow in a supersonic air stream.

V. A.C. GLOW

As the shortcomings of the D.C. glow became apparent, consideration was given to either switching the D.C. glow at relatively low frequencies (less than one cycle per second) or using a high frequency A.C. glow (greater than 100 kilocycles). A discussion of these preliminary attempts will be found in Reference 14. The high frequency A.C. glow which was finally constructed caused a symmetrical glow discharge which burned uniformly with minimum sputtering. The electrodes looked polished and were not pitted or badly eroded after an hour of running. Polishing techniques were thereby not as critical as they were for the D.C. glow. The effects of sputtering and of the asymmetric burning properties on the electrodes which were troublesome in the case of the D.C. glow seemed to be overcome by the use of the A.C. glow.

A. Equipment

1. Wind Tunnel. Some preliminary tests of the A.C. glow were made in an open jet wind tunnel at velocities up to 100 meters per second. Most of the data on the A.C. glow which is presented in this paper was obtained in the 20-inch supersonic wind tunnel of the Jet Propulsion Laboratory. At the conclusion of tests in the 20-inch wind tunnel, check runs were made in the 12-inch wind tunnel of the Jet Propulsion Laboratory and these will be discussed in succeeding sections. The glow was run simultaneously with other models in the tunnel. During most of the tests, the flow about the models that were in the tunnel did not interfere with the glow probe. The probe was mounted in the ceiling of the 20-inch supersonic wind tunnel (Fig. 18) on a vertical traversing strut which could move the glow probe through the boundary

layer on the top wall of the tunnel into the free stream. Part of the tests were conducted with the other model mounted on a side wall balance which prevented schlieren pictures from being taken, and part of the tests were conducted with the model mounted on the main model holding strut. During the tests the wind tunnel was run at Mach numbers between 1.33 and 4.06, at approximately atmospheric supply pressure, and static pressures between 15 and 300 mm Hg.

2. Electronic Equipment. A functional block diagram of the basic components in the A.C. glow is given in Figure 19. All of the electronic equipment to be described in the following paragraphs is shown as it was used in Figure 20.

3. Transmitter. A GO-9 Navy transmitter (Ref. 17) was the source of the high A.C. voltage. Only the low frequency (Intermediate Frequency) section of the transmitter was used; it had a standard circuit as shown in Figure 21. A carrier freqrency of 700 kc. was employed because it was the highest frequency attainable on the low frequency part of the transmitter and would enable amplitude modulation frequencies of 100 kc. or more to be detected on the 700 kc. carrier frequency. Except for the installation of a filter on the transmitter power supply, the transmitter needed no modifications. The A.C. glow tended to arc and spark unless a current limiting resistance or capacitance was used in series with the glow in the high voltage lead near the electrodes. Since physically small high voltage capacitors were available, a 10 micromicrofarad capacitor mounted in the probe was used as a current limiter to make a stable glow discharge.

The capacity and inductance of the coaxial lead to the glow probe were made to resonate at 700 kc. with the antenna coil by adjusting the Antenna Loading and Antenna Tuning controls. It was thereby possible to obtain the high voltages necessary to strike the A.C. glow. The antenna coupling was increased until the glow struck, and then the antenna coupling was used to control the current in the glow. The transmitter was able to supply 7 to 20 ma. (milliamperes) for the glow at 300 - 500 volts rms (root mean square).

Unlike the D.C. glow system there were no provisions for maintaining a constant current discharge in the transmitter supplying the high voltage A.C. Fortunately, the current in the glow tended to remain constant as the glow was moved through the boundary layer at all Mach numbers below three. This was caused by electrical characteristics of both the transmitter and the glow discharge.

4. Remote Cathode Follower. Since a 700 kc. glow is a high impedance discharge, it is very difficult to measure the voltage directly across the glow. As discussed in the section on discharges, the A.C. glow has a starting peak in the voltage as the voltage changes sign which makes the impedance even higher than would be present for a 700 kc. pure sine wave. Thus, any instrument which is placed across the electrodes would stop the glow, and any instrument placed across the electrodes before the glow was struck would prevent it from glowing. Therefore, it was decided to make the effective capacity of any system placed across the glow less than one micromicrofarad, (i.e. high impedance). This was done by building a capacity divider. The divider consisted of approximately a 1/4 $\mu\mu$f (micromicrofarad)

capacitor in series with the input capacity (paralleled by the grid resistance) of the cathode follower (6T4). The 1/4 $\mu\mu$f capacitor had to be placed very near the glow because any coaxial cable leading from the glow would have placed enough capacity across the glow electrodes to prevent a proper discharge. The tube could have been placed far from the glow, but the lead capacity to the grid of the tube paralleled by the tube capacity would then reduce the A.C. voltage into the tube too much. In some applications the tube will have to be outside of the wind tunnel and thus the gain of the modulation will have to be increased.

The circuit of the glow probe and the remote cathode follower is shown on the left side of the circuit diagram of Figure 22. The capacity divider and the cathode follower system provide a scheme whereby the signal voltage across the glow may be changed to a low impedance signal. This then enables one to measure the voltage across the glow at a position far removed from the glow probe without destabilizing the glow or distorting the signal being measured. The remote cathode follower is shown in Figure 23 and is shown being assembled to the strut and glow probe in Figure 24.

5. Modulation Amplifier and Carrier Voltage. The attenuated glow voltage signal from the cathode follower is received by the modulation amplifier (Fig. 22). The carrier, which is amplitude modulated by the fluctuations in the air stream which strike the glow discharge, is rectified and filtered. Two filters are used in the system. The first is a low pass 200 kc. filter and the second is a 700 kc. band elimination filter. Due to the carrier frequency, any

modulation frequencies above 100 kc. will tend to be attenuated and distorted in wave shape. This is the only limitation on the modulation frequencies since the amplifier has an almost flat frequency response from less than 20 cycles to 200 kc. (Fig. 25). The gain of the amplifier is about 500 and gives an output voltage which is approximately one-half the original modulation voltage on the glow. The attenuation factor of the signal across the glow by the capacity divider and cathode follower is about one-thousand. The output of the modulation amplifier was fed to vacuum thermocouples whose output was read on a D.C. microammeter. This gave the mean square of the fluctuating output voltage. A signal of 3.5 volts rms of modulation at the glow probe gave a full scale output of 50 microamperes on the microammeter. The magnitude of extraneous signals on the output, such as carrier frequency and the ripple from both transmitter and modulation amplifier power supplies,was approximately 5 percent of the actual fluctuation output voltage. This 5 percent value did not show on the mean square output meter. The amplifier noise was negligible. The fluctuating output voltage could also be fed to other instruments such as wave analyzers and an oscilloscope.

The carrier voltage was measured by the system shown in the lower part of Figure 22. The carrier voltage was rectified on a full wave germanium diode bridge rectifier in order that this voltage measurement would be insensitive to the percentage of carrier modulation. With the bucking voltage system shown, changes in the carrier voltage up to 100 volts rms could be read on a 5 mv. (millivolt) Brown indicating potentiometer with no change in the bucking voltage settings.

For example, by bucking out three hundred volts, the 5 mv. Brown would then read in the 300 - 400 volt range to within 0.1 percent. The system was calibrated by modulating a 700 kc. carrier with a known percentage of modulation and introducing this modulated carrier at the probe. Therefore the output of the modulation amplifier was a known percentage of the carrier voltage which was measured on the 5 mv. Brown. Having calibrated the system in this manner, it was not important to make an accurate voltage calibration of the system. The current in the glow was found by measuring the carrier voltage across a one hundred ohm resistance in the ground lead of the A.C. glow discharge. This system could give only relative values of current due to the interlead capacity in the glow probe.

6. Harmonic Wave Analyzers. Two wave analyzers were used to obtain the power spectrum of the fluctuations. A Hewlett-Packard Harmonic Wave Analyzer, Model 300-A, was used in the frequency range of 30 cycles to 16 kc. The analyzer had two effective band widths, 11 cycles and 42 cycles, which were used. The analyzer output was fed into a vacuum thermocouple which was used with the microammeter described above. The analyzer was calibrated using a sine wave output from an audio oscillator. A Sierra Wave Analyzer, Model 121, which had a frequency range of 15 to 500 kilocycles was also used. It had an effective band width of approximately 220 cycles. A cathode follower was added to its output in order to use the vacuum thermocouple system described above. Again, this analyzer was calibrated using a sine wave from a signal generator. Therefore, spectrum measurements could be made from 30 cycles to over 200 kc. by using the two wave analyzers.

7. Probes, Electrodes and Vertical Traversing Struts. Since there were both high frequencies and high voltages in the A.C. glow, the problem of a proper glow probe configuration arose. This was complicated further by the fact that the probe and electrodes had to be used in a supersonic airstream. In order that the interlead capacity be minimized, the current limiting capacitor was placed in the probe. A machinable polystyrene, CP-2, was used for the probe material. Electrode leads were spaced as far apart as possible. A total head tube was also attached to the probe. The electrodes were mounted in polystyrene and were easily removed and replaced. One of the probes, a current limiting capacitor, and several electrodes are displayed in Figure 26. An assembly of the probe and a vertical traversing strut is pictured in Figure 24. A typical probe on one of the struts is shown installed in the ceiling of the 20-inch supersonic wind tunnel in Figure 18.

The removable electrode holders had platinum tips (.030" diameter) which were mounted in steel rods in a similar manner and configuration as were those used with the D.C. glow (Fig. 11). Circular, wedge, and diamond shaped platinum electrodes cross sections were tried. The electrode surfaces were almost flat and parallel. Electrode gap spacings of .002" to .005" were used. The most successful spacing at all Mach numbers was approximately .0025". The electrode gaps were adjusted by bending the electrodes. The gaps were measured with the microscope comparator described in the D.C. glow section.

Two vertical traversing struts were used, one with three inches and the other with twenty inches of travel. Figure 24 shows the former and Figure 18 shows the latter. Similar probes were used with both struts. The small strut was used when a contractor's model was mounted on the main model support system and the large strut was used with the model mounted on the side wall. Each strut had a large hole bored in it to accommodate the remote cathode follower (Fig. 24). Schlieren pictures of the glow probe in the boundary layer and free stream are shown in Figure 27.

B. Experimental Results

1. General. The 700 kc. glow was operated successfully at Mach numbers between 1.33 and 4.06. Most A.C. glow measurements had to be made within approximately one-half hour of continuous wind tunnel running time.

The electrode spacings had to be less than .003" at most Mach numbers. If the spacing was larger than this, it took more current to operate the glow and this caused high electrode erosion rates. At the Mach numbers above 2.55, a large spacing, which required a high current, caused the glow to glow along the electrodes. In this case the glow would burn along the downstream side of the electrodes as much as one-quarter of an inch from the gap. This was due in part to the low static pressure in the wind tunnel (e.g., static pressure = 15 mm Hg at M = 4.06). Although all of the electrode cross sections were run at most Mach numbers during the test, the cross section, spacing, and surface of the electrodes were most critical at the high Mach numbers. If the electrodes were not flat or properly aligned, the glow would either burn out of the gap or have to be run at too high a current. The glow required more current to burn steadily without being blown out as the Mach number was increased and as the pressure level of the tunnel was increased at a given Mach number.

By observing the changes in the mean square voltage of the fluctuations, the carrier voltage, and current in the glow discharge at a given position in the boundary layer, the time stability of the glow for a given current and configuration could be determined. Of greatest interest was the change in sensitivity which could be determined from changes with respect to time of the mean square of the fluctuations when the probe was held in a fixed position. During some of the runs, the voltages and current were fairly constant for more than one-half hour. Some of the electrodes needed no polishing or adjustment after more than one hour of running. In each instance of good time stability, in which the mean square of the fluctuations remained fairly constant or was repeatable when the probe returned to the same position in the boundary layer, the gap was small (.002" to .003") and the current was low (7 to 10 ma.). Unfortunately, the time stability of a given electrode configuration could not be predicted since it is difficult to reproduce a given configuration of electrode cross sectional shape, electrode surface shape, and electrode spacing. Anomalies which arose with each type of measurement will be discussed in the succeeding paragraphs.

The aerodynamic problem of the glow electrodes in a supersonic airstream was considered only in a qualitative way. For example, the wedge and diamond shaped electrodes caused the glow to burn near the downstream side of the gap and this would indicate a higher air velocity or mass flow between the electrodes than was present for the round electrodes. The primary interest at this point was to observe only the effect of the supersonic airstream on the voltage and current of the discharge for a particular electrode configuration, rather than be concerned quantitatively with the details of both the discharge and the airflow in the glow. As has been stated in the section on discharges, the fluctuating quantities in a supersonic airstream to which the glow responds are not known at this time. Since it is not certain to which fluctuating quantities (pressure, density, velocity, and temperature) or combinations of these quantities the glow is responding in a supersonic airstream, the disturbances that the A.C. glow picks up in the air stream will be called "fluctuations".

2. A.C. Glow Sensitivity. As in the D.C. glow, electrode surface shape, electrode spacing and glow current determine the sensitivity of the A.C. glow to fluctuations. In high speed flow, electrode cross section also affects sensitivity as was discussed in the last paragraph.

The curves presented in Figures 28 and 29 were obtained by varying the current in the glow while the probe was 0.1" from the wall in the turbulent boundary layer. During this run, the tunnel was operated at lower supply pressures than usual and fairly low A.C. glow currents could be attained. The highest current (10 ma.) used at this low supply pressure was low enough to have minimum erosion effects on the electrodes. The curve in Figure 28 shows how the 700 kc. carrier voltage varied with the current. The points not on the curve and denoted by tagged symbols were repeated points during the survey. The scatter is less than 0.2 percent and is due in part to the drift in the bucking voltage supply during the run. One of the characteristics of glow discharges is that the voltage does not change very much with large changes in current and this was the case here (Fig. 28). After the cathode gets completely covered by the glow, the voltage across the glow will increase as the current in a glow increases. This may account for the increasing voltage with increasing current. At very low currents the discharge tends to be lengthened by burning downstream partially out of the gap and thus accounting for the increase in voltage at very low currents.

More important than the effect on carrier voltage is the effect on sensitivity of the current in the A.C. glow discharge. The sensitivity of the glow discharge to the fluctuations in the airflow is important since the higher the sensitivity, the larger the fluctuating voltage available for measurements. It is clear from Figure 20 that the glow is most sensitive to the fluctuations in the flow at low currents in the glow. The units of the "Mean Square Fluctuations" axis (Fig. 29) are readings on the microammeter used with the vacuum thermocouple but can be related to the mean square of the fluctuating voltage on the glow. As can be seen from the repeated points, the sensitivity was relatively constant with respect to time. The sensitivity of both the A.C. and D.C. glow varies inversely with the current in the glow.

3. Fluctuations in the Boundary Layer. The A.C. glow discharge probe was moved through the 20-inch supersonic wind tunnel turbulent wall boundary layer and the carrier voltage and mean square voltage of the fluctuation (i.e. the energy of the fluctuations) were recorded.

When time allowed, the procedure was repeated several times during a run. One of the runs is presented in Figures 30 and 31. Most surveys showed more scatter than the one presented in Figure 31. During some boundary layer surveys the glow was so unstable that the free stream measurements of fluctuation energy were actually higher than those in the boundary layer. The energy of the fluctuations would seemingly increase with respect to time independent of position in the boundary layer. Sometimes the fluctuation measurements would repeat well several times and then drift to higher and higher values.

Figure 30 shows how the glow carrier voltage increased as the glow was moved into the free stream. The boundary layer at M = 1.97 is about one inch thick. The A.C. voltage on the probe also indicates that the boundary layer is approximately one inch thick. Qualitatively, the A.C. voltage across the glow probe increases in the same manner that the mass flow, velocity, and density increase as the probe is moved through the boundary layer into the free stream.

In this investigation of the applicability of an A.C. glow discharge to measurements in supersonic flow, it was felt that the response of the glow to fluctuations in the boundary layer was the important feature of the test. Therefore, the measurement of the fluctuation energy distribution in the turbulent boundary layer was undertaken. The response of the glow to the fluctuations in the boundary layer is shown in Figure 31. The energy of the fluctuations increases and then decreases as the probe is moved through the boundary layer into the free stream. This is due to two effects: Firstly, the wall has a capacity effect with the glow probe and tends to bypass the voltage across the glow as the probe is moved very near to the wall; second, the fluctuation energy does drop off in the boundary layer very near the wall. Kovasznay (Ref. 1) found that the turbulent velocity fluctuations acted in a similar manner in a supersonic boundary layer. At this point it should be noted that during these profile surveys through the boundary layer the sensitivity of the glow was not necessarily constant throughout the large velocity and density differences in the boundary layer. The slope of the calibration curve, if such a curve could have been obtained, might not have been constant. It is then clear that the response of the glow to the mean square of fluctuations is, in a qualitative way, comparable to the actual energy of the fluctuations (turbulence, perhaps) that would be expected in a supersonic turbulent boundary layer.

On an oscilloscope, observation of the fluctuating voltage across the glow probe indicated that the wave form near the wall is asymmetric but becomes symmetric then asymmetric in the opposite direction as the probe is moved from the wall to the free stream. Since schlieren pictures could not be taken during most of the survey, it was not clear whether weak shock waves emanating from the tunnel wall caused this effect. Near the wall, similar results have been observed in the asymmetry of the wave shape with a hot wire. During a check run made in the 12-inch supersonic wind tunnel at a Mach number of 1.97 and a supply pressure of 800 mm Hg., oscilloscope pictures were taken as the glow was moved through the boundary layer; and Figure 32 shows the asymmetry in the fluctuation wave shape at .527 inches from the wall in a boundary layer approximately .80" thick.

At this Mach number, several electrode configurations were used and all gave similar results. The rounded cross sections gave the greatest time stability due to the large electrode surface area.

4. Power Spectrum of Fluctuations. One of the primary criteria of any instrument which is to be used to observe fluctuations in supersonic flow is that the frequency response of such an instrument must be high in order to make power spectrum measurements. The power spectrum is the fraction of the total energy of the fluctuations between f_o and $f_o + \Delta f$, where f_o is a given frequency and Δf is a small increment of frequency (Ref. 18). With the two wave analyzers described previously, the power spectrum of the fluctuations was measured. Power spectrum measurements were made at several Mach numbers and stations in the boundary layer. A check run in the boundary layer of the 12-inch supersonic wind tunnel provided the best results. Spectrum measurements were made at two stations in the boundary layer (y = .14" and .54" from the wall) and the data is presented in Figure 33. It should be mentioned again that the sensitivity of the glow, which changed during each spectrum measurement, is not necessarily the same for both of the curves presented in Figure 33. From the power spectrum measurements (Fig. 33) in the boundary layer in supersonic flow, it is clear that much of the energy of the fluctuations lies in the high frequency range. It is also clear that the A.C. glow discharge was able to pick up some energy at frequencies above 100 kilocycles.

The units of power are such that the area under the spectrum curve is equal to the mean square of the fluctuating voltage at the output of the amplifier. Each point on the curve was found by taking the reading from the analyzer and dividing by the effective band width of the analyzer. The amplitude of the power spectrum curve above 100 kc. may be in error due to the demodulation distortion when the carrier frequency to modulation frequency ratio gets much less than ten.

In contrast to the hot wire, no compensation system need be used to boost the response of the instrument to high frequencies. Again in contrast to the hot wire, the noise level of the amplification circuits was too low to be plotted on Figure 33. There is scatter in the data of Figure 33, some of which is due to the fact that the fluctuation sensitivity was not constant throughout the run. Some of the points were repeated and are shown. Kovasznay (Ref. 1) obtained a power spectrum measurement of the fluctuations in a supersonic boundary layer with a hot wire anemometer. The noise level of Kovasznay's hot wire compares to the signal level at the higher frequencies. In a qualitative way, the shape of the power spectrum curve measurement of Figure 33 compares with Kovasznay's. However, his measurements could only be carried to 70 kc.

5. Glow Response to High Frequency Sound Waves. In order to be certain that the glow would actually respond to high frequency fluctuations rather than produce them, a source of high frequency fluctuations was desired. Krishnamurty* was able to produce such a source of ultrasonic sound waves issuing from a transverse slot in a flat plate or wedge in high speed flow (see sketch Fig. 36). The

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* The work is unpublished at this time and is being done for a doctoral thesis at the California Institute of Technology under Dr. H. W. Liepmann.

frequency of the sound waves seems to depend on the slot dimensions and the velocity of the air passing over the slot. A 5° half angle wedge and a support system to be used in conjunction with the strut holding the glow were constructed. The wedge is shown mounted with the glow probe on the strut (Fig. 34A) and in the ceiling of the wind tunnel (Fig. 34B). The wedge was positioned so that the Mach lines from the slot, along which the sound waves seemed to travel with greatest intensity, intersected the glow probe. Spark schlieren pictures were taken and they show the sound waves issuing from the slot in the wedge (Figs. 35A and 35B). Figure 35A showed the sound waves best. Round electrodes were used on all the runs.

The Sierra Wave Analyzer was used with the A.C. glow to determine the frequency of the sound waves. The glow probe and wedge were in the free stream during the measurements. The results of several test configurations are presented in Figure 36. The voltage measured was not corrected by the effective bandwidth of the analyzer in Figure 36 because the frequency of the sound wave was the primary concern. From the four runs presented in Figure 36, one can see that the glow did respond to the frequency, f_W, produced by the slot. The amplitude of the sound waves from the slot had to be higher than the level of the power spectrum curve of the fluctuations in the free stream in order to be detected. Figure 36 shows that this was the case. The resonant peaks were sharp; the output of the analyzer was observed carefully for these peaks before data was recorded. Some of the data points, especially near the resonant frequency of the slot, f_W, were repeated and several runs were repeated. Since the resonant peaks were so sharp, it was difficult to tune the analyzer carefully enough to record the maximum voltage on the microammeter which was used with a vacuum thermocouple.

The 0.4" wide slot produced the lowest resonant frequency, 47.6 kc., at M = 2.55 and also produced first, second and third harmonics. There is some question as to whether all of the harmonics were really produced by the source of the sound, due to the character of the demodulation system at frequencies above 100 kc. The 0.2" slot produced a frequency of 109.7 kc. at M = 2.55 and 104.8 kc. when the pressure level of the tunnel was lowered and a part of this change in frequency is due to the change in supply temperature. This measurement at two pressure levels was made at the lowest current possible at each pressure. Note that at the higher pressure more current was required to maintain the discharge. For a 0.2" slot at M = 1.97, the resonant frequency was 87.2 kc. and this shows the dependency of f_w on Mach number. A comparison of the amplitudes of the resonant peaks cannot really be made, since the sensitivity of the glow was not the same in each run and since the glow probe may not have been at the position of maximum amplitude of the sound wave. The 0.4" gap produced the largest amplitude that was recorded for three possible reasons: The glow might be more sensitive to the lower frequency fluctuations than to the high; the large slot probably produced stronger waves; and the fixed location of the glow probe in the sound wave was not as critical as in the narrow gap. A 0.1" gap was used at M = 2.55 and the glow seemed to indicate a resonant peak at over 200 kc., but these runs were not conclusive due to the demodulation effect.

VI. CONCLUDING REMARKS

A current regulated D.C. glow anemometer was designed, constructed and calibrated for low speed turbulence measurements. Its frequency response was estimated to be in excess of 50 kc. from shock tube experiments. It was found that the D.C. glow had several shortcomings for turbulence research. Anomalies in calibration curves and turbulence measurements were introduced due to the asymmetric burning properties and sputtering at the cathode of the discharge.

In order to eliminate the asymmetric burning and reduce the effects of sputtering which were present in the D.C. glow, a 700 kc. A.C. glow was designed and constructed. The A.C. glow largely eliminated the shortcomings of the D.C. glow, but the results with the A.C. glow showed some scatter and changes of sensitivity with respect to time. Measurements in the wall boundary layer of supersonic wind tunnels indicated that the A.C. glow responded to the fluctuations in the turbulent wall boundary layer of a supersonic wind tunnel. Power spectrum measurements were made at several stations in this boundary layer with the A.C. glow, and these measurements revealed that fluctuation frequencies in excess of 100 kc. were present in the boundary layer. A transverse slot in a wedge in supersonic flow provided a source of ultrasonic sound waves. The A.C. glow picked up these single frequency sound waves, in excess of 100 kc., issuing from the slot.

In general, the A.C. glow in its initial phase of development has shown enough promise (especially in regard to its frequency response in supersonic flow) to warrant additional consideration. Further investigation may result in an instrument with applicability in high speed flow comparable to that of the hot wire in low speed flow. It is felt that considerable time and effort will have to be spent until the glow technique will furnish reliable quantitative results.

There are several suggestions for further research that can be made in order to make the glow a practicable instrument for turbulence research in supersonic flow. First, it is extremely difficult to relate analytically the glow circuit characteristics, such as current and voltage, to the various parameters in the high speed flow field impinging on the discharge. Therefore, experiments must be devised to determine such a relationship. Preliminary attempts with the 700 kc. A.C. glow were not conclusive in this determination. Second, the A.C. glow circuit should be revised to make the glow a constant current discharge. Consideration should be given to the possibility of increasing the carrier frequency in order to raise the amplitude modulation frequency which might be detected on the carrier. The possibility of using a microwave carrier frequency should also be investigated.

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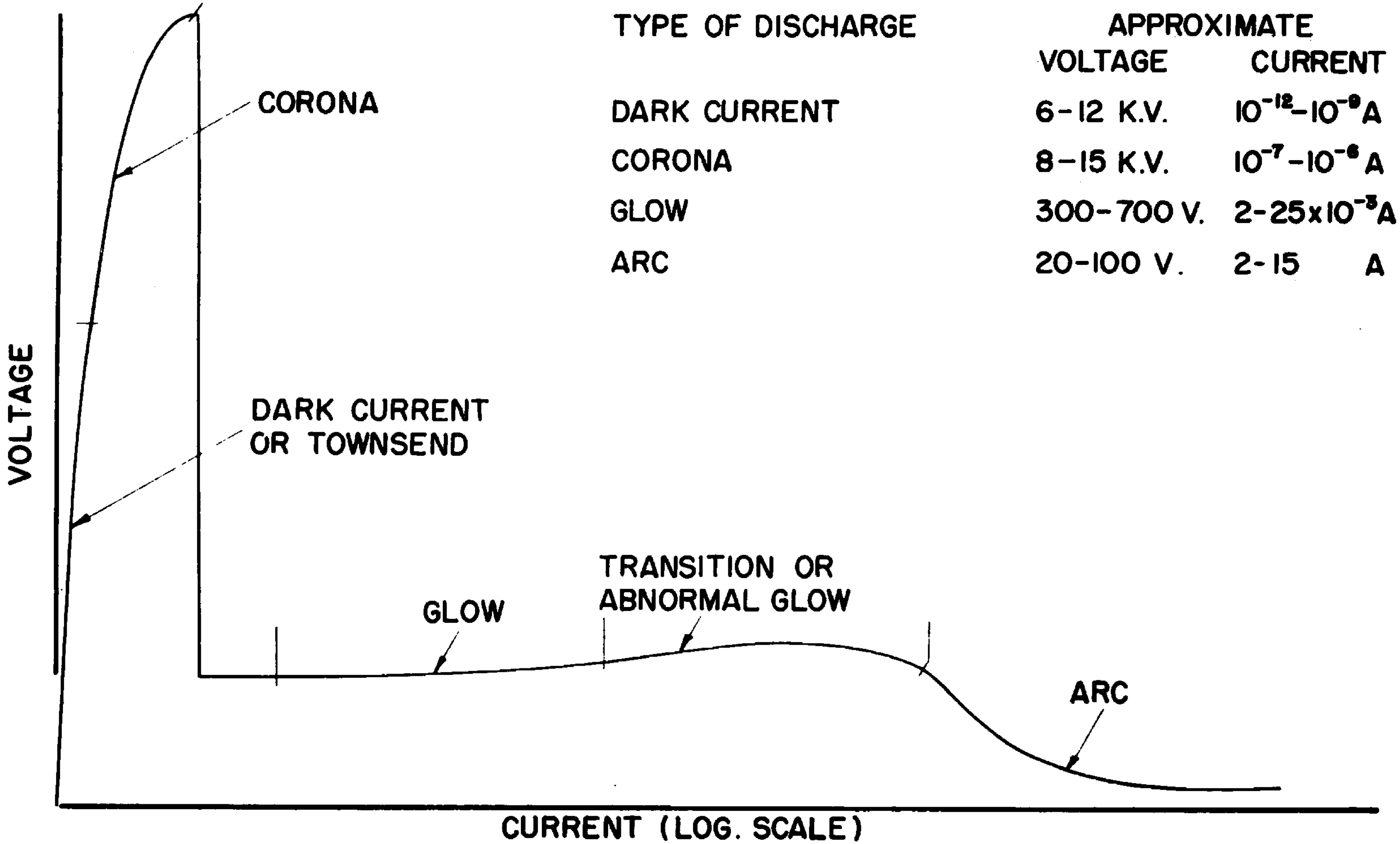


FIGURE 1. VOLTAGE VS. CURRENT FOR DISCHARGE ACROSS AN AIR GAP AT ATMOSPHERIC PRESSURE

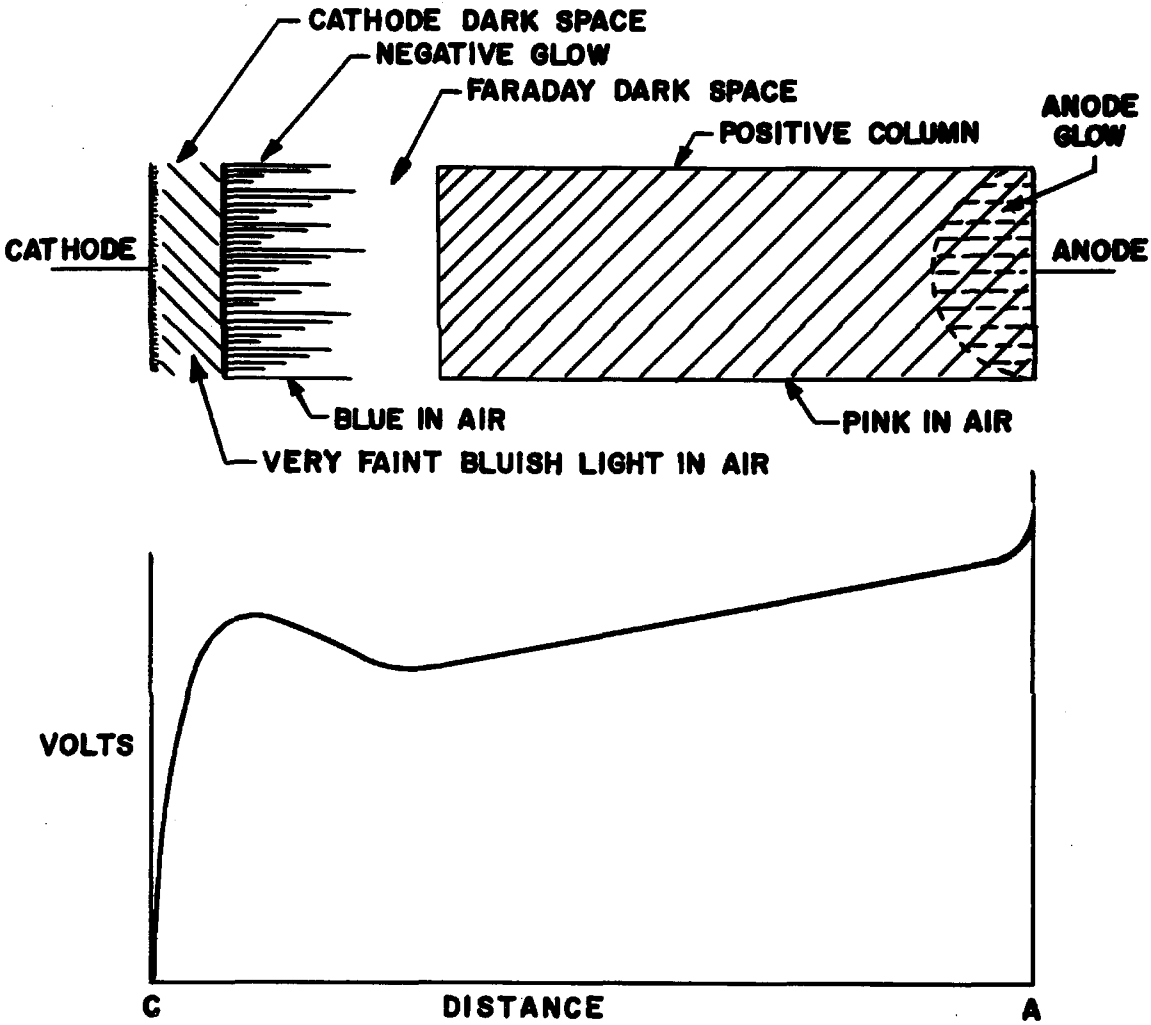


FIGURE 2. APPEARANCE, NOMENCLATURE, AND POTENTIAL DISTRIBUTION OF A GLOW DISCHARGE

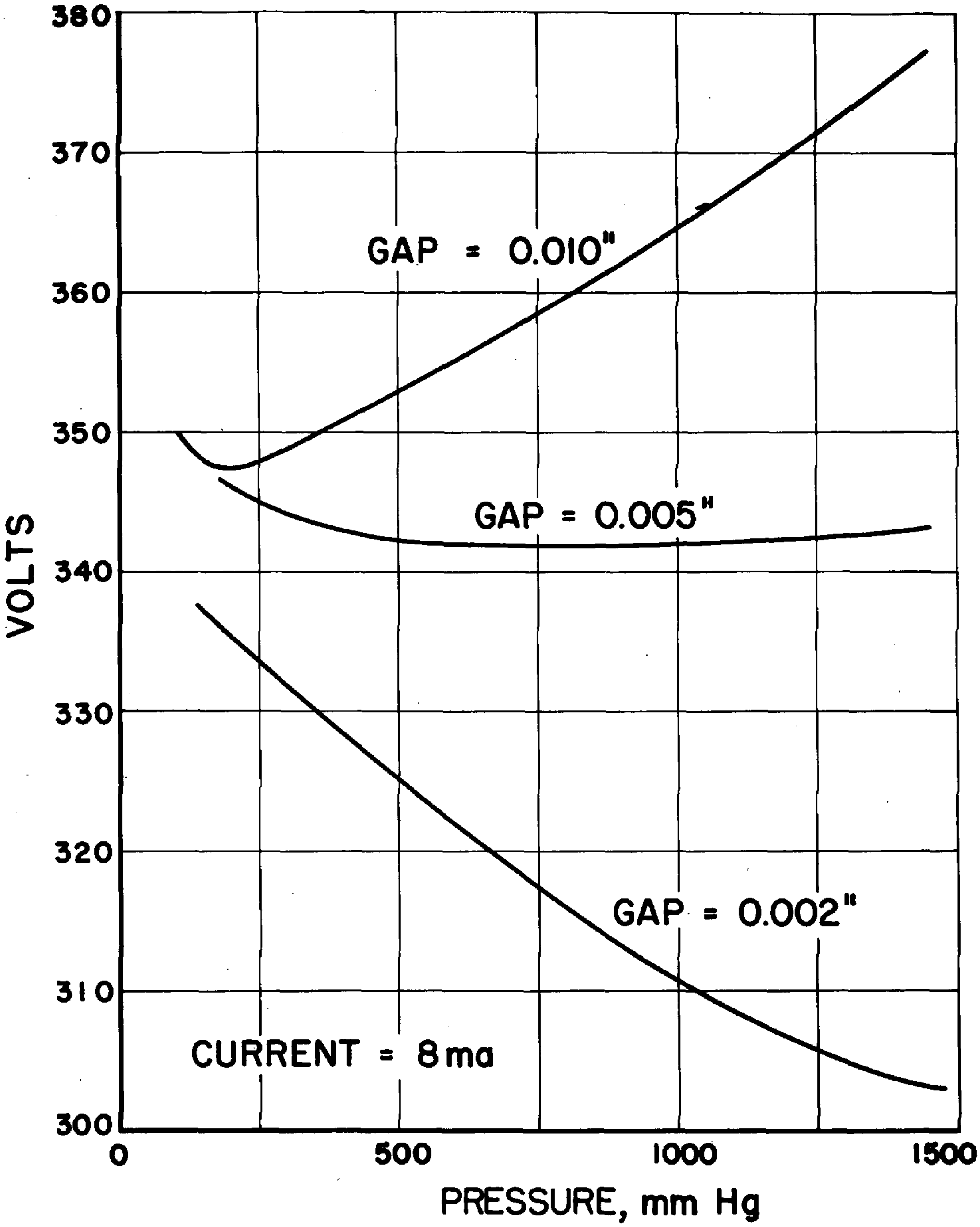


FIGURE 3. VOLTAGE vs PRESSURE FOR THE D.C. GLOW ANENOMETER

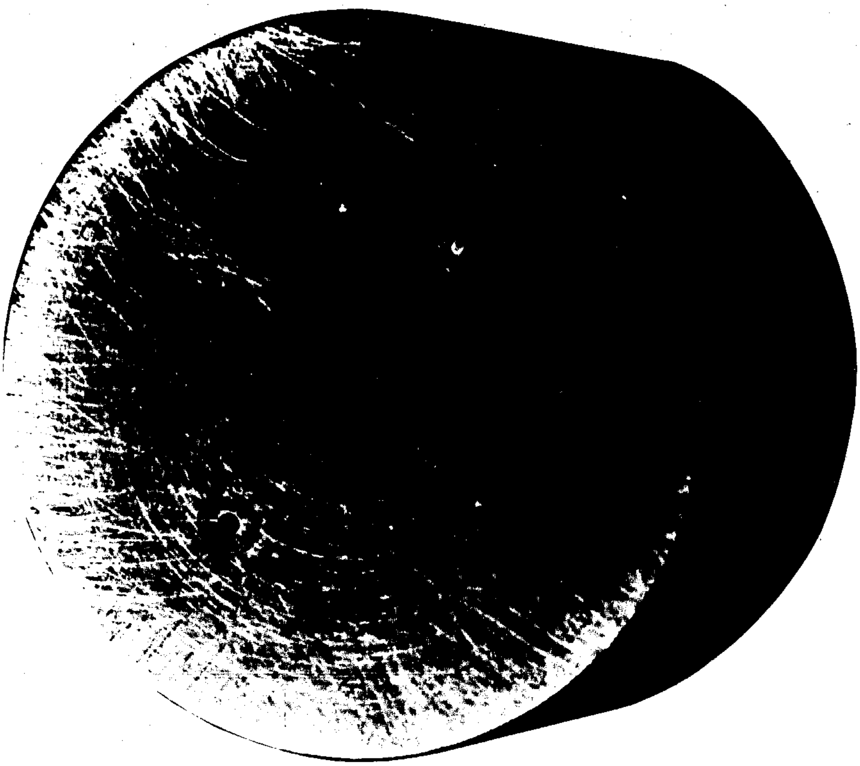


FIGURE 4. FLAT ELECTRODE POLISHING JIG

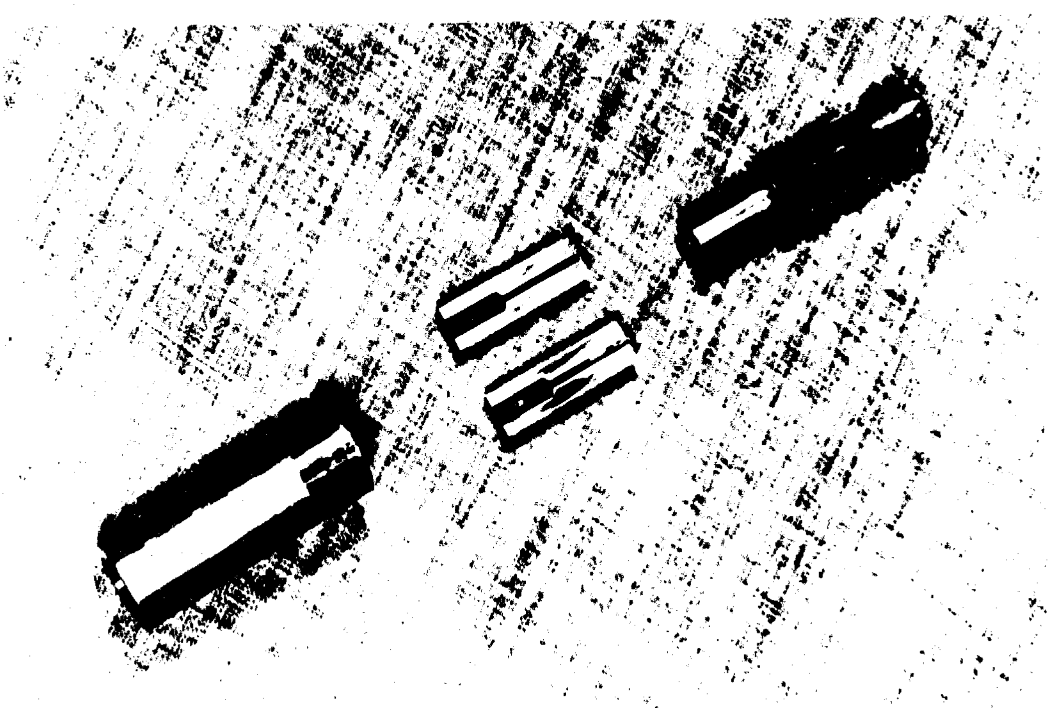


FIGURE 5. SPHERICAL ENDED ELECTRODE COLD-FORGING JIG

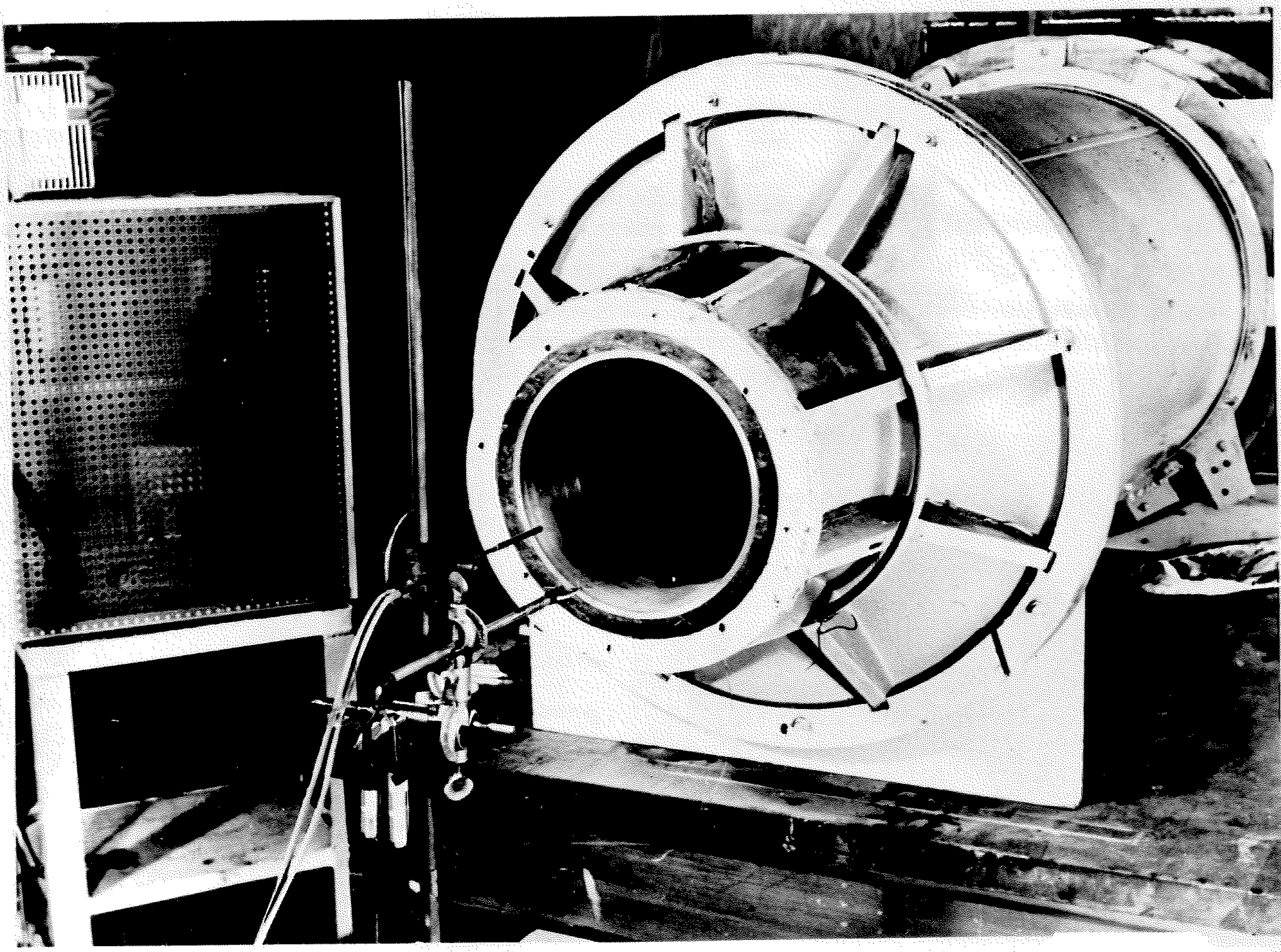


FIGURE 6. LOW SPEED PROBE MOUNTING AND 8" JET

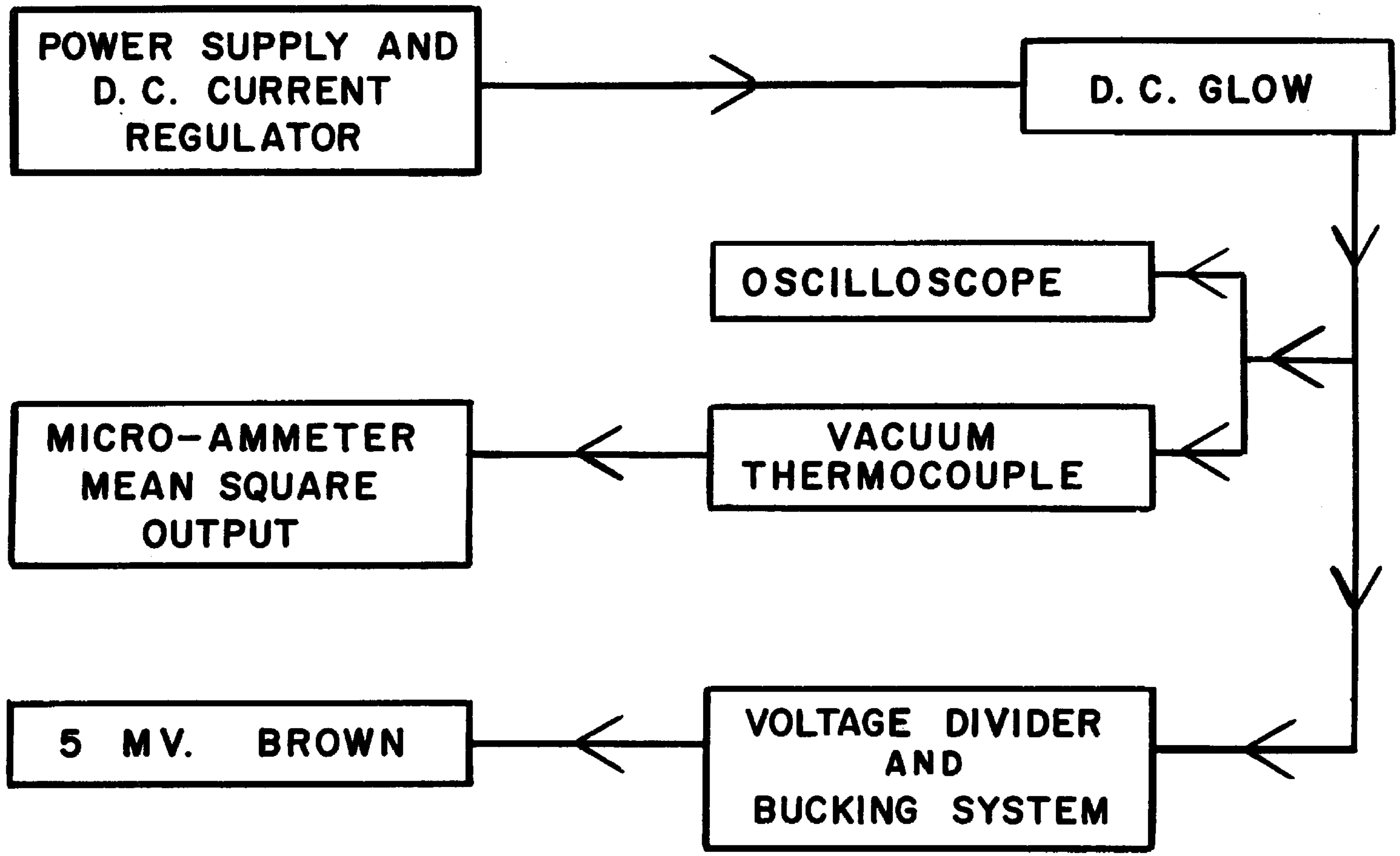


FIGURE 7. FUNCTIONAL BLOCK DIAGRAM OF D.C. GLOW

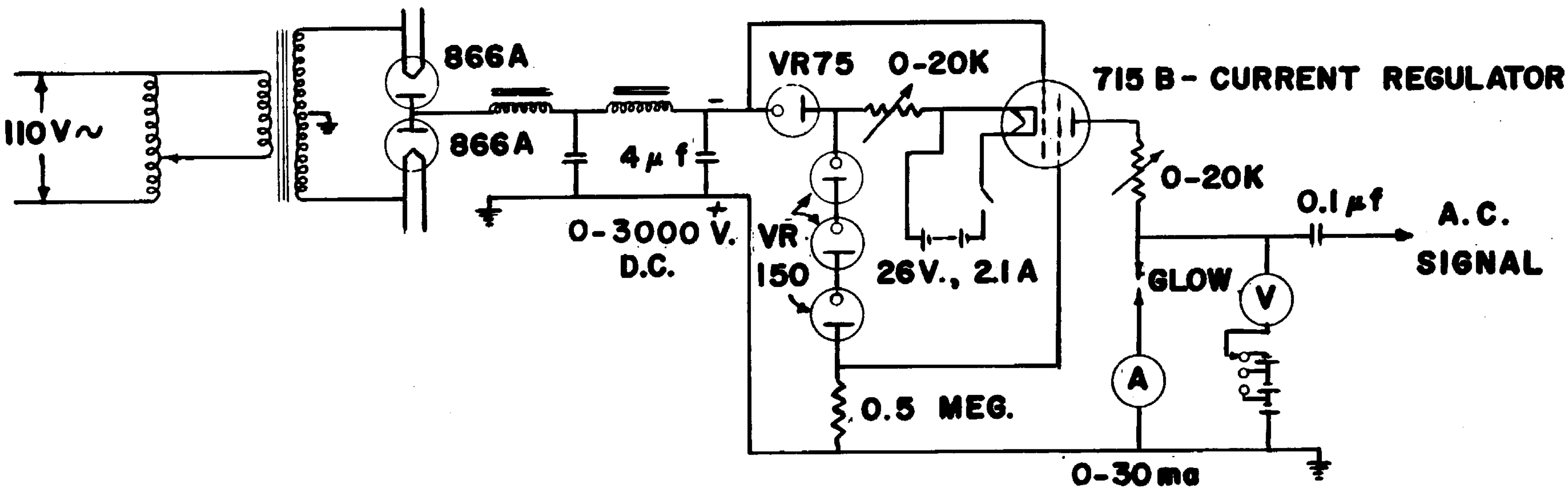


FIGURE 8. D. C. GLOW ANEMOMETER CIRCUIT

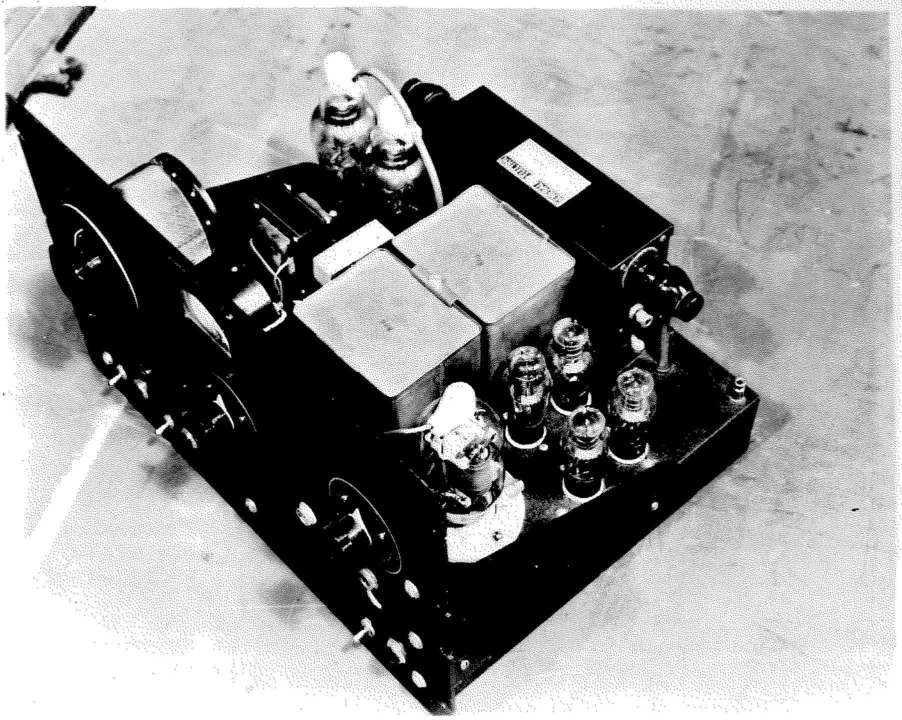


FIGURE 9. D.C. POWER SUPPLY AND CURRENT REGULATOR

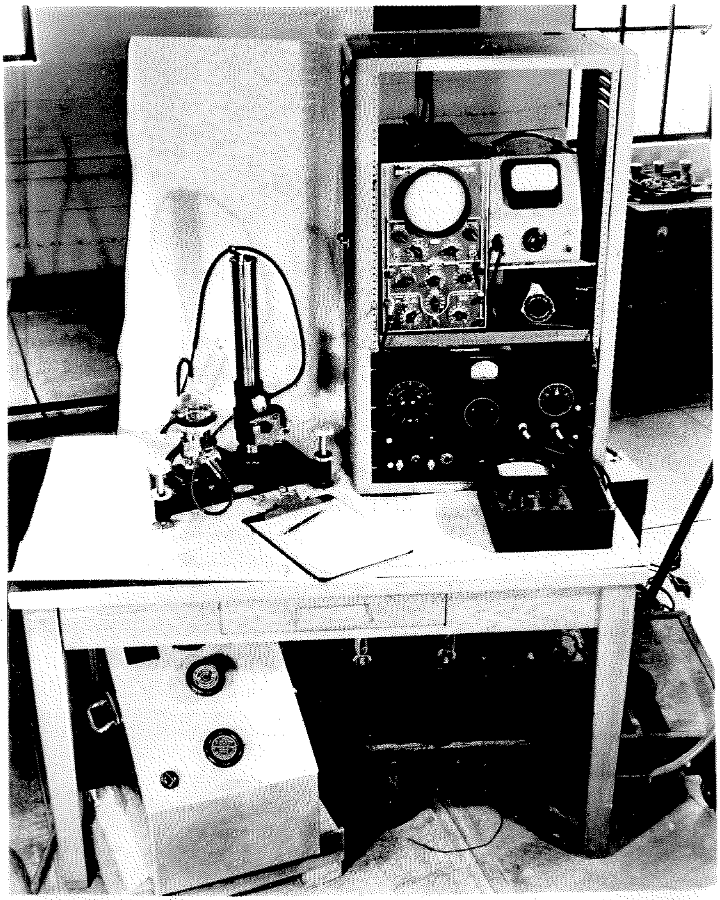
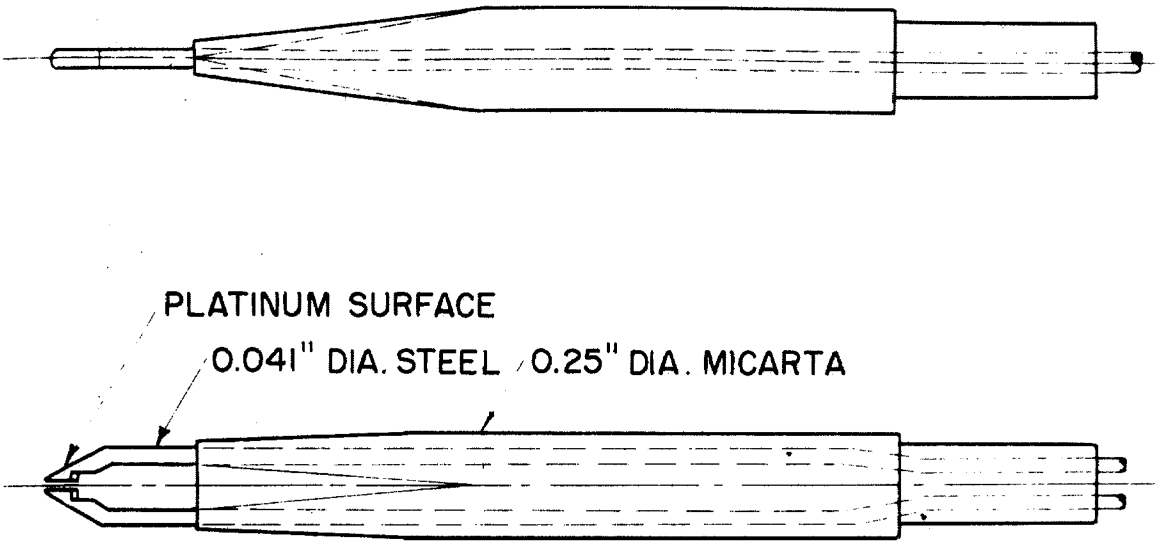
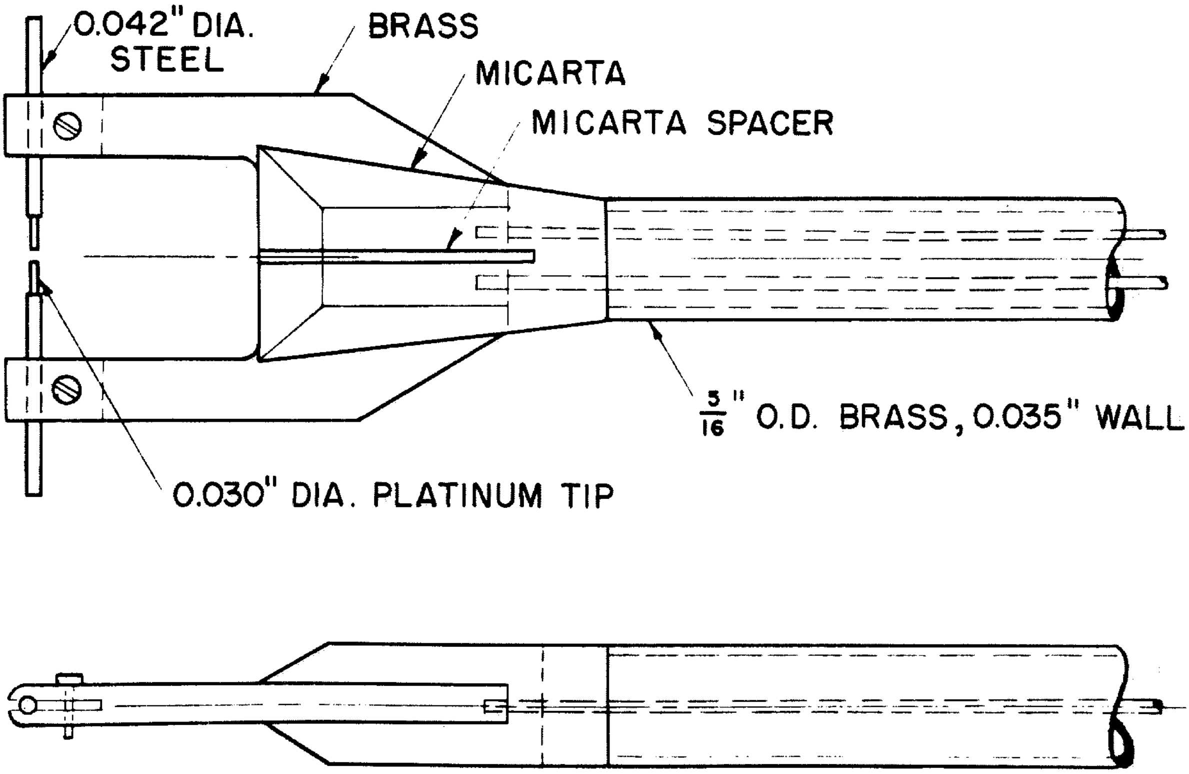


FIGURE 10. D.C. GLOW ELECTRONIC EQUIPMENT



HIGH SPEED PROBE (DOUBLE SIZE)



LOW SPEED PROBE (DOUBLE SIZE)

FIGURE 11. D.C. GLOW PROBES

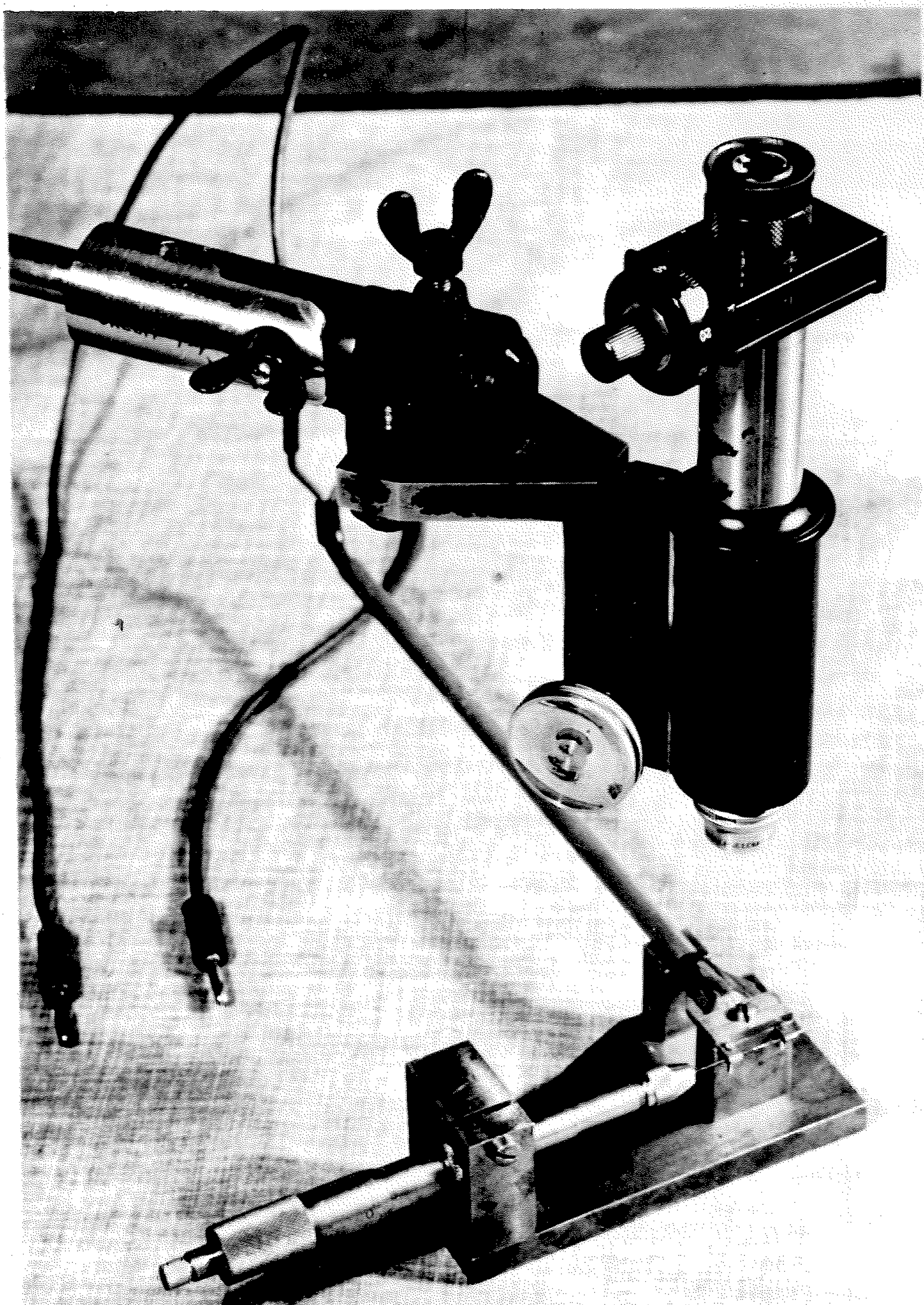


FIGURE 12. SPACING JIG, LOW SPEED PROBE AND MICROSCOPE COMPARATOR

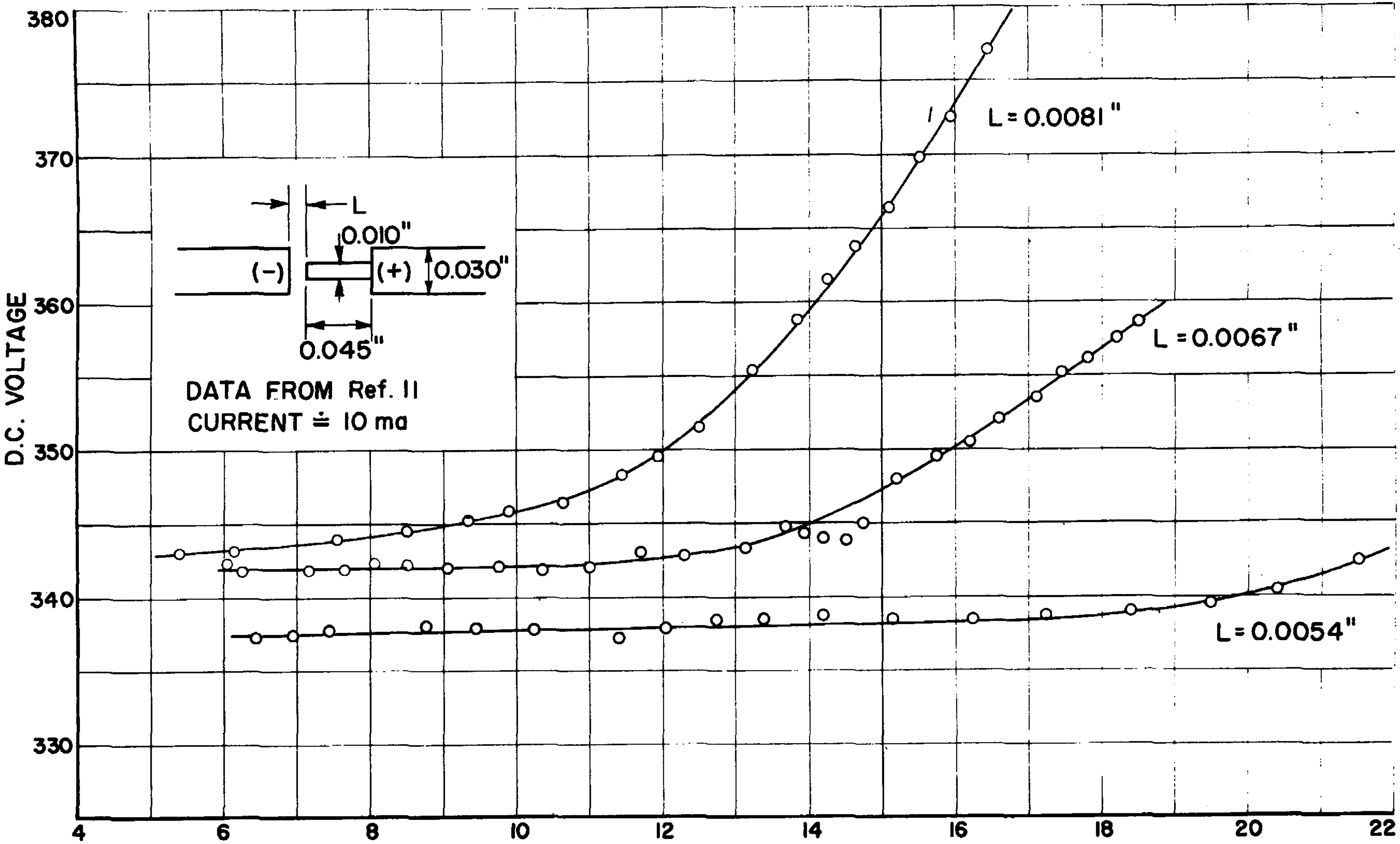


FIGURE 13. VOLTAGE-VELOCITY CALIBRATION CURVES

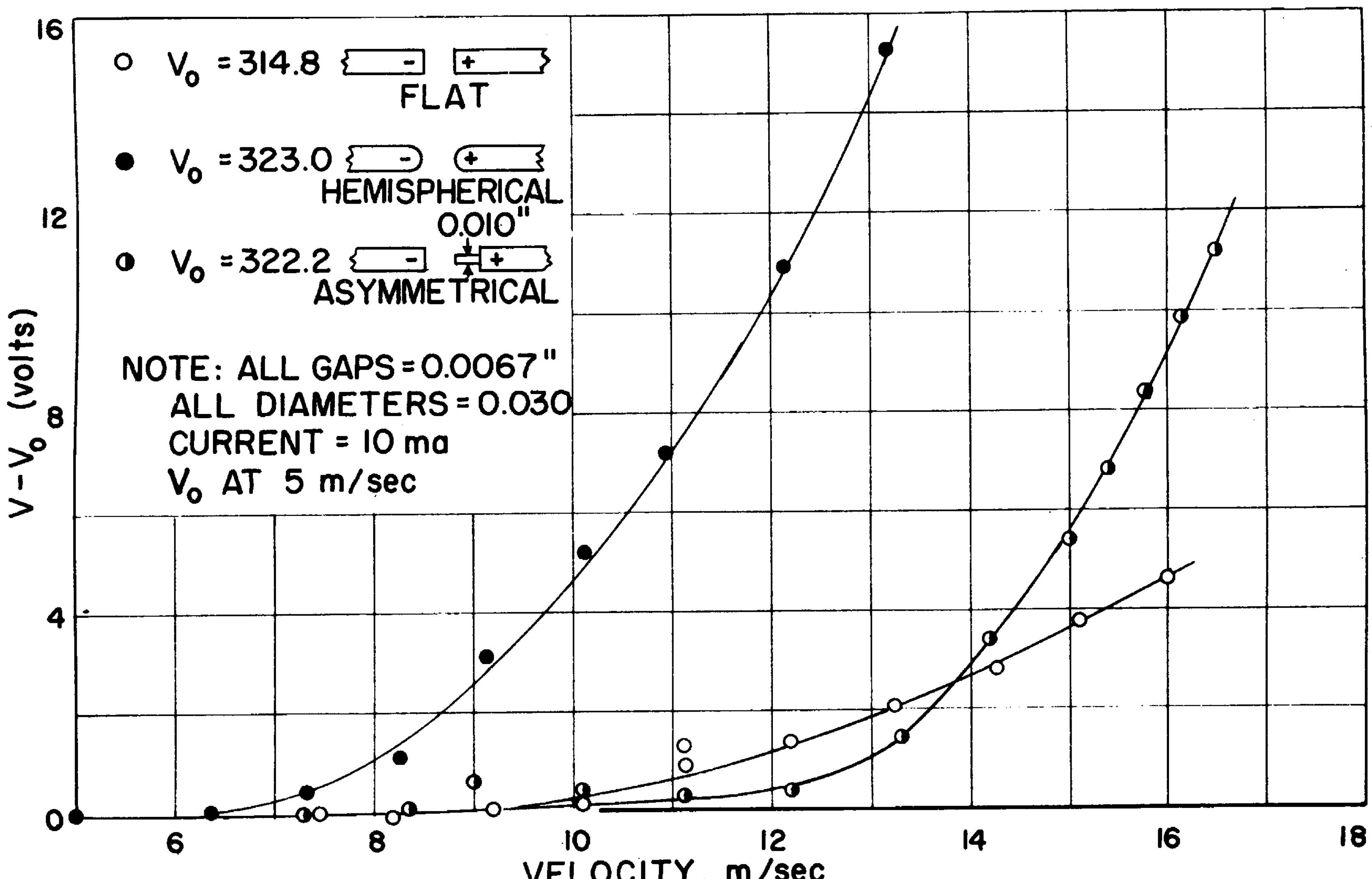


FIGURE 14. EFFECT OF ELECTRODE SHAPE

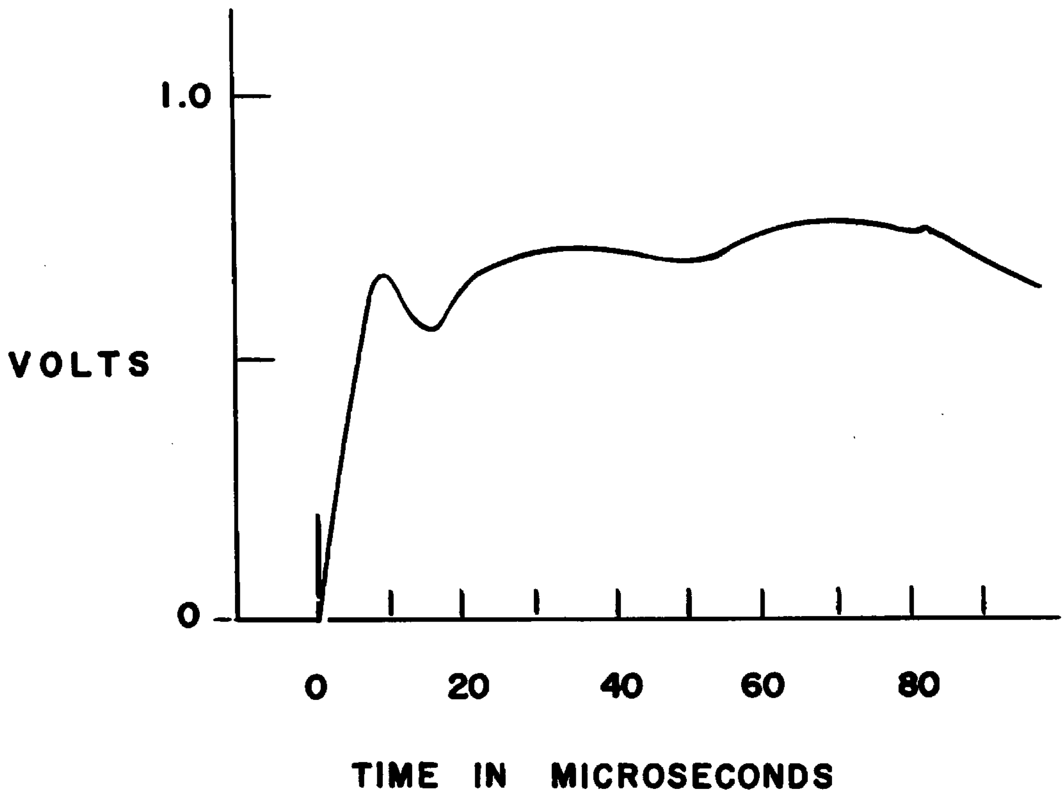
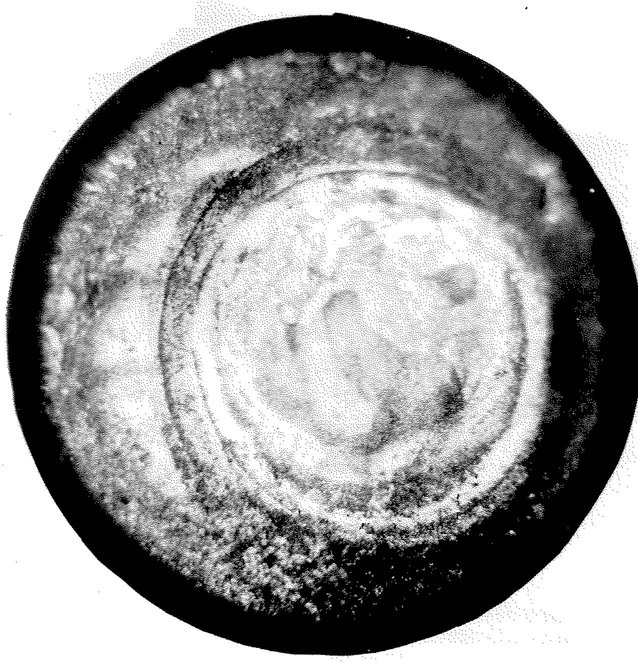
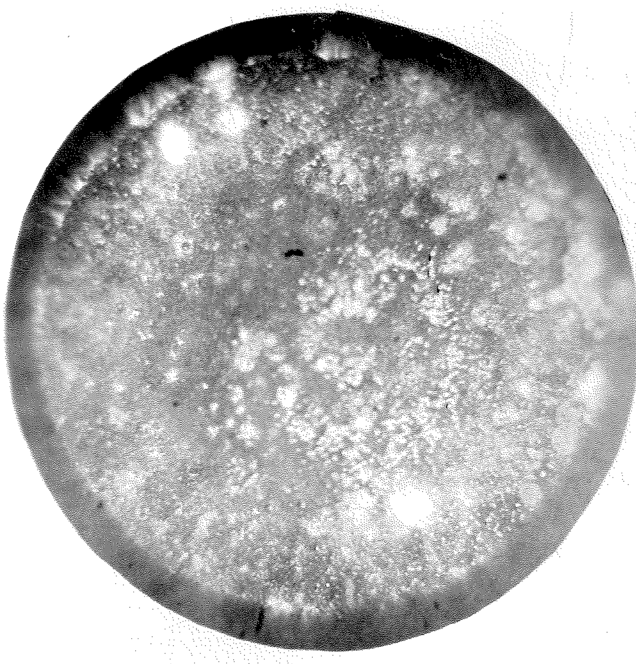


FIGURE 15. VOLTAGE RISE ON D.C. GLOW IN SHOCK TUBE



CATHODE



ANODE

FIGURE 16. EFFECT OF SPUTTERING ON ELECTRODE SURFACES (0.030 INCHES DIAMETER) AFTER 1.5 HOURS OF OPERATION AT 10 ma AND ELECTRODE SPACING OF 0.070 INCHES (DIRECTION OF AIR STREAM IS FROM LEFT TO RIGHT)

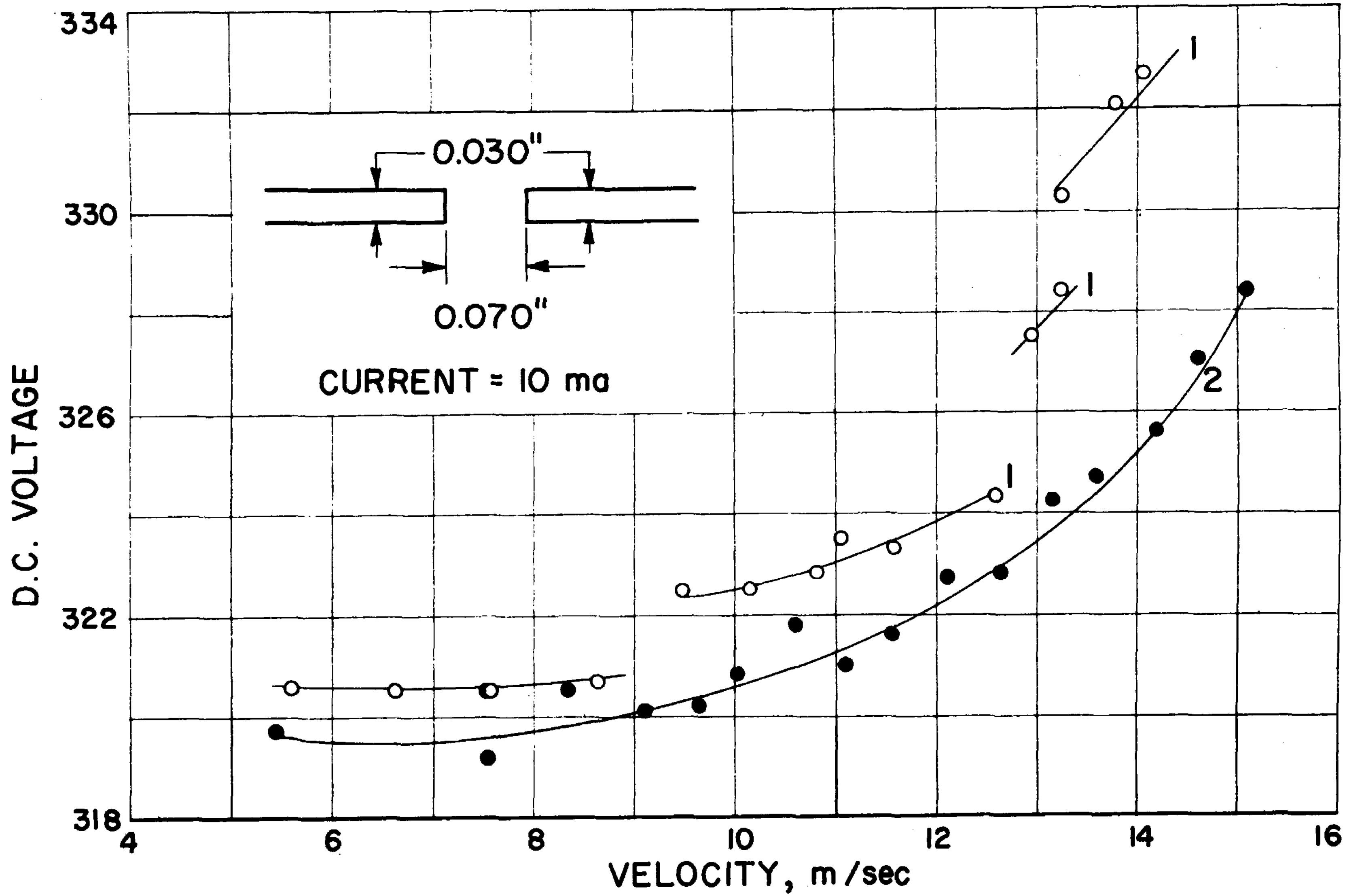


FIGURE 17. EFFECT OF SPUTTERING ON VOLTAGE-VELOCITY CALIBRATION CURVE

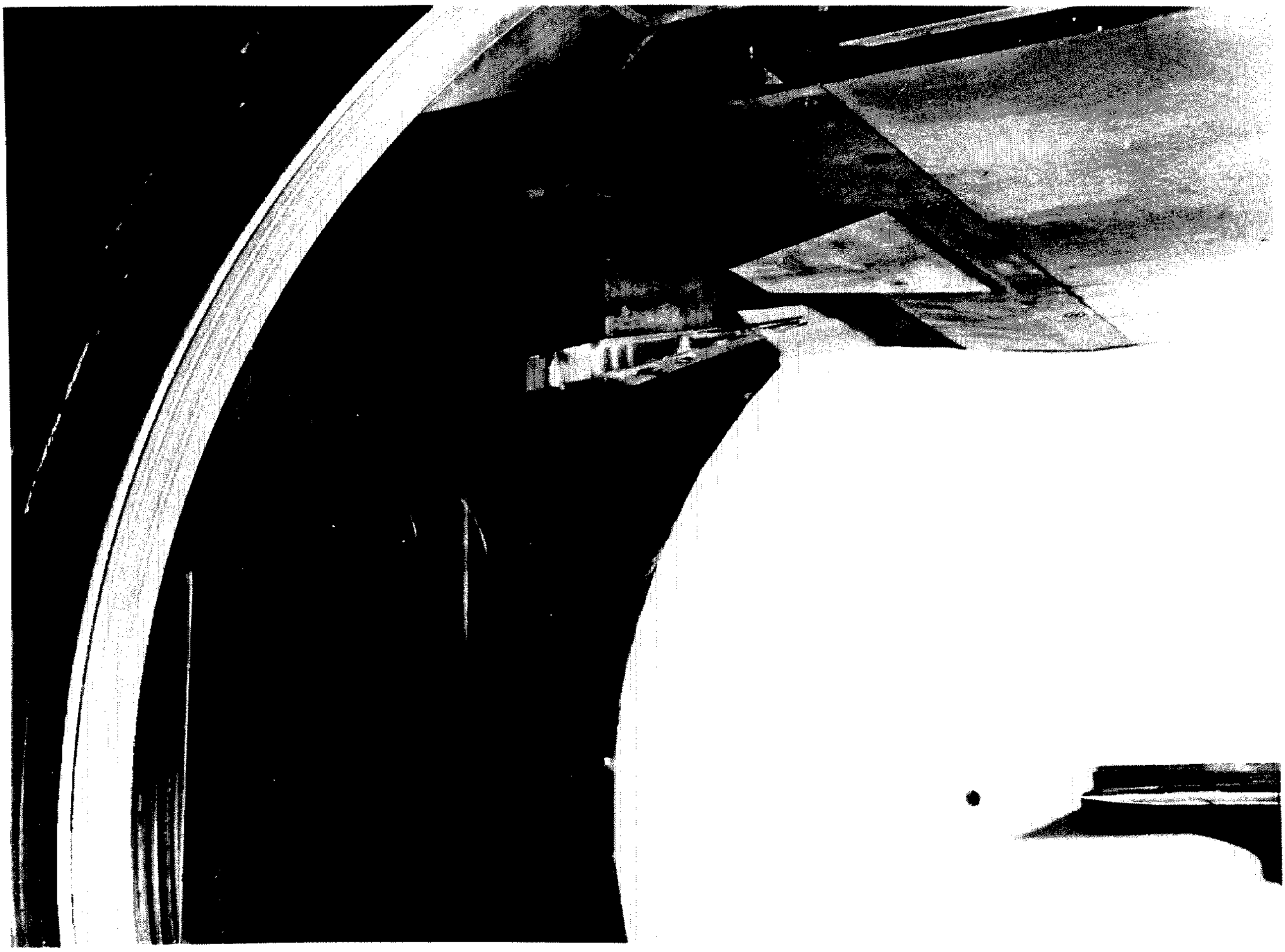


FIGURE 18. A.C. GLOW PROBE IN 20" SUPERSONIC WIND TUNNEL

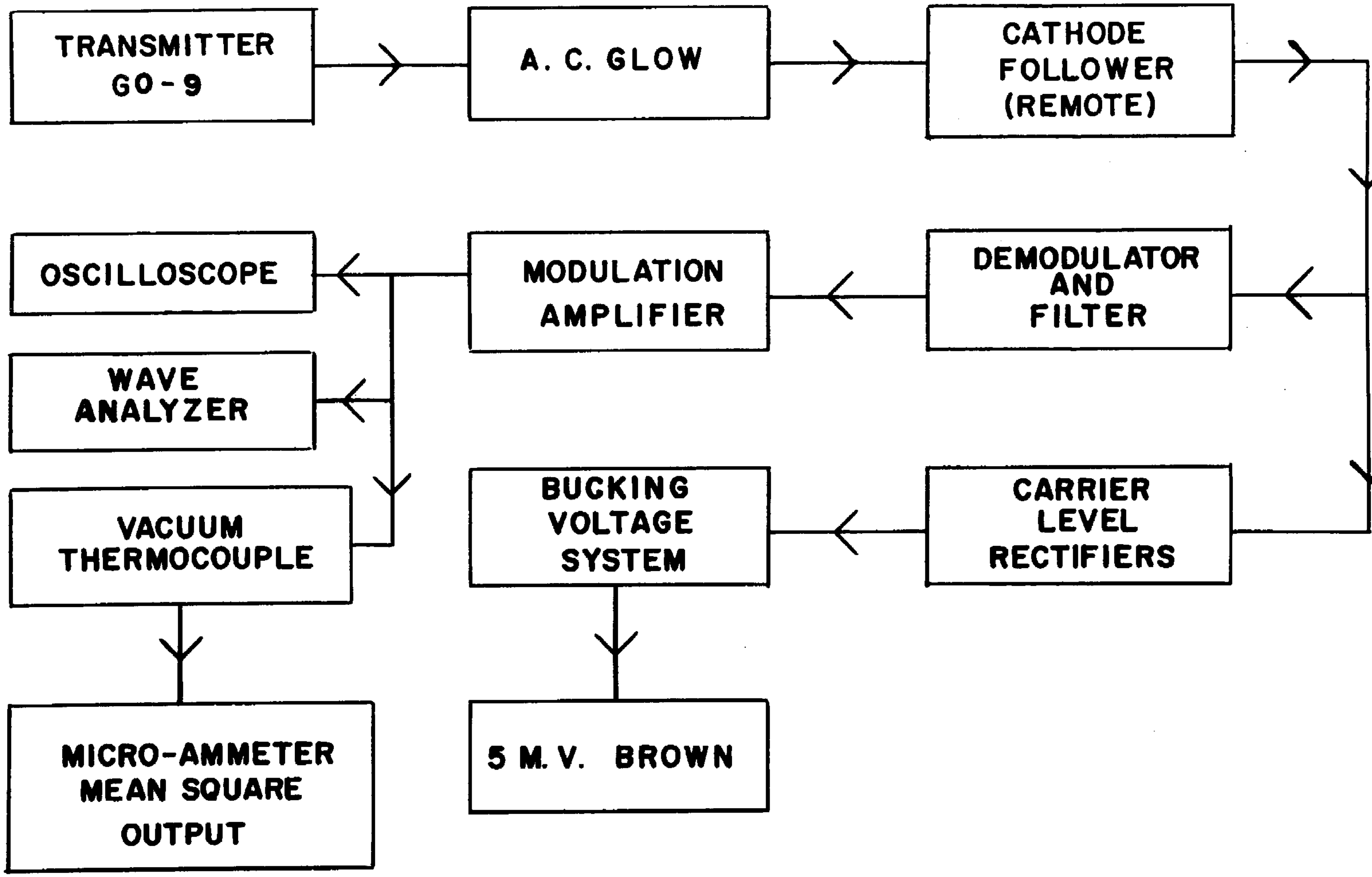


FIGURE 19. FUNCTIONAL BLOCK DIAGRAM OF A. C. GLOW

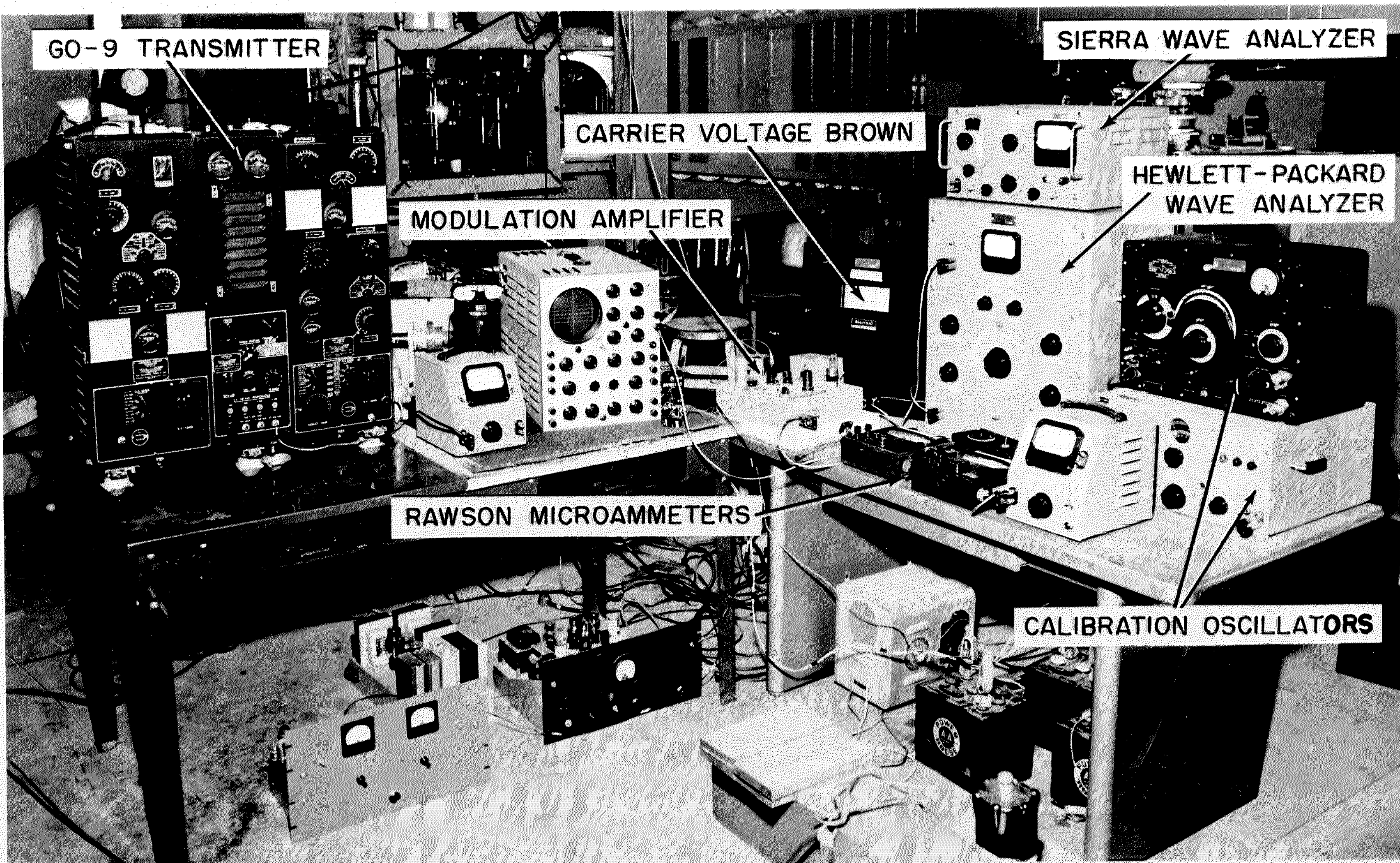


FIGURE 20. A.C. GLOW ELECTRONIC EQUIPMENT

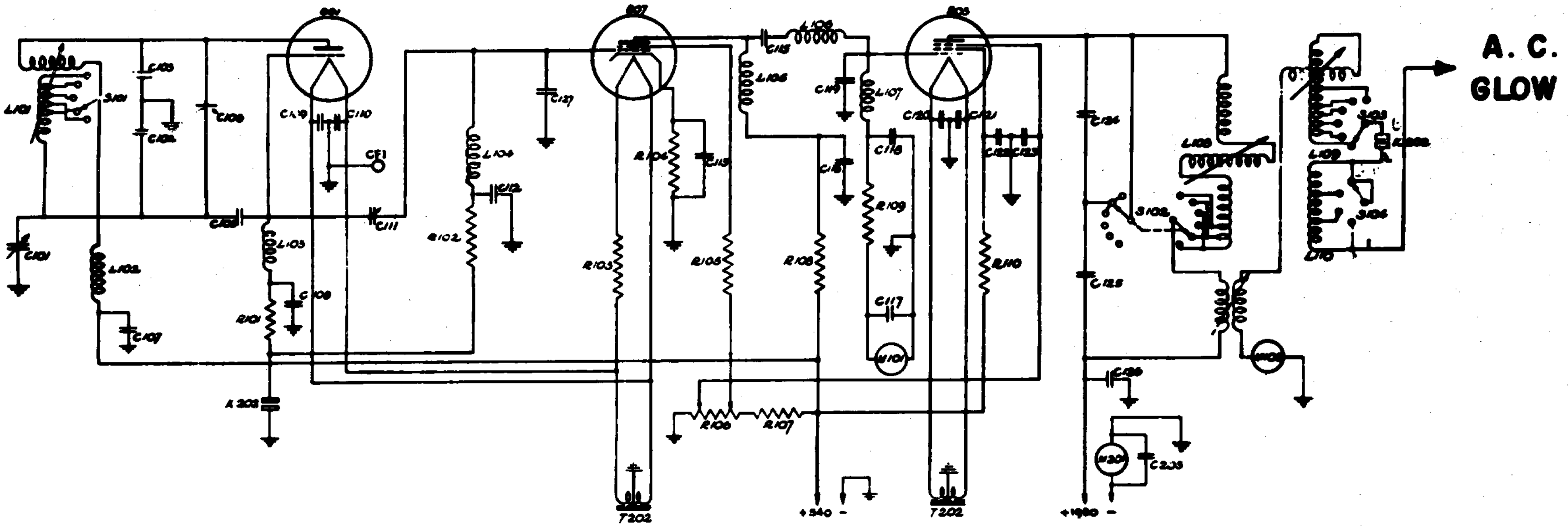


FIGURE 21 SCHEMATIC OF GO-9 INTERMEDIATE FREQUENCY TRANSMITTER

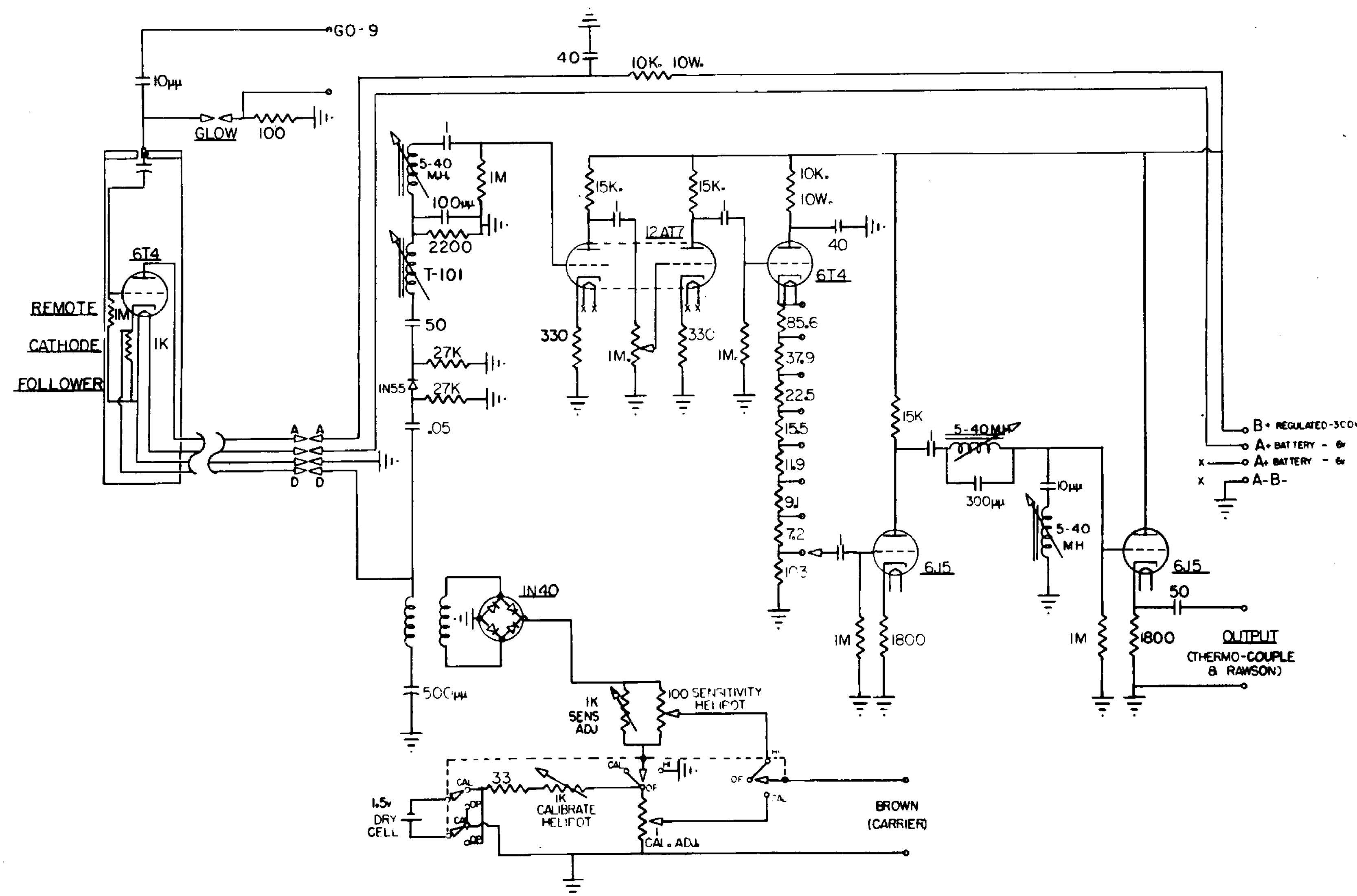


FIGURE 22 A C. GLOW PICK-UP CIRCUITS

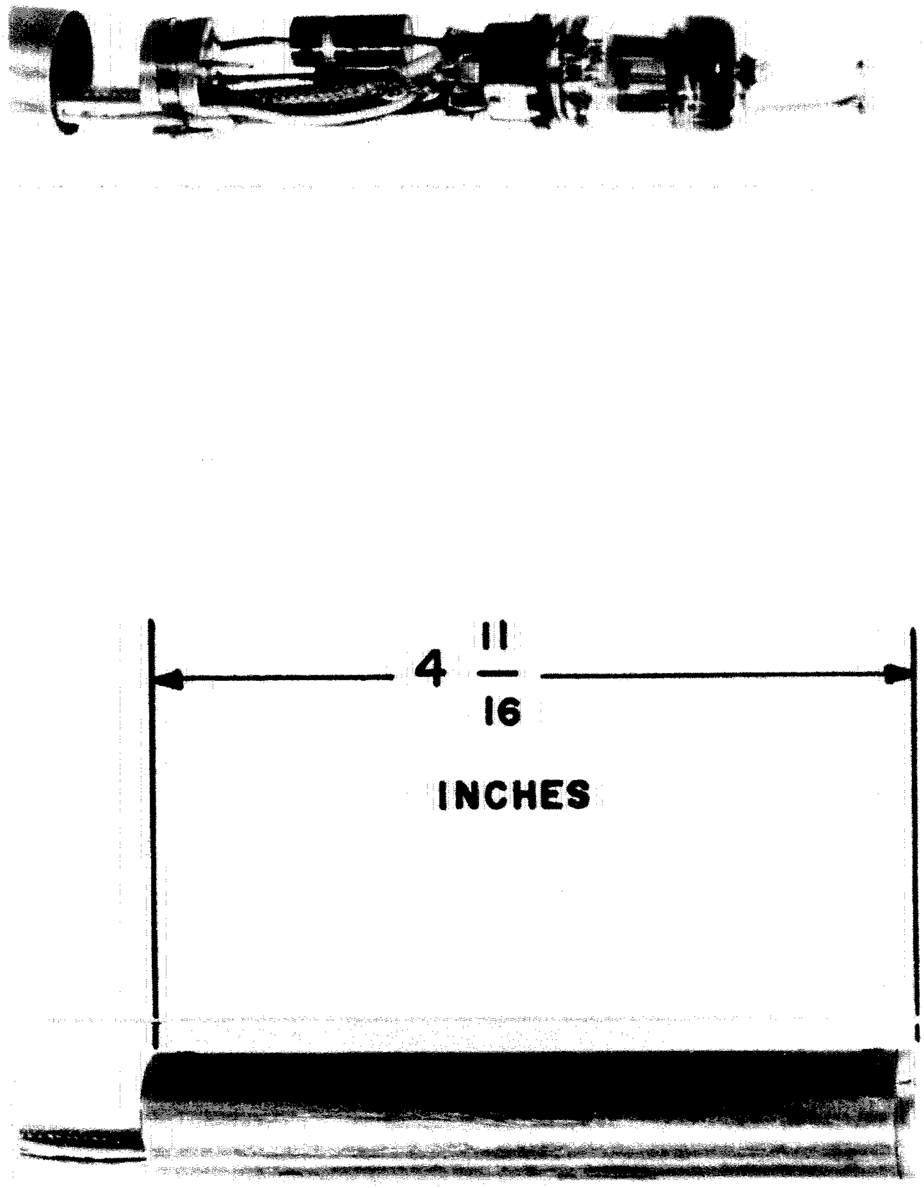


FIGURE 23. REMOTE CATHODE FOLLOWER

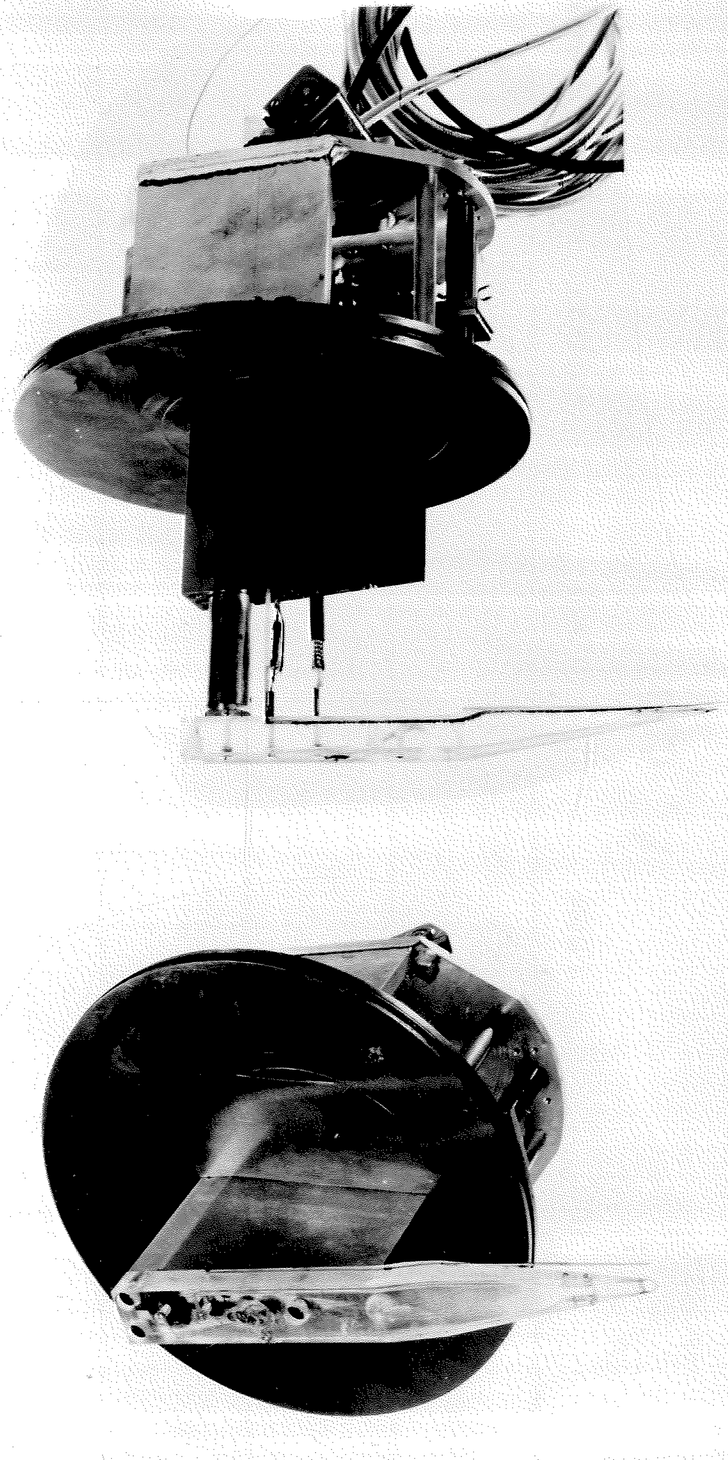


FIGURE 24. STRUT, PROBE AND CATHODE FOLLOWER ASSEMBLY

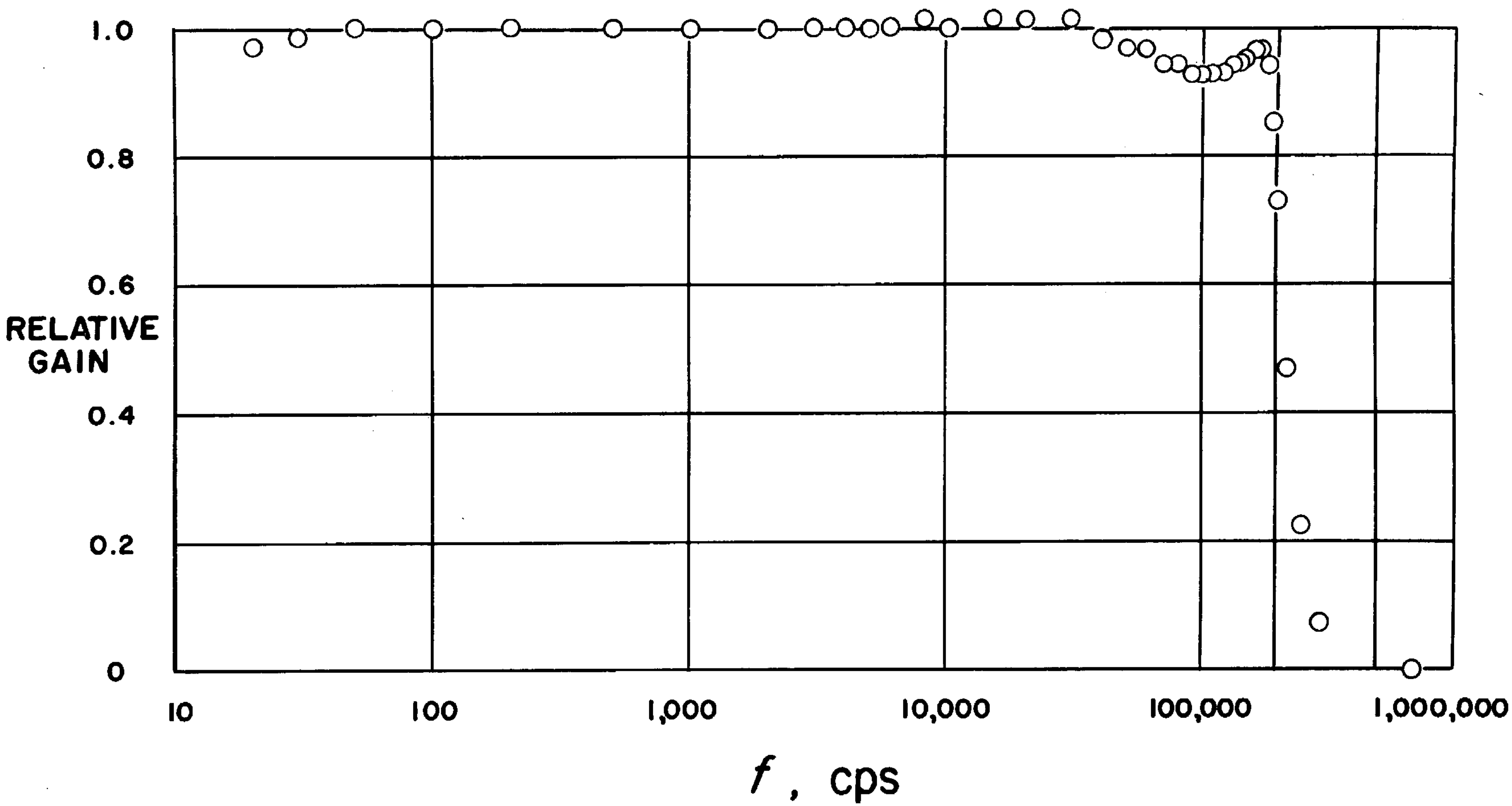


FIGURE 25 MODULATION AMPLIFIER FREQUENCY RESPONSE

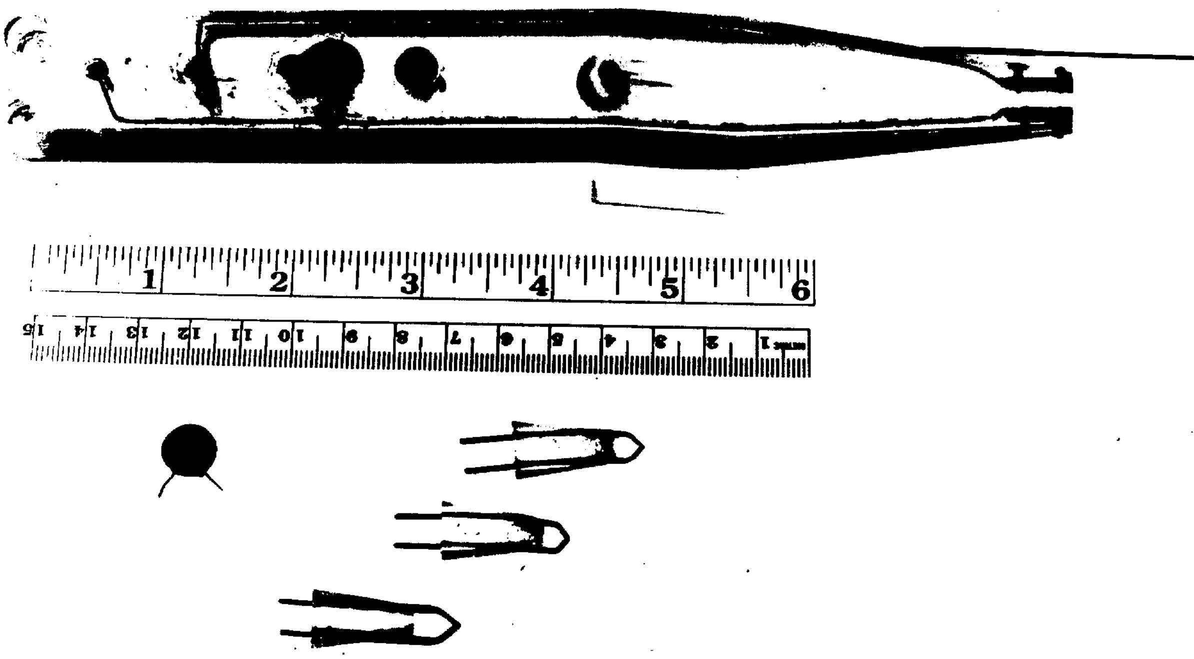


FIGURE 26. A.C. PROBE, CURRENT LIMITING CAPACITOR AND REMOVABLE ELECTRODES

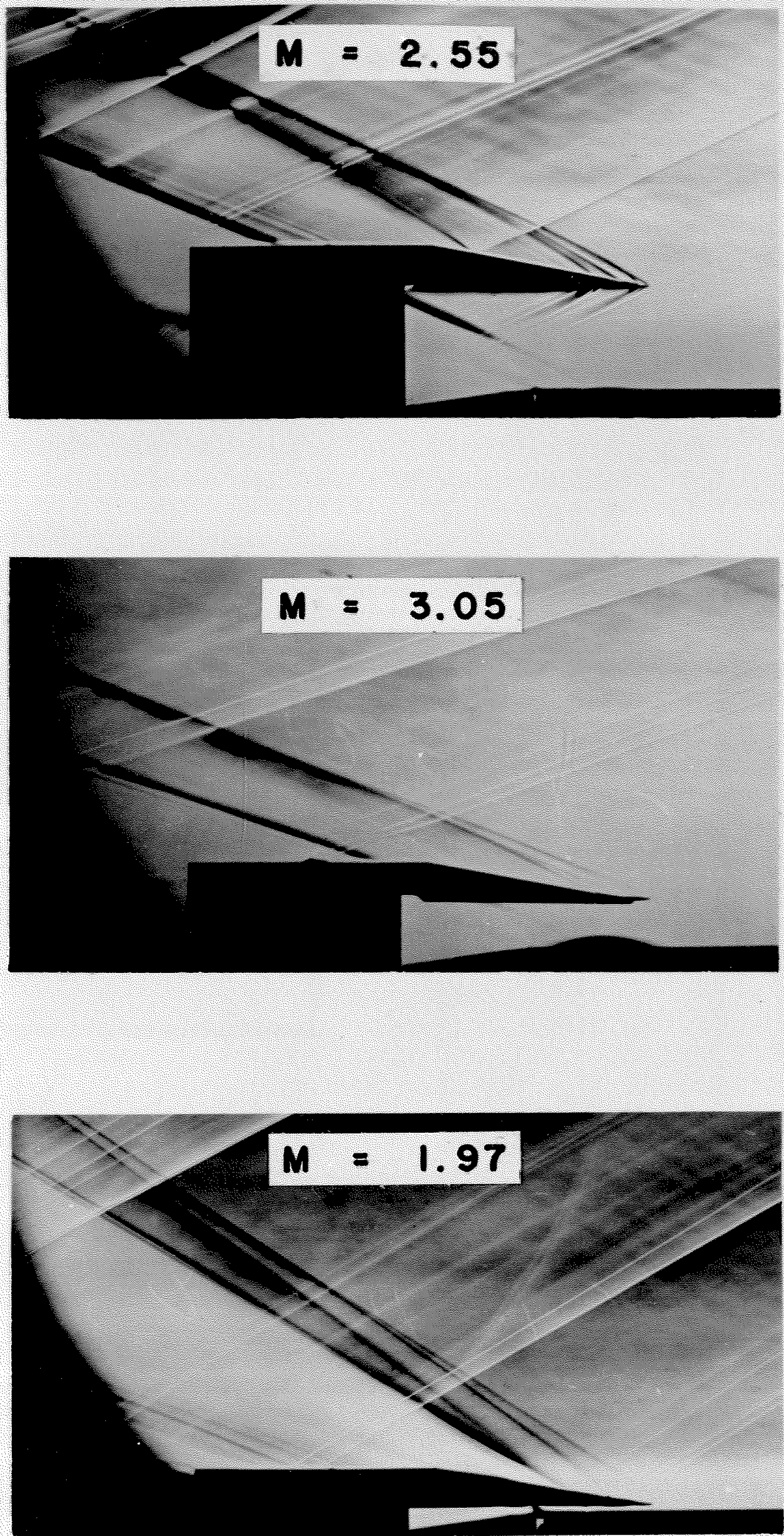


FIGURE 27. SCHLIEREN PICTURES OF THE A.C. GLOW PROBE IN SUPERSONIC FLOW

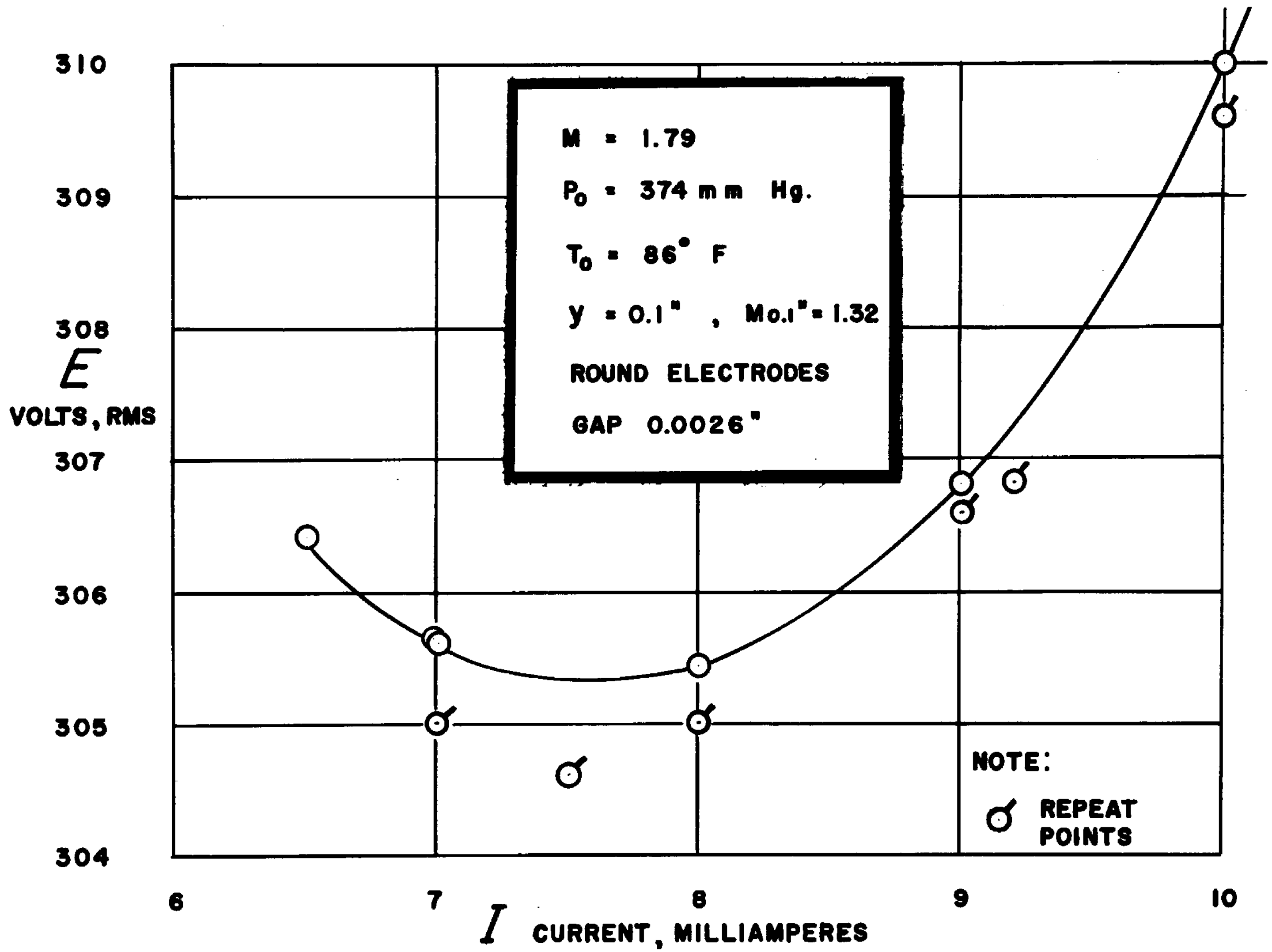


FIGURE 28. CARRIER VOLTAGE VS CURRENT

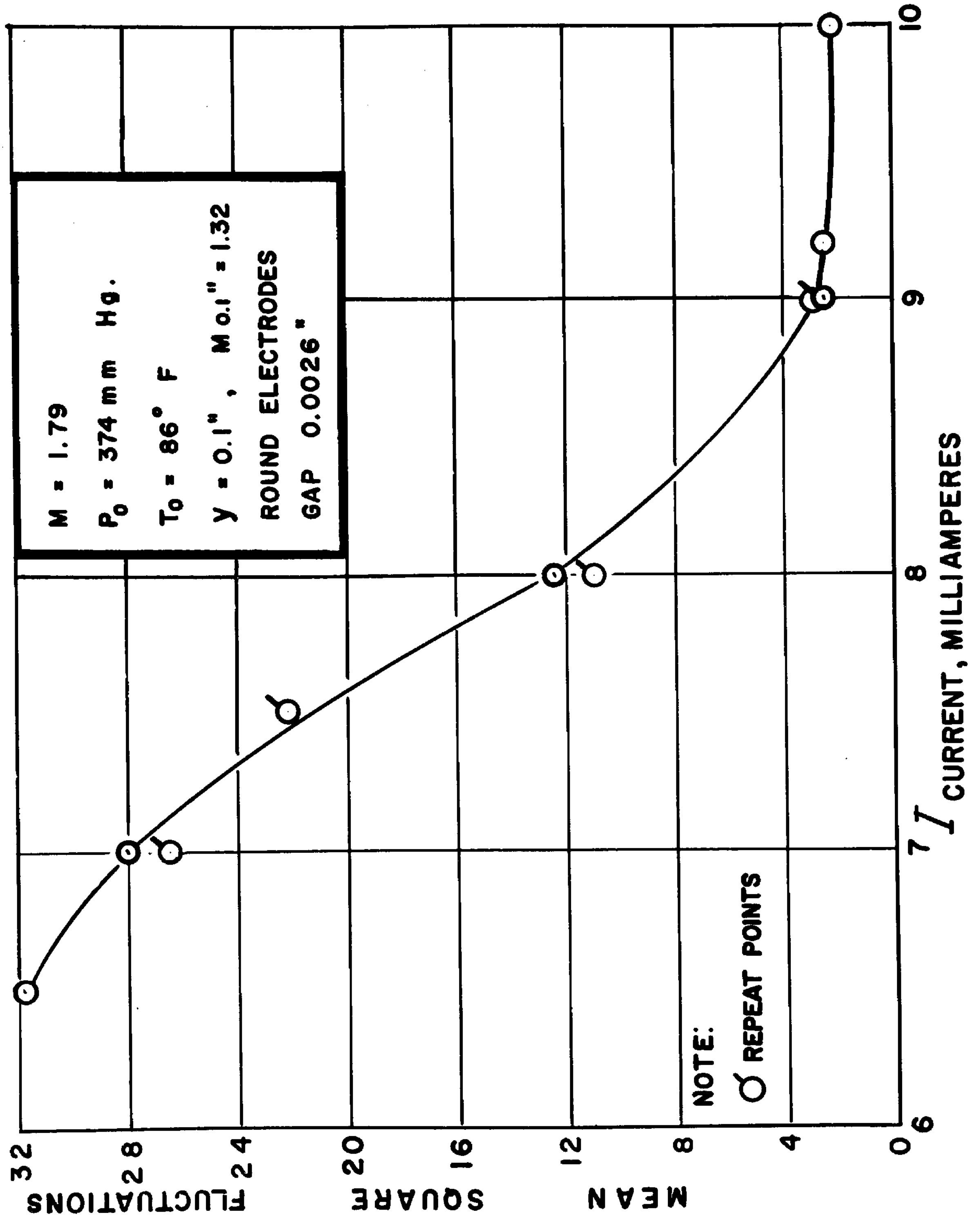


FIGURE 29. MEAN SQUARE FLUCTUATION SENSITIVITY VS CURRENT

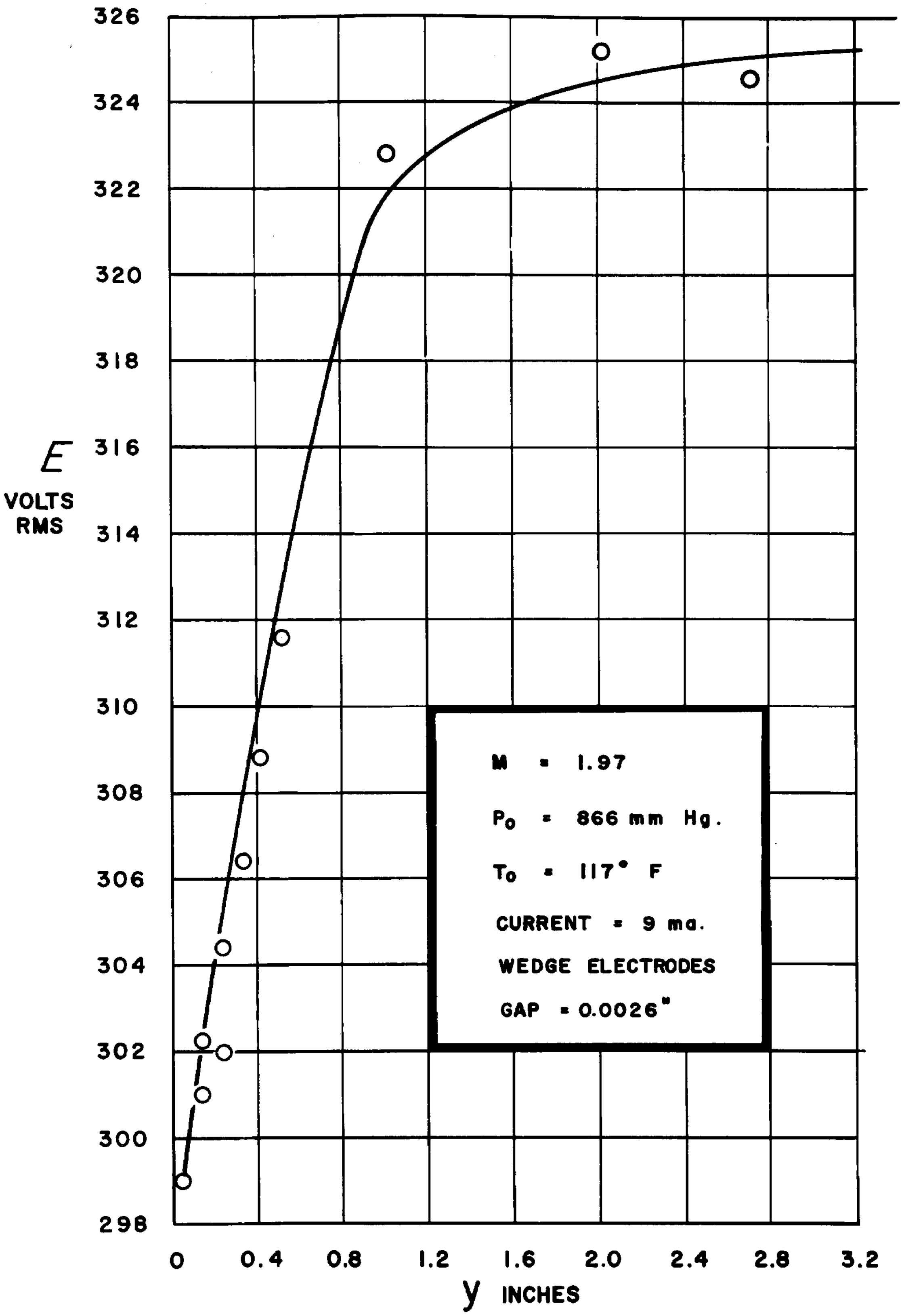


FIGURE 30 A.C. VOLTAGE ON PROBE IN BOUNDARY LAYER

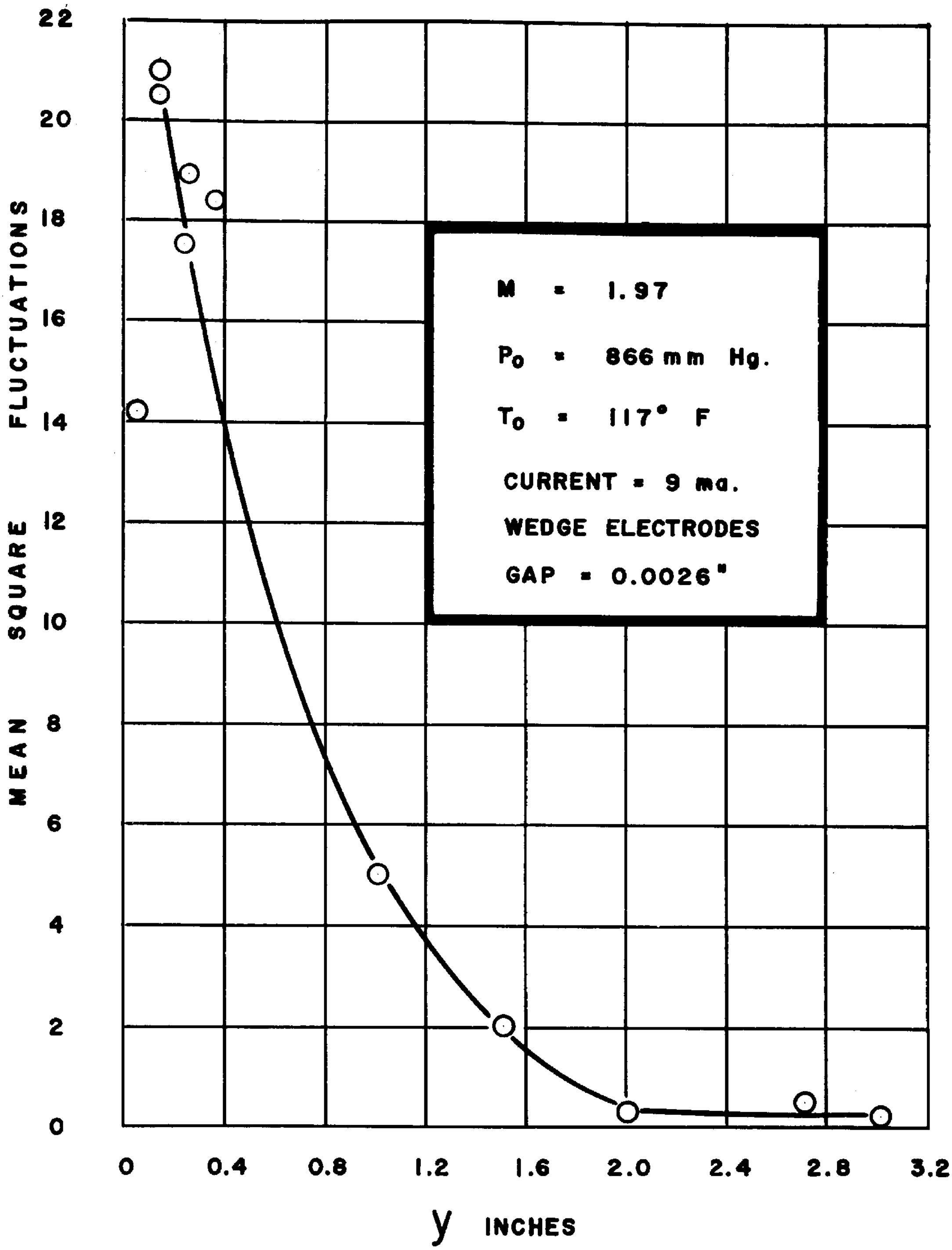
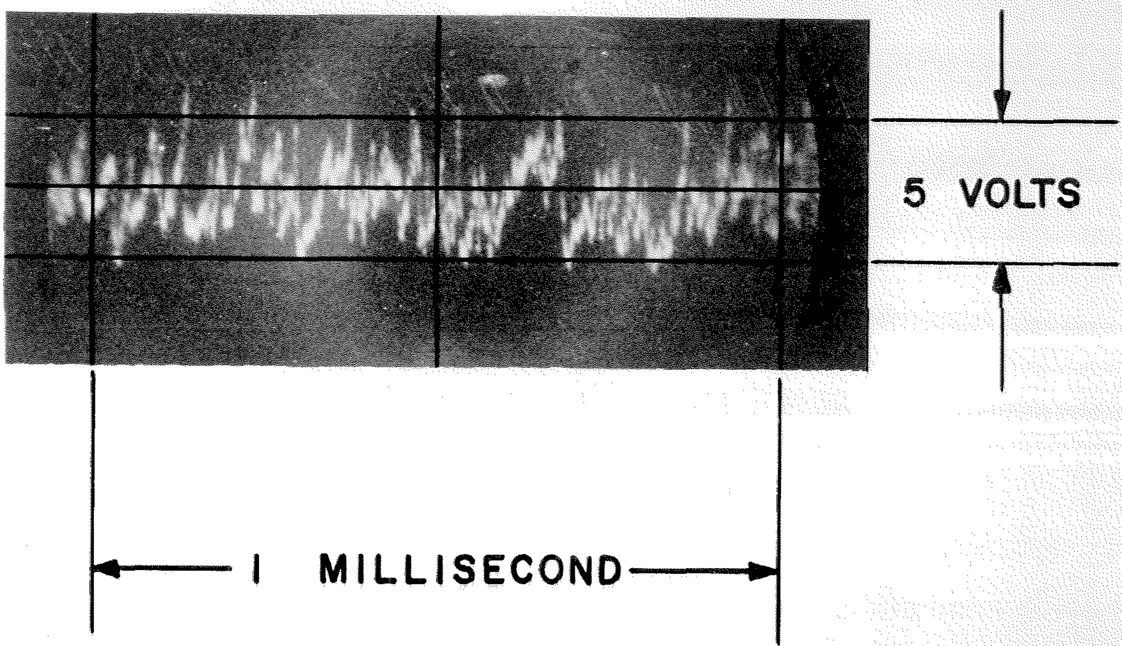


FIGURE 31. MEAN SQUARE OF FLUCTUATIONS IN BOUNDARY LAYER



M = 1.97, y = .527"

FIGURE 32 PICTURE OF FLUCTUATION ACROSS A.C. GLOW IN BOUNDARY LAYER

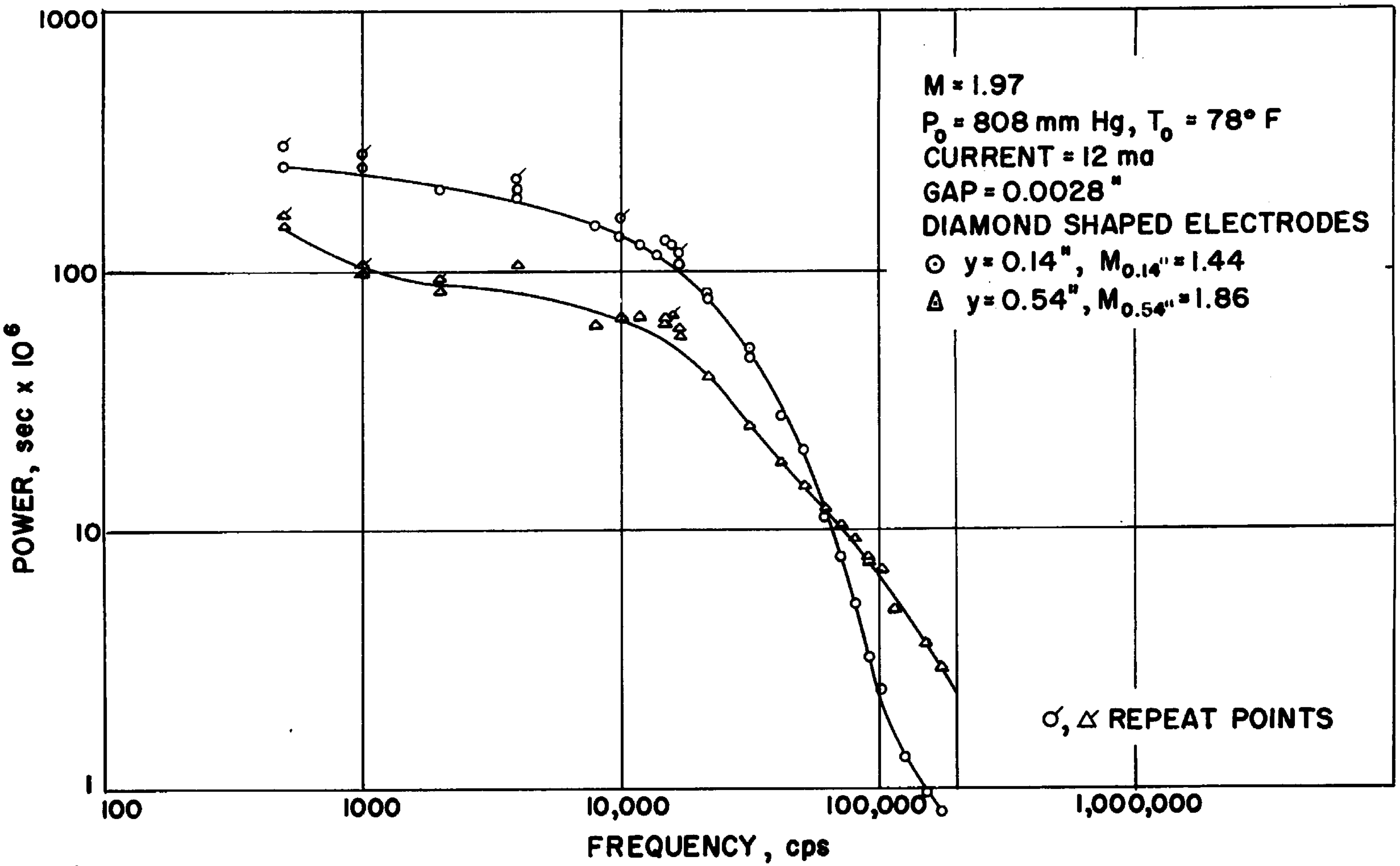
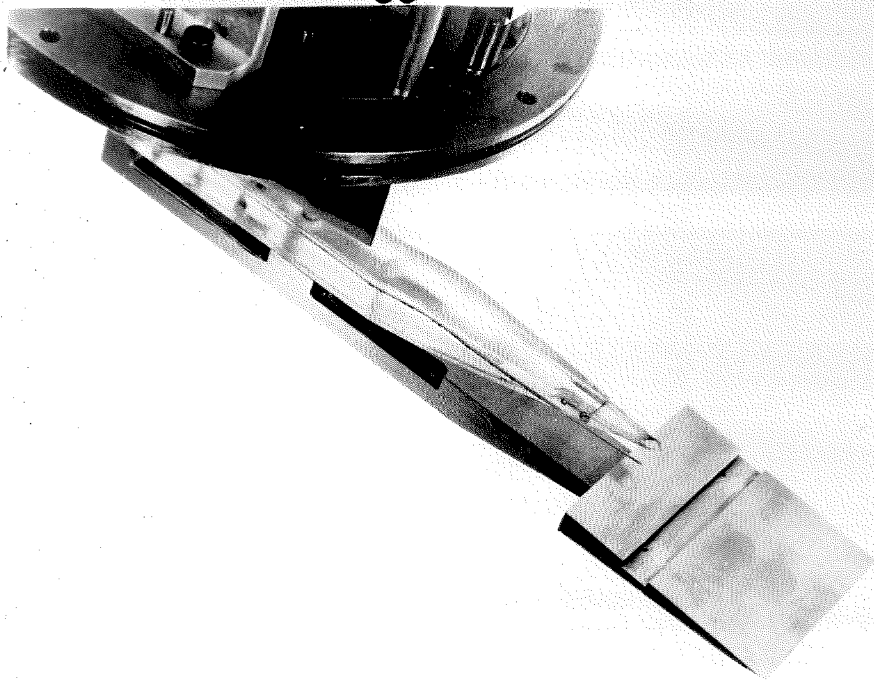
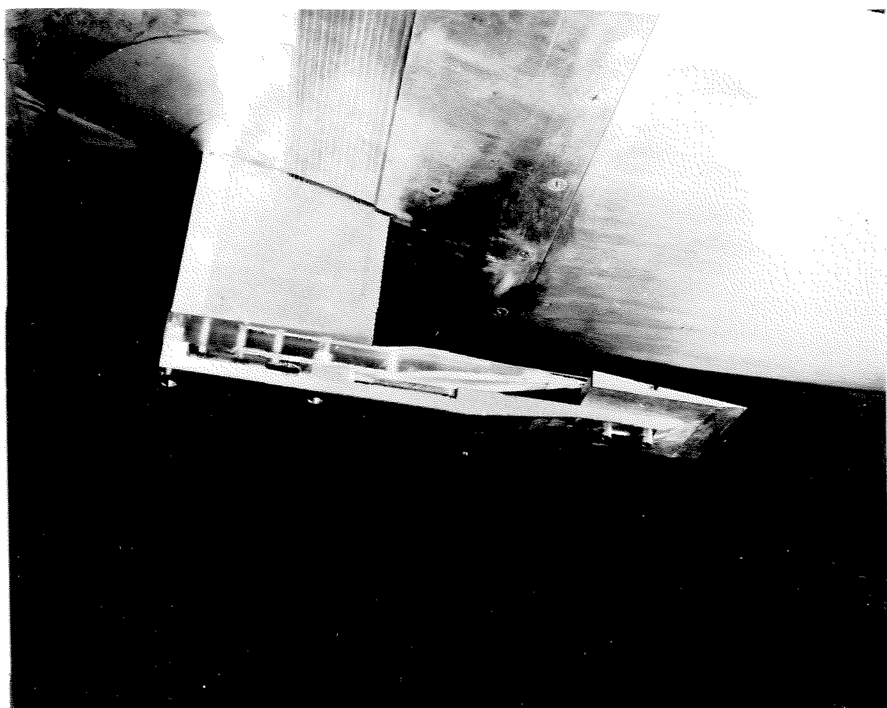


FIGURE 33. POWER SPECTRUM OF FLUCTUATIONS ON A.C. GLOW AT TWO STATIONS IN THE WALL BOUNDARY LAYER OF THE 12" WIND TUNNEL

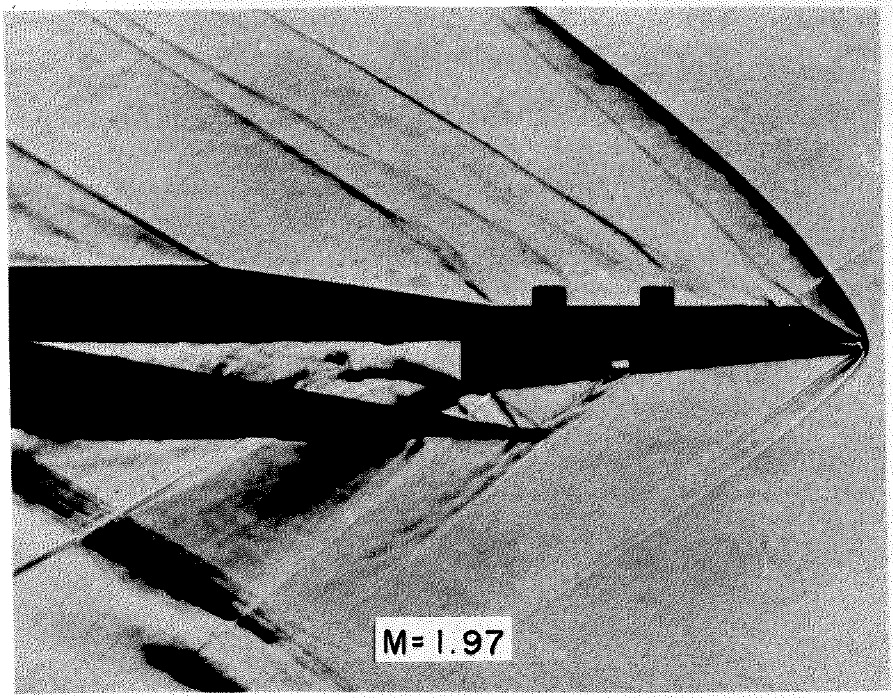


A. SLOT IN WEDGE

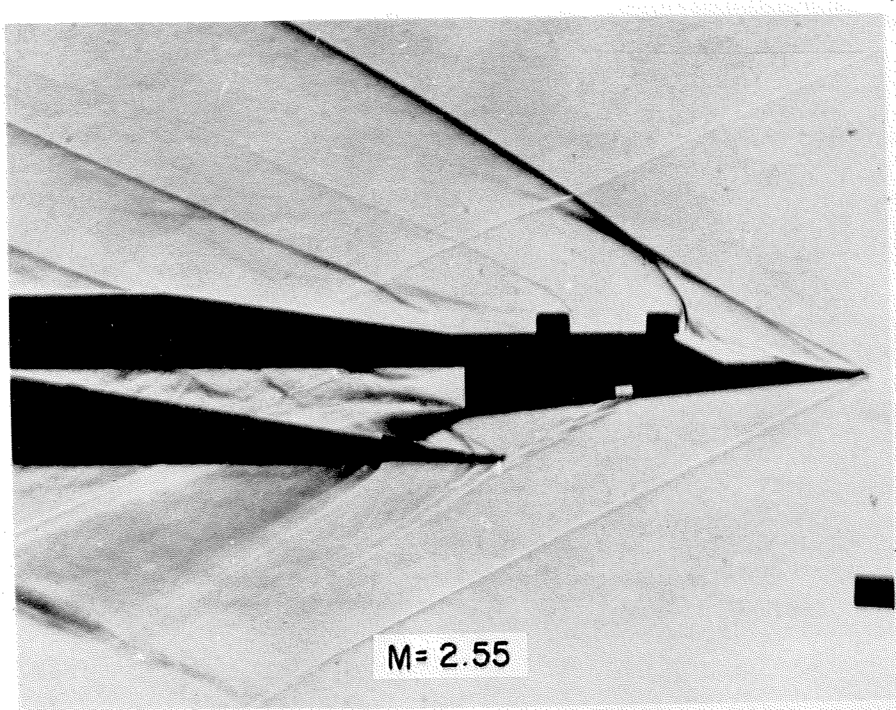


B. PROBE AND WEDGE IN 20" TUNNEL

FIGURE 34. SLOTTED WEDGE AND GLOW PROBE



A



B

FIGURE 35. SPARK SCHLERIEN PICTURES SHOWING SOUND WAVES FROM 0.2" SLOT IN WEDGE

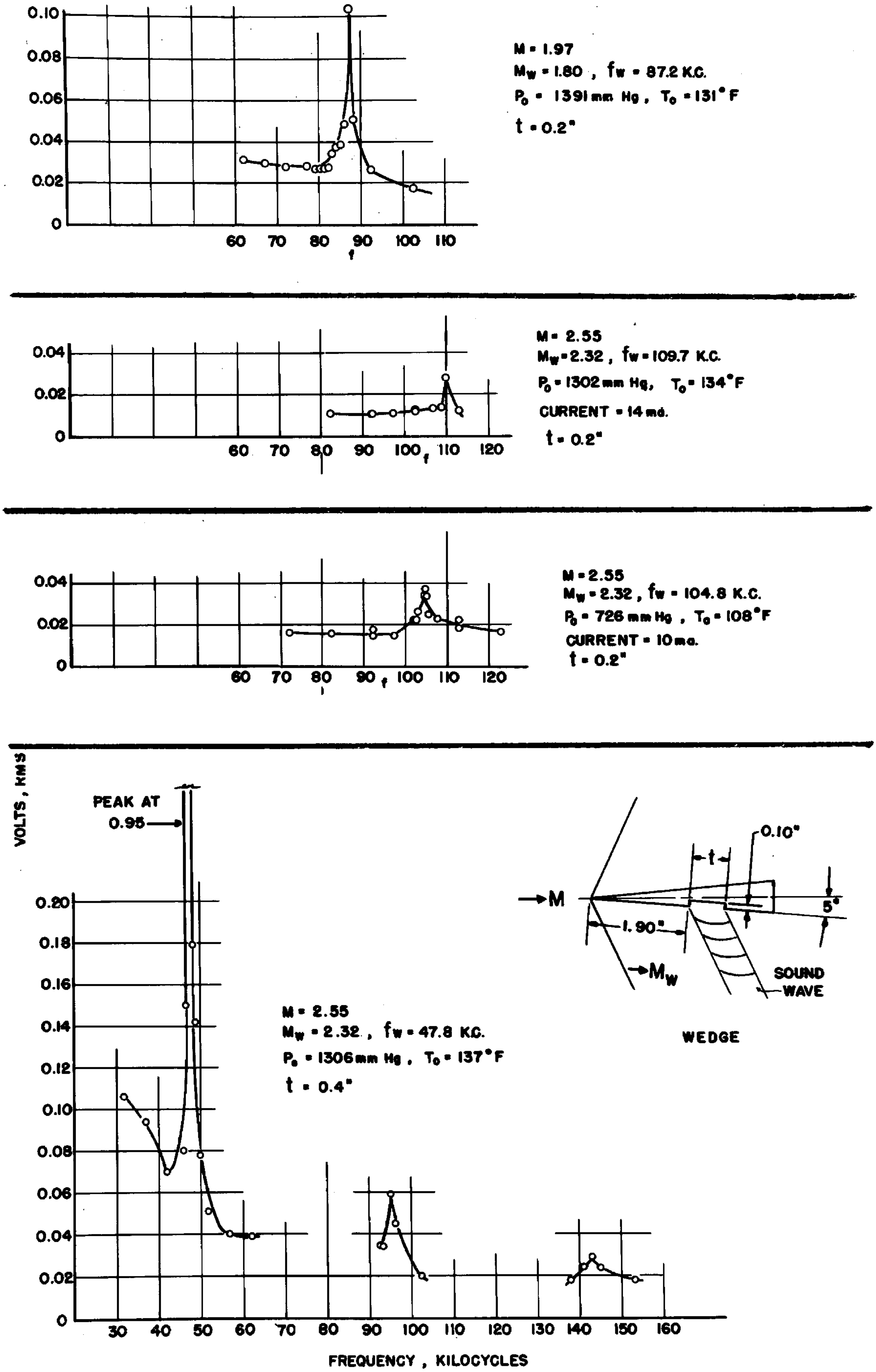


FIGURE 36 DISTURBANCE FREQUENCY INDUCED BY A SLOT IN A WEDGE IN SUPERSONIC FLOW