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ION TRACER TECHNIQUE FOR AIRSPEED MEASUREMENT AT LOW DENSITIES

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SUMMARY

A study has been made of the aerodynamic and production-detection problems associated with ion tracer velocity measurement technqiues, with particular emphasis on those aspects unique to low-density gas dynamics. A critical survey was made of the various techniques which have been employed and specific suggestions are offered relative to the successful use of ion tracer velocity measuring methods at low densities. A description is also included of some experimental work which was carried out with an ion-pulse airspeed indicator developed by the Ames Aeronautical Laboratory Low Pressures Group of the National Advisory Committee for Aeronautics for use in low-density wind tunnels.

INTRODUCTION

In recent years considerable interest has been directed toward the use of ion tracer techniques for the measurement of gas velocities. The methods holding the most promise appear to be those in which small packets or clouds of ionized molecules are produced at some point in the gas flow field. These "marked" packets can be detected electrically and hence their time of transit between any two points along a streamline can be measured.

Although much useful information is currently available on the ion tracer technique for velocity measurement (refs. 1 to 5), no systematic study has yet been made concerning the applicability of this method to low-density aerodynamics in the region below 1 mm Hg static pressure. An instrument capable of making direct velocity determinations would be particularly desirable in this field of research where interpretation of results obtained by the conventional methods, that is, utilization of impact and static pressure probes, is rendered difficult because of large viscosity effects and departures from continuum behavior of the gas.

In this report a study has been undertaken of the aerodynamic and production-detection problems associated with ion tracer velocity measurement techniques, with particular emphasis on those aspects unique to low-density gas dynamics. A critical survey has been made of the various techniques which have been employed, and some specific suggestions are offered relative to the successful use of ion tracer velocity measuring methods at low densities.

Appended to the body of this report is a description of some experimental work which was carried out with an ion pulse airspeed indicator developed by the Ames Aeronautical Laboratory Low Pressure Group of the National Advisory Committee for Aeronautics for use in low-density wind tunnels. In addition to the evaluation of the performance of this specific instrument, these experiments provided certain more general conclusions which have been incorporated in the main portion of the report.

This work was conducted at the University of California under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

AERODYNAMIC REQUIREMENTS

In order to gain a better insight into the problems involved in the design and operation of an ion cloud airspeed measuring device, it will be instructive to review here some of the aerodynamic requirements of such an instrument with regard to precision of velocity determination and probe geometry.

Precision of Velocity Measurement

The aerodynamicist is usually more interested in determining the Mach number of the flow than the absolute velocity. The Mach number can, of course, be calculated directly from the measured airspeed if the sound speed is known. In the case of wind tunnels, it should be remembered, however, that the velocity of the flow asymptotically approaches a finite limit as the Mach number increases to infinity. Consequently, the accuracy of velocity determinations required to yield a given accuracy in the derived Mach number increases rapidly with the absolute value of the Mach number. The relationship between the relative errors can easily be expressed mathematically since u is a known function of M:

$$u = \left(\frac{\gamma R T_0 M^2}{1 + \frac{\gamma - 1}{2} M^2}\right)^{1/2} \tag{1}$$

where

M	Mach number
R	gas constant
T_o	stagnation temperature
u	stream velocity
γ	ratio of specific heats, 1.40 for air

To express the error in Mach number in terms of the error in velocity one writes:

$$\frac{\delta u}{u} = \frac{\partial u}{\partial M}\frac{\delta M}{u} = \frac{M}{u}\frac{\partial u}{\partial M}\frac{\delta M}{M} = f(M)\frac{\delta M}{M} \tag{2}$$

The function $f(M)$ turns out to be independent of the stagnation temperature T_o:

$$f(M) = \frac{M}{u}\frac{\partial u}{\partial M} = \frac{1}{1 + \frac{\gamma - 1}{2}M^2} = \frac{\delta u/u}{\delta M/M} \tag{3}$$

For air, taking $\gamma = 1.40$, $f(M)$ is plotted in figure 1. In terms of the time of transit t of an ion packet between two points spaced a distance s apart the allowable absolute error becomes

$$\left|\delta t\right| = \frac{s}{u} f(M) \frac{|\delta M|}{M} = sg(M) \frac{|\delta M|}{M} \tag{4}$$

The function $g(M) = f(M)/u$ expressed in microseconds per inch is plotted in figure 2 for the case of $T_o = 535^\circ$ R, using $\gamma = 1.40$. It is seen that even for a measuring distance as large as 1 inch the time of transit at $M = 3$ must be determined accurate to about 10^{-7} second if the error in the calculated Mach number is to be less than 1 percent. These considerations are applicable to wind-tunnel testing at all density levels, though they do not apply to free-flight testing, where the Mach number increases linearly with the absolute velocity at a given altitude. But the above limitations on the accuracy of airspeed determinations are particularly serious in low-pressure wind-tunnel work, inasmuch as precise transit-time measurements become more difficult when the density of the gas stream is reduced.

It may be pointed out in this connection that the fundamental assumption in the ion tracer method is the identification of the velocity of the ion cloud with that of the gas stream. Strictly speaking, such an assumption can be made only for the central concentration maximum of a spherically symmetric ion packet in the absence of external electric fields. Any error introduced by the unavoidable assymetry of the charge distribution and the presence of external electrical fields, and through the difficulty in locating the maximum concentration, will be enhanced at low gas densities where both the diffusion coefficient and the ionic mobility are high. These aspects will be discussed more fully later.

Localization of Measurement

From the foregoing discussion it is also clear that it is impossible to make exact point velocity determinations with any time-of-transit method and that a compromise must be sought between the desired accuracy and the localization of the velocity measurements. The least count of the timing device is usually a fixed quantity; hence, as the measuring distance is decreased, the relative error must increase. On the other hand, if the separation between reference points is increased, nonuniformities in the velocity within this distance can no longer be detected and only an average speed is found. Moreover, change of shape of the ion distribution by diffusion, self-repulsion, and minute external electric field becomes increasingly more significant as the time of transit between the two measuring points is made longer. Again, these last considerations are of particular importance at very low pressures.

Interference With Flow

In any measurement technique it is desirable to keep to the absolute minimum the interference of the measuring device with the flow. In the case of ion tracer measurements, interference with the flow could be caused by the presence of the ion cloud itself and by probes used to detect the cloud. Fortunately, it can be asserted that the effect of any not too violent or concentrated ionization within the gas on the mass motion of the gas is, in general, entirely negligible. The necessary presence of ion generating and detection electrodes or probes may present serious problems, however. For some studies it may be possible to utilize electrodes mounted flush with the walls of the wind tunnel so that disturbance of the flow is avoided entirely. This technique has been applied with some success by Boyd, Dorsch, and Brodie (ref. 4) in subsonic and supersonic wind tunnels at pressures upward of 5 mm Hg. Distortion by the nonuniformity of the stream near the boundary, difficulties in making measurements of ion clouds which are well inside a large channel, or the resulting limitation to rather narrow channels detract from the merits of this method and probably render it entirely impractical for gas pressures below 1 mm Hg.

Electrodes which project into the channel, while more suitable for localized measurements, suffer from the objection that a disturbance in the flow is produced. In a supersonic stream shock waves will be formed ahead of the electrodes and the velocity of the gas passing the detection probe will be less than the velocity ahead of the shock. In particular, the disturbance produced by the ion generating system (spark gap, corona points, etc.) must be of limited size if useful data are to be obtained. Electrodeless ion production is, of course, to be preferred if sufficient intensity of ionization can be obtained. At low gas densities the disturbance of the flow by production and detection electrodes can be minimized if the dimensions of the electrodes are made sufficiently small (of the order of a mean free path or less). The effect of the shock waves ahead of the detection probes can be canceled out if a single pickup electrode is used in successive positions along a streamline and the difference in times of flight is taken for the evaluation of the velocity (cf. ref. 5). This method, however, requires extremely high reproducibility of the ion production mechanism or averaging over a large number of readings, since measurements on different ion clouds are required for each stream velocity determination. Whenever it is not possible to circumvent large fluctuations in the ion generation process, and in particular in the time taken for the charge build-up, each time of flight measurement should be performed on one individual packet by means of two simultaneously operating detectors. In this case disturbance of the flow can be minimized only by using very small detection probes. As will be shown later in this report, such a procedure introduces new problems which seriously limit the value of the method.

DETAILS OF METHOD

Production of Ions at Low Pressures

A summarizing table of methods of ion production is given in reference 3. The following section reviews the important facts with reference to low pressures.

The three chief mechanisms by which ion packets can be created in a gas are: (1) Electron impacts, most efficient at energies of the order of 100 electron volts (i.e., somewhat higher than the ionization potentials of the gas), (2) positive ion collision, efficient only at high ion energies (above 10,000 electron volts), and (3) photoelectric effect, efficient only at photon energies slightly exceeding the ionization potentials.

The cross sections for these processes usually are considerably lower than those for elastic kinetic collisions between like gas molecules. The copious production of ions in a gas at low density therefore requires a high concentration of the ionizing agency. For this reason the photoelectric and positive ion collision mechanisms are not very suitable for the present application. A positive ion gun used to form an ionizing beam would require a rather large current density and a very high accelerating voltage. Radioactive sources would have to have an excessive strength to yield a narrow beam of α particles of sufficient intensity. Similar arguments apply to the use of soft X-rays for photoionization at low pressures. It is very difficult to produce a well-collimated X-ray beam of sufficient intensity.

The simplest method for producing a relatively high ion density, makes use of an electrical discharge in the gas itself. Such discharges involve chiefly ionization by electron collisions and emission of electrons from the cathode. The large production rate is brought about by the fact that the newly freed electrons themselves are utilized to ionize in turn, thus causing an accelerating cumulative liberation of charge. The velocities acquired by the electrons must be such that a sufficient fraction of them exceeds the minimum energy needed for the action.

The technique has several disadvantages, however, because an electric field is required. Conductors must be introduced to supply the necessary high voltage and electrode surface. Therefore, special care must be taken to avoid aerodynamic disturbances of the flow and electrical coupling with the detector. A more serious handicap is the diffuse nature of electric discharges at low gas densities; sparks or coronas cannot be produced. The mean free path is too long to permit the existence of high space charge concentrations, as those found in sparks and arcs at higher pressures, so that it is not possible to produce strong fields in confined regions at some distance from any metal surface. Only in the immediate neighborhood of very small conductors such as fine points and thin wires can high fields of small extent be maintained and even then the associated charge cloud of elevated concentration will have a radius of 10 or more electron mean free paths.

It is clear that in order to obtain a relatively well confined discharge of adequate intensity a small conductor with a high negative potential should be used as cathode. The anode is less important except for defining the initial predischarge field. Any grounded conductor will serve to receive the negative charge current. In this configuration a brushlike glow discharge is set up which will concentrate the positive ion packet near the cathode, while the liberated electrons will drift in all directions along the lines of force in the low field region. Given enough time, these electrons will attach to oxygen molecules and form negative ions.

In a stream of fast-moving gas as in a supersonic wind tunnel the ion distribution will be drawn out in the direction of the flow and some positive charge will be lost downstream. If the discharge is pulsed, this oblong distribution with a nucleus of positive charge and a broad fringe of negative charge will drift with the stream as a whole, spreading by diffusion as time goes on. At low gas densities of 10^{14} to 10^{16} molecules per cubic centimeter (static pressures of the order of 10^{-2} to 1 mm Hg at room temperature) the initial charge density can be estimated at 10^9 ions per cubic centimeter or more at the center, falling off rapidly to perhaps 10^7 ions per cubic centimeter within a few mean free paths. The high charge concentration at the center will decrease rapidly by diffusion and self-repulsion after the field is removed. Since the detector will have to have some least distance from the discharge cathode to reduce the direct current pickup and minimize initial capacitative coupling, the unavoidable spreading during this minimum time of flight adds to the already large diameter of the cloud. If high accuracy is required, therefore, a pulsed discharge does not seem suitable at pressures below 1 mm Hg.

It may be possible to use an electron beam of sufficient energy and intensity to produce a narrow trail of ions of adequate density. Electrons of 10,000-volt energy are not appreciably scattered during 6 inches of flight through air at a pressure of 100 microns. Under these conditions there is one ion pair created on a 10-centimeter path for each electron in the beam (ref. 6). To liberate 10^7 ion pairs per centimeter path in a 2-microsecond pulse, the latter should contain 10^8 electrons, representing a current of 8 microamperes. This beam could have a cross section of several square millimeters in the test region. This method would have the great advantage that no obstacles need be introduced into the stream and no high-voltage pulse has to be brought into the test chamber of the wind tunnel. The equipment required would be somewhat more complicated than that for the discharge pulse. The technique seems feasible if the width of the channel ionized in this manner does not turn out to be too large. Some of these proposed methods are discussed in the appendix.

Motion of Ions

The charges produced in the manner described before are mainly singly ionized molecules and electrons. Negative ions will be extremely rare because the probability of electron attachment to oxygen is too small to be effective at pressures below 1 mm Hg within times of 1 millisecond or less. Because of the large differences in mass the behavior of the positive and negative charge carriers will differ widely. In general, the motion of these particles can be divided into three parts to indicate the different nature and cause of the various phenomena.

Inasmuch as the constituents will belong to the gas, they will drift with the body of the stream as any neutral molecule provided that there are no electric fields present. This behavior, which might be called convection, is the property to be exploited in the present application. The situation is complicated, however, by two additional effects influencing the motion of the charge particles.

When an electric field is present, ions and electrons will drift with respect to the gas in the direction of the force at a velocity more or less proportional to the field strength. The drift velocity divided by the field strength is called the mobility of the particle in the given gas. (The mobility of electrons is several hundred to several thousand times larger than that of ions, depending on the electric field strength and the gas density.) The drift of these charged particles, particularly the electrons, will cause the gas to become a conductor. Since positive and negative charges drift in opposite directions in the field, a separation is effected which may or may not be desirable in any given case. The drift of air ions (nitrogen or oxygen) in air is given approximately by (ref. 7, p. 76):

$$v = KE \approx 2 \times 10^3 \frac{E}{p} \tag{5}$$

where

v drift velocity, cm/sec

p air pressure at room temperature, mm Hg

E electric field strength, v/cm

Here K is the mobility provided E/p does not exceed a few hundred. Clearly E/p must be kept low in any region where it is required that the electric drift be negligible compared with the gas velocity. Near a metallic surface the induced charges on the conductor will set up a field attracting the mobile charges in the gas. While these forces usually are rather weak, they often are sufficient to affect the motion of the extremely mobile electrons. This is one reason why the suitability of the latter as tracers might be doubtful even if great effort is made to eliminate external electric fields.

The other complication arises from the fact that these tracers, being part of the gas, will be subject to diffusion. Since the particles are charged, this action will be accentuated by two factors. In an electric field, and in particular in a discharge, the kinetic energy of the charged particles (i.e., the temperature and therefore also the diffusion coefficient) will be higher than that of the molecules of the neutral gas and some "cooling" time will be required before equilibrium is reached when the field is removed. Secondly, any concentration gradient of charges creates itself an electric field in such a direction as to aid diffusion so that the latter never is purely due to random motion alone, but is increased by mutual repulsion. These effects are much more pronounced for electrons than for ions because the former, with their smaller mass and size, have higher velocities, longer mean free paths, and poorer momentum exchange with the gas molecules. If electrons and positive ions are present simultaneously and in equal number, as would be the case along the path of an ionizing beam, the fast radial diffusion of electrons will be retarded by the attraction of the more slowly moving positive ions which would be left behind. If the ion concentration is high enough, hardly any of the electrons can escape and the net diffusion of the cloud proceeds almost as slowly as if only massive ions were involved. This phenomenon is termed ambipolar diffusion. A purely qualitative sketch of the charge distribution along the diameter of such an ion cloud is shown in figure 3. The diffusion coefficient of ions is somewhat smaller than that of the neutral molecules in the same gas. In air at atmospheric pressure the diffusion coefficient for positive ions is of the order of 0.03 cm^2/sec; at 0.1 mm Hg it is roughly 200 cm^2/sec (ref. 7, p. 165).

These considerations will have to be kept in mind in the interpretation of gas speed measurement particularly since the method of detection also must utilize the motion of ions with respect to the receiver for the creation of an electric signal.

Detection of Charges

Inasmuch as the accurate time measurement desired for the present application involves an interpretation of the pulse shape, a detailed analysis of the origin of the received signal must be carried out. Also the possible effect of the method of detection on the time of flight of the ions themselves should be investigated. In connection with this aspect much confusion can be avoided if a few general principles are well understood.

The macroscopic phenomena associated with electric charges are commonly divided into several distinct groups. The two of interest here are the presence of separated positive and negative charges causing fields and potentials (static electricity) and the motion of charges representing real currents and causing displacement currents (quasi-static electricity). The two are related, of course, by the condition of continuity (conservation law) and by the laws of motion.

While the two effects can never be entirely separated (for example, accumulation or separation of charge in itself requires or represents a current), the detecting device can be designed to emphasize one or the other aspect. Basically, an electrometer is sensitive to voltage. If the potential of an isolated conductor (e.g., one side of a capacitor) is measured, the amount of charge on it can be derived; and, if the voltage drop across an impedance (e.g., a resistor) is utilized, the current through it can be determined. In practice, some capacity C and some leakage resistance R are always present simultaneously, giving the instrument a certain time constant characterized by the product RC. If the time of charging of the capacitor is short compared with RC, the instrument will indicate the amount of charge accumulated or induced. On the other hand, if RC is much shorter than the charging time, the instrument essentially will measure the collected or induced current. In the intermediate region the response is a mixture and generally very difficult to interpret. In designing an ion cloud detector amplifier it is therefore important to have some previous knowledge of the expected pulse rate of rise, amplitude, and decay.

In the airspeed measurements it is essential to locate accurately the point in time at which a concentration maximum of positive ions passes a given point in space. The following sections discuss the possible methods by which this can be achieved in the case of low gas densities.

Detection by induced effects.- Most of the previous work avoided or neglected the collection of charge by the detector probes and utilized the induction effects for the locating and timing of the ion packets. A fairly complete analysis of the phenomena involved in this method can be found in reference 3. At low gas densities, however, several difficulties appear. First of all, the ion clouds are usually spread out over a rather large region so that the signals received are very broad. It should be realized in this connection that the induced voltage is highest or the induced current is zero when the total charge on the probe, induced by the whole cloud (induction effect integrated over all space), is largest. This instant need not coincide with the moment at which the point of highest charge concentration is closest to the probe. In any ion packet whose distribution is strongly dominated by diffusion, however, the deviation will be very small.

A more serious problem is caused by the unavoidable distortion of the signal due to the collection of charge by the detector probe wire or plate at low pressures. The ion clouds are so large that it does not seem possible to place the induction pickup electrode entirely outside the trajectory of the charges as was done in some of the studies at higher densities (refs. 3 and 4). Any exposed conductor projecting into the path of the ions will collect charges unless it is given a retarding potential of sufficient magnitude (probably of the order of 1 volt positive for the suppression of the ion current). Such a procedure would introduce electric fields distorting the ion cloud trajectory, however, and, what is worse, would make the probe an efficient electron collector, thus introducing new and probably even more serious distortions of the received signal.

A third difficulty arises from the fact that the induction pickup responds only to the net charge of any given volume element in its neighborhood. Since ion production by electrodeless means, as for instance by an electron beam, creates essentially neutral ionized regions in the gas, poor induced pulse amplitude will result with this method of detection unless the discharge-type ion generation is employed.

Detection by ion collection.- The collection of ions itself can, of course, be used as a means of detecting the arrival of the concentration maximum. High efficiency can be guaranteed if a negative potential is given to the pickup probe so that ions will be attracted. Certain precautions must be taken, however, to avoid two sources of error. As pointed out in the section "Motion of Ions," the electric field associated with a probe at negative voltage with respect to its surroundings should not be permitted to penetrate appreciably into the ion drift space. Acceleration of the ion packet would result and unreliable measurements would be obtained except, possibly, if the difference method mentioned in the section "Interference With Flow" is employed. More seriously disturbing is the fact that any charge-collecting action by a detector is always associated with a certain amount of induction effect. The related phenomena can best be illustrated by a few sketches shown in figures 4 and 5. The instant of actual collection of an ion by an electrode is the point in time at which the ion hits the metal surface and is neutralized, that is, at which the ion reaches the end point of its trajectory. The associated current registered by the electrometer is the rate of change of induced charge immediately preceding this instant of ion collection. If all ions in a given packet were caught by a certain electrode, the signal could probably be properly interpreted. Inasmuch as a small collecting probe in the present application will presumably catch only a fraction of the passing ion cloud, a distorted and shifted signal will result which will, in general, not be suitable for the detection of the ion density maximum.

The only possible way to avoid both the difficulty of the drift disturbance and the signal distortion is the introduction of a small, screened collecting probe as indicated in figure 6. A few volts negative potential on the central collector with respect to the grounded shield will, in general, be sufficient to insure rapid, complete collection of all positive ions entering the cage. No appreciable electric fields can penetrate to the outside and disturb the ion motion there and very little induction effect due to the motion of ions outside the probe is felt by the inside conductor. The pulse shapes received by such a shielded probe are sketched in figure 6. An additional advantage of this arrangement is the selectivity as to sign of the charged particles in the tracer packet. The negative screened probe will respond almost exclusively to the positive ions in the stream and the signal will be relatively little distorted by the accompanying electron distribution. The only serious difficulty in the shielded-collector method of detection is the unavoidable disturbance of the flow by this necessarily bulky probe. If a single detector can be employed, however, this disturbance can be canceled out in the manner described in the section "Interference With Flow."

CONCLUDING REMARKS

On the basis of the preceding discussions it can be concluded that there is reasonable hope that the ion tracer technique can be applied to low-density gas velocity determinations, in particular if well-localized electrodeless ionization turns out to be feasible. The details involved in the actual time-of-flight measurements to be performed need not be explained here, since they are the same as those at higher pressures and have been described in the various previous publications referred to before. Moreover, a specific example is given in the appendix.

It might be pointed out, however, that if an accurately pulsed, well-collimated transverse electron beam is used for the ion production there is little doubt that sufficient reproducibility for a single-detector method can be obtained. In such a case the most reliable data will be obtained when the shielded collector detection probe is kept fixed for a given velocity determination and the pulsed electron beam is moved along a streamline. In this way any possible effect of the probe on the flow is kept absolutely constant and the times of flight of the ion clouds can be used to map the stream velocity ahead of the obstacle. Or better still, if sufficient resolution can be obtained, it would be most convenient to employ two simultaneously pulsed parallel electron beams transverse to the stream so that the interval in the times of arrival at the probe can be used directly to indicate the velocity of the flow in the region between the two beams.

Considerable experimentation will probably be needed before the electrodeless ionization technique can be incorporated in a useful laboratory instrument.

University of California,
Berkeley, Calif., February 20, 1953.

APPENDIX

INSTRUMENTATION AND EXPERIMENTAL WORK

NACA INSTRUMENT

The National Advisory Committee for Aeronautics Low Pressures Research Group at the Ames Aeronautical Laboratory, Moffett Field, California, has constructed an ion-pulse true-airspeed indicator for low-density supersonic wind tunnels. The instrument utilized a pulsed discharge for the generation of ion clouds and as originally constructed was equipped with two unshielded collecting electrodes spaced about 1 inch apart. The detector preamplifier could be connected to either of the two probes by means of a manually operated switch. The pulse generating and timing circuits included in the complete unit are indicated schematically by means of a block diagram in figure 7. Details of the circuitry and operation of this instrument are contained in an internal Ames Laboratory memorandum.

The device was tested in the small low-density wind tunnel at the Ames Laboratory (unpublished work). The measured velocities seemed to be in reasonable agreement with the calculated ones, but careful checks could not be made because the region of uniform flow was too limited in the small test section of the tunnel. Subsequently, the equipment was shipped to Berkeley where further investigations could be carried out in the large low-density supersonic wind tunnel (ref. 8).

Adaptation for Work at Berkeley

For the tests in the large wind tunnel at Berkeley certain modifications were desirable. The preamplifier carrying the pickup probes was detached from its battery power supply and inserted as a whole into the test section and was mounted rigidly on the remotely controlled traversing carriage so that the probe position with respect to the nozzle could be changed. The manual selector switch connecting the probe wires to the preamplifier was replaced by an electrically operated one. Fifteen feet of low-capacity coaxial cable was used to lead the high negative voltage pulse into the test section to the 0.010-inch-diameter tungsten discharge wire which protruded through the nozzle wall into the center of the stream. Shielded microphone cables connected the preamplifier output signals to the remainder of the timing circuit outside the tunnel. Because of the long connections needed the pulse applied at the discharge gap as well as the received signals suffered a certain unavoidable attenuation and distortion.

In the original tests conducted at the Ames Laboratory it was possible - because of the small size of the air jet - to shield the detection probes from the discharge. This was not feasible in the Berkeley wind tunnel.

To facilitate time measurements with a calibrated Tektronix synchroscope the differentiated multivibrator signal of the NACA instrument was brought out separately and fed into the external trigger input terminal of the synchroscope. The time elapsed between the discharge pulse and the starting of the synchroscope sweep could thus be varied by means of the multivibrator controls. Since it was expected that time of flight measurements in the Berkeley wind tunnel would extend over intervals of several hundred microseconds, corresponding to distances up to 10 inches, the range of the first multivibrator was increased 10 times to a maximum period of 800 microseconds. The intervalometer provided in the original design was not used. A schematic diagram of this modified arrangement is shown in figure 8.

Measurements With Unshielded Probe

Attempts to determine the airspeed in the Berkeley wind tunnel with this instrument using unshielded probes were not successful. The peak voltage which could be applied to the discharge electrode was estimated from oscillograms to be about 2,500 volts. This was not sufficient to cause reproducible impulse breakdown in the fast-moving air at pressures below 0.10 mm Hg. Above this minimum pressure the pulsed discharge appeared as a diffuse purple glow of about 1-inch diameter surrounding the tungsten wire sometimes along its total length. The current spread in all directions, presumably returning to ground through the tunnel walls.

The signal received by the detector was not suitable for transit-time measurements. Excessive interference from the discharge both by capacitive coupling and by direct current was noted (a strong negative signal deflection, the time of arrival of which was essentially independent of the probe position but having an amplitude which decreased as the distance from the nozzle was increased). The portion of the signal which could be clearly associated with the positive ion drift was too broad to operate the peak selector. Crude measurements made using the apparent shift of certain points of the ion signal gave erratic results, presumably because the wave shape was caused by a mixture of collected and of pure induced current.

Measurements With Shielded Probe

In line with the discussions of the section "Detection of Charges," it was believed that many of the difficulties encountered could be eliminated by proper shielding of the probes. As an attempt to verify this interpretation and in the hope of obtaining better results, the tips of the probe wires were surrounded by grounded cylindrical screens constructed of 0.001-inch-diameter tungsten wire (see fig. 9). It was found that this screening attenuated the outside field signals by a factor of about 20. The remainder of the circuit was left unaltered. This shielded probe system was mounted in the test section of the wind tunnel as before and a plastic nozzle with design Mach number 3.1 was selected for the velocity measurements.

The signal received by the improved probe differed from that of the unshielded detector as expected. The induction effect due to outside electric fields and charge motion was reduced considerably, while the response to positive ions entering the detector was stronger than before. The direct discharge current from the pulsed high-voltage wire, however, turned out to be still considerable. Apparently the electric field of the strongly negative pulse still penetrated far enough to drive electrons from the discharge into the shielded probe. For this reason it was not possible to use the signal when the detector was less than 2 inches downstream from the high voltage wire. In order to make measurements closer to the nozzle exit, the discharge wire had been bent so that its tip was located on the axis about 1 inch upstream of the exit of the nozzle.

The positive ion current collected by the probe appeared in pulses 300 to 400 microseconds long. Unless these pulses were considerably broadened by the amplifier, they must be interpreted as associated with ion clouds 8 to 10 inches long, which would indicate that these clouds extended 6 to 8 inches upstream into the nozzle during the discharge. This is surprising, since in the cross-stream directions the ion clouds were clearly limited to a diameter of about 2 inches. It must be concluded then that the discharge mainly took place between the negative wire and the grounded metal wall surrounding the nozzle entrance. Undoubtedly a wide grounded region on the inside of the nozzle wall immediately upstream of the discharge wire would have improved the situation considerably.

Unfortunately, the preamplifier belonging to the detector unit of the NACA instrument was not designed to handle pulses of such a long duration but acted more or less as a differentiating circuit for the signal (simultaneously yielding poor amplification). This partially differentiated signal appeared on the low-level output line of the preamplifier (connected to the input of the third stage). Because long shielded leads with considerable capacity had to be used in these tests the last stage of the preamplifier had an integrating action such that the high-level output of the detector system reproduced the original pulse although undoubtedly in a somewhat distorted shape.

Freehand sketches of the signals received by the upstream detector probe as they appeared on the synchroscope are shown in figure 10, where A signifies the stationary part of the pulse, clearly caused by direct negative discharge current, and B marks the section of the signal associated with the collected ion current. Both parts decreased in amplitude as the distance between the detector and the nozzle was increased. The length of pulse A did not change, as expected, and pulse B spread only slightly as the distance of flight was increased. The signal received by the downstream probe was always considerably attenuated and differed somewhat in shape from the pulse received by the upstream probe. A shadowing and flow-distortion effect was clearly indicated.

All signals were very steady and reproducible as long as the discharges were stable. The gas flow velocity could thus be measured by noting the shift in time of the collected pulse for a given displacement of the detector.

Again, unfortunately, the signals from the last stage of the preamplifier were much too broad to operate the "peaking circuit" (pulse shaper) in the proper fashion. It was therefore decided to utilize the differentiated pulse appearing on the low-level output for the time-of-flight measurements. Two points on the oscilloscope trace could be located easily: The point of zero signal or crossing point a and the negative peak b as indicated in figure 10. Point a was considered to be relatively closely associated with the maximum concentration of the ion cloud. Moreover, point a could be located more accurately (±0.5 microsecond) than point b (±1 microsecond) on a 100-microsecond synchroscope sweep.

In practice, the measurements were carried out in the following manner. When the airstream was stabilized, the pulsed discharge was started and the upstream detector probe was moved into position. The signal put out by the preamplifier was fed into the synchroscope, the calibrated sweep of which was triggered by the variable multivibrator pulses (variable delay synchronized with the discharge pulses). The gate of the coarse multivibrator was adjusted to bring point a or b into the field of view of the 100-microsecond sweep of the synchroscope. The gate of the fine multivibrator was adjusted to line up point a or b accurately with one of the marks on the oscilloscope screen. The detector was then moved 1 inch in the direction of the flow, and the shift of point a or b on the screen was recorded. Subsequently, the multivibrators were readjusted to shift the signal back into the first position on the screen and the detector was moved another inch, and so on. This was carried on over a total length of 6 inches along the axis of the supersonic jet and was repeated at a level 1.50 inches below the axis. All measurements were done using both points a and b. The results are shown in figure 11. The reproducibility of any given measurement (scatter) was within about 3 percent. The difference between the velocities of point a and point b is seen to have been less than the probable error, indicating that the effect of diffusion was negligible in this part of the ion cloud. Apparently the ion cloud was spread over too large a volume and was too uniform in density to show rapid diffusion in the center portion. Moreover, the differentiated signal probably was so badly distorted that it was not possible to be certain of the exact location of points a and b within the cloud.

Comparison with the velocity corresponding to the measured Mach number as determined by impact and stagnation pressure measurements and assuming isentropic flow reveals a consistent discrepancy. Because of the rather limited accuracy of all these measurements, coupled with some uncertainty in the isentropic-flow assumption, the lack of agreement should not be regarded as too serious. In addition, it should be pointed out that a systematic error in the ion cloud transit-time determination could have been introduced by an inaccuracy of the synchroscope sweep speed which is guaranteed to only 3 percent. For reliable measurements calibration with an absolute standard such as a crystal controlled signal generator would be needed.

In spite of the rather sketchy results so far, it should be quite clear from the preceding discussions that the shielded detector probes are considerably more suitable for ion cloud detection in a low-pressure gas stream than the unshielded ones.

SUGGESTIONS FOR FURTHER DEVELOPMENT

Detection Amplifier

For reliable measurements it is of considerable importance that the amplifier for the ion current pulse does not distort the signal. It is necessary, therefore, that the detector be provided with a wide-band pulse preamplifier which can readily be inserted into the test sections of wind tunnels. A reliable peak selector or a good differentiating circuit should be included to facilitate locating the time of maximum ion current.

Electron Beam Ion Source

It is clear that a pulsed electric discharge is not a suitable means for well-localized ion production at gas pressures in the neighborhood of 0.1 mm Hg. It is advised, therefore, that a suitable electron gun for the production of ions by a pulsed electron beam be developed. Several methods seem possible for the present application (see also refs. 2 and 3). An auxiliary pulsed discharge could be produced at test-section pressure in a well-shielded side tube. A small hole in the anode would permit the electrons to leave the gun, and it is known that many electrons will fall through the total potential without noticeable loss in energy. For reliable operation it would probably be best to maintain a steady weak glow discharge at about 500 volts and $100 \mu a/cm^2$ in this side tube to keep it filled with conducting plasma, so that a 5,000- to 10,000-volt negative pulse at the cathode could produce the desired electron beam without any loss in time for breaking down the gas. The anode and shield of this gun could be kept at ground potential at all times. The only remaining problem then would be the introduction into the tunnel of a sufficently short and strong potential wave to force the pulse through the discharge.

The difficulties involved in producing a high-voltage pulse can be avoided if a conventional-type electron gun is employed. Here the accelerating potential may be kept constant and the electron beam could be suppressed and released at will by a shutter grid at the low-voltage end. This method would have the added advantage that electrostatic focusing of the beam could be obtained without much effort. The chief objection to this method is the fact that a rather fast additional pump is needed for the continuous evacuation of the gun chamber. The pressure in the gun should be 0.01 micron, while the collimating hole through which the beam passes and gas from the test section enters may have to be 0.1 square millimeter in area to obtain sufficient ionization. For a test-section pressure of 100 microns the pump speed would have to be at least 1 micron-liter, that is, at least 100 liters at a pressure of 0.01 micron. While cumbersome, such an arrangement is definitely possible (in a large free-jet wind tunnel, for instance, a diffusion pump can be mounted totally inside the test chamber). The rear end of a suitable cathode-ray tube could be used to great advantage to form the electron beam if an additional accelerating electrode is added. If it were not possible to reactivate the oxide-coated cathode of such a tube with sufficient ease, a thoriated tungsten filament would be used. Several milliamperes total emission current would probably be needed for the manufacture of an adequate electron beam.

Eventually, a double-beam electron gun should be designed, since it appears likely that the best results will be obtained with a two-pulse single-detector method as described previously, as long as the clouds can be kept sufficiently well separated. It may turn out that even a collimated energetic electron beam produces very diffuse ion clouds at low gas densities because most of the ionizing is done by the few strongly scattered electrons. In this case it would be necessary to investigate the possibility of adding a longitudinal magnetic field to the electron gun to keep the electrons in the narrow beam. A field of 400 gausses will keep 600-volt electrons on a 2-millimeter radius while having only a small effect on the massive positive ions (in spite of their low kinetic energy, since they have a much shorter mean free path). Such a method would permit the use of lower energy electrons because of the reduced loss by scattering. Softer electrons, however, have a higher ionizing probability, so that a less intense beam would have a sufficient yield. Moreover, the lower voltage in the electron gun will permit operation at higher gun pressure so that smaller pumps could be employed.

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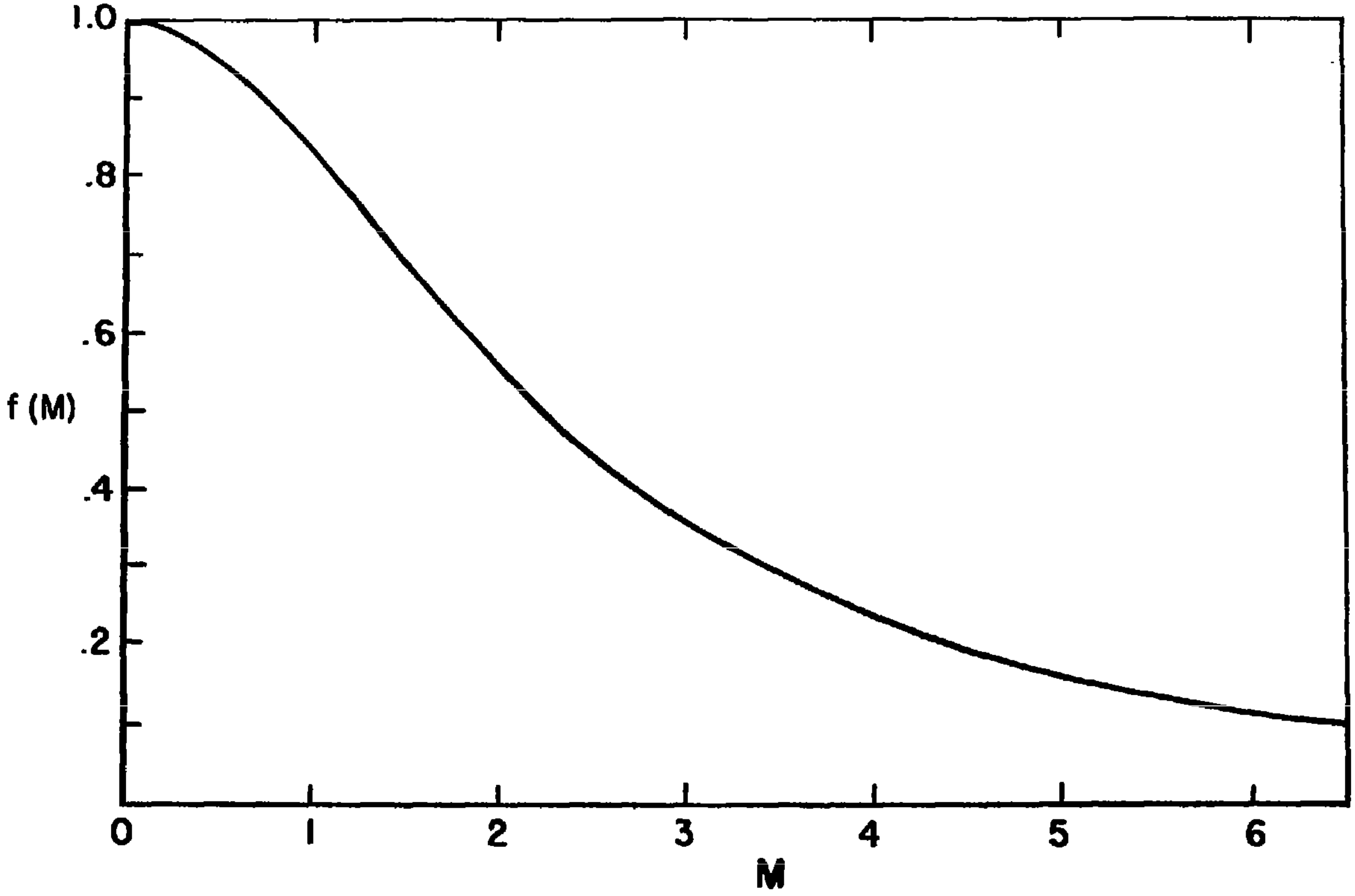


Figure 1.- Ratio of relative error in true air velocity to relative error in Mach number as a function of Mach number for adiabatic expansion of the gas. $\frac{\delta u}{u} \Big/ \frac{\delta M}{M} = f(M) = \frac{1}{1 + 0.2M^2}$.

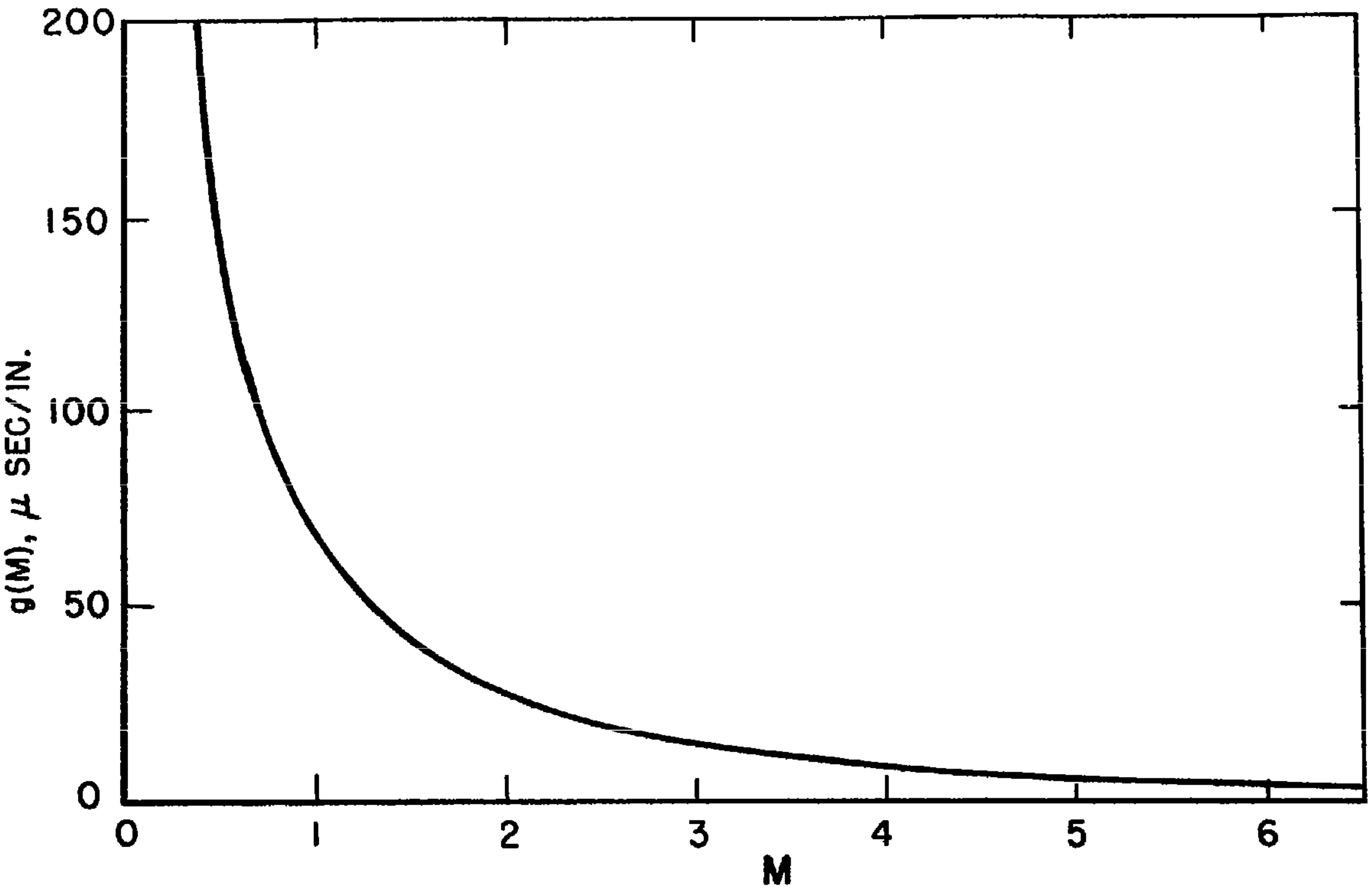


Figure 2.- Precision required for time-of-flight measurement for a given flight distance and a given precision in Mach number in case of adiabatic expansion of air. $|\delta t| \Big/ s\frac{|\delta M|}{M} = g(M) = \frac{73.8}{M\sqrt{1 + 0.2M^2}}$; $T_o = 535^\circ$ R; $\gamma = 1.40$.

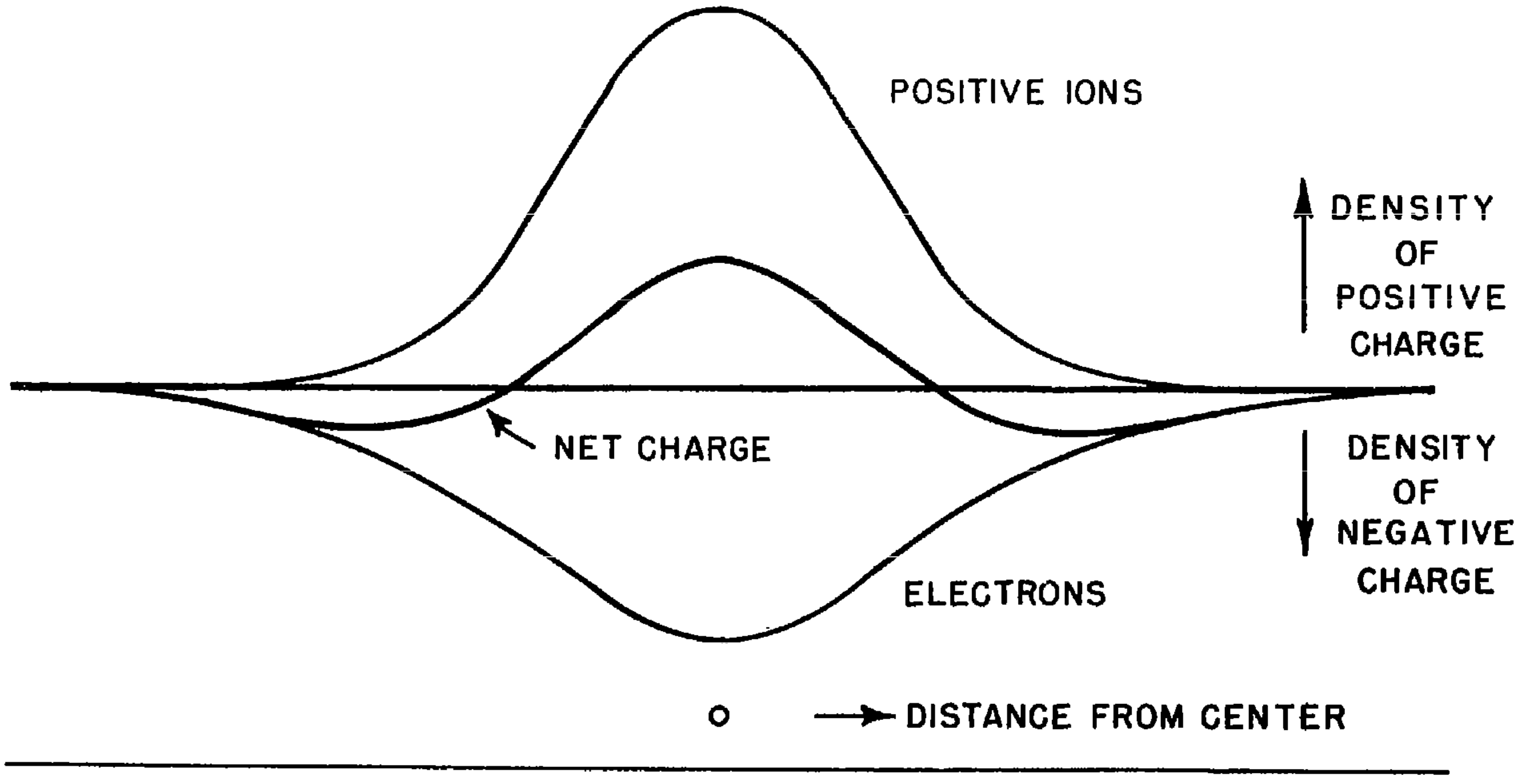
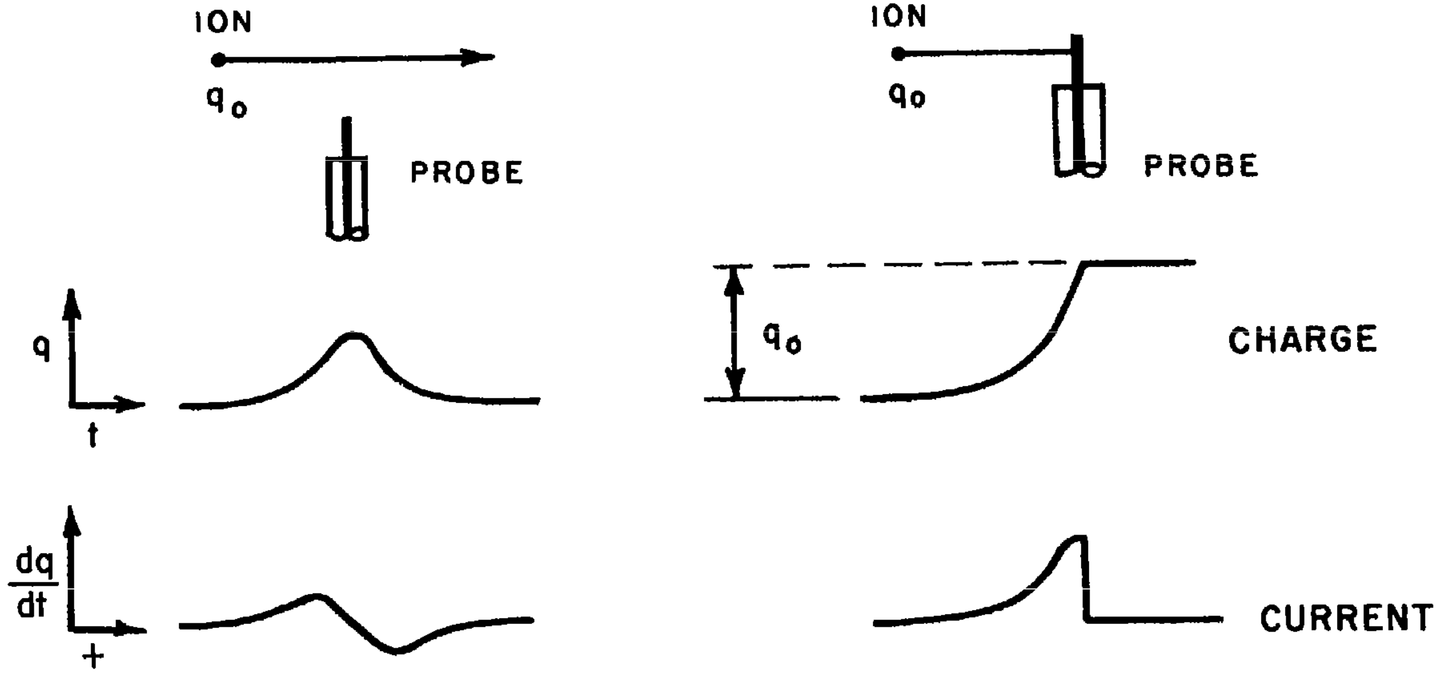


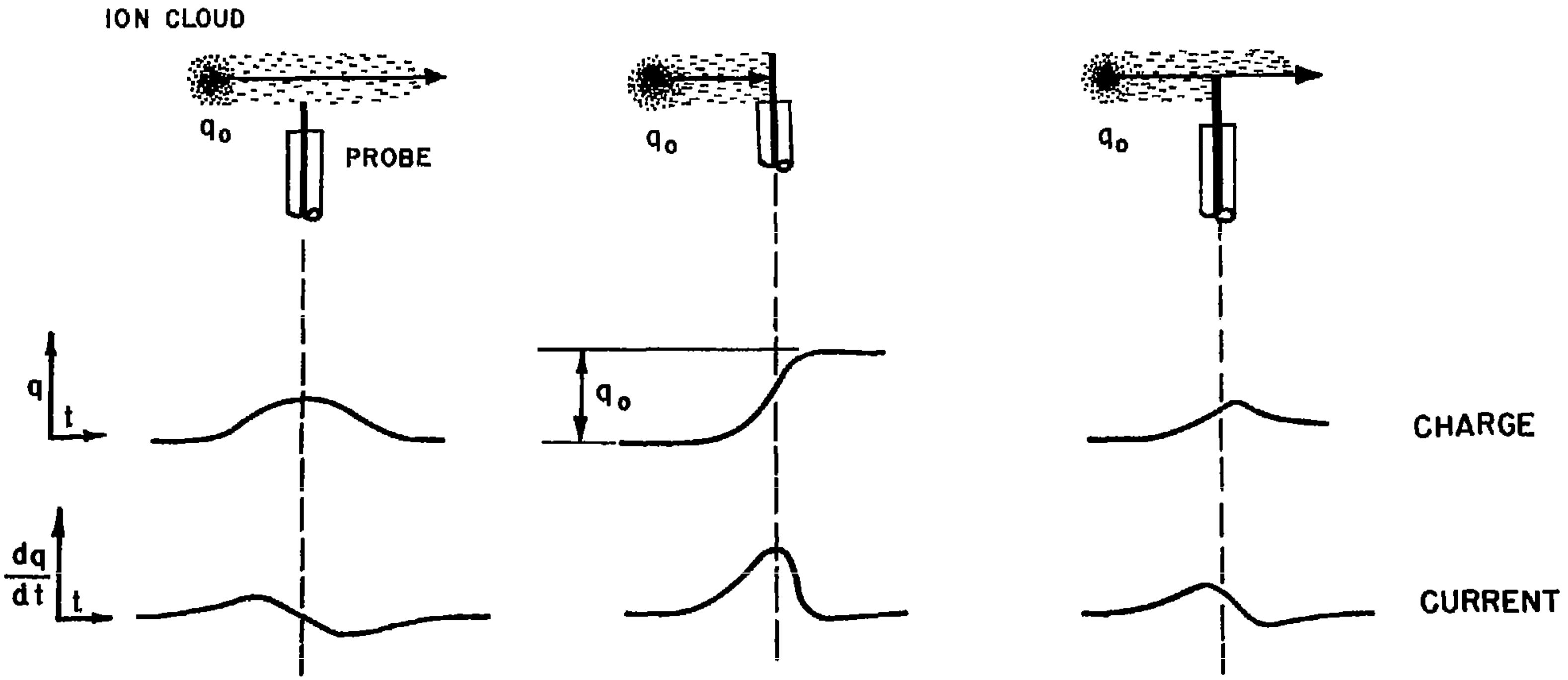
Figure 3.- Qualitative sketch of charge distribution in an initially uniformly ionized packet after some time.



(a) Induction only.

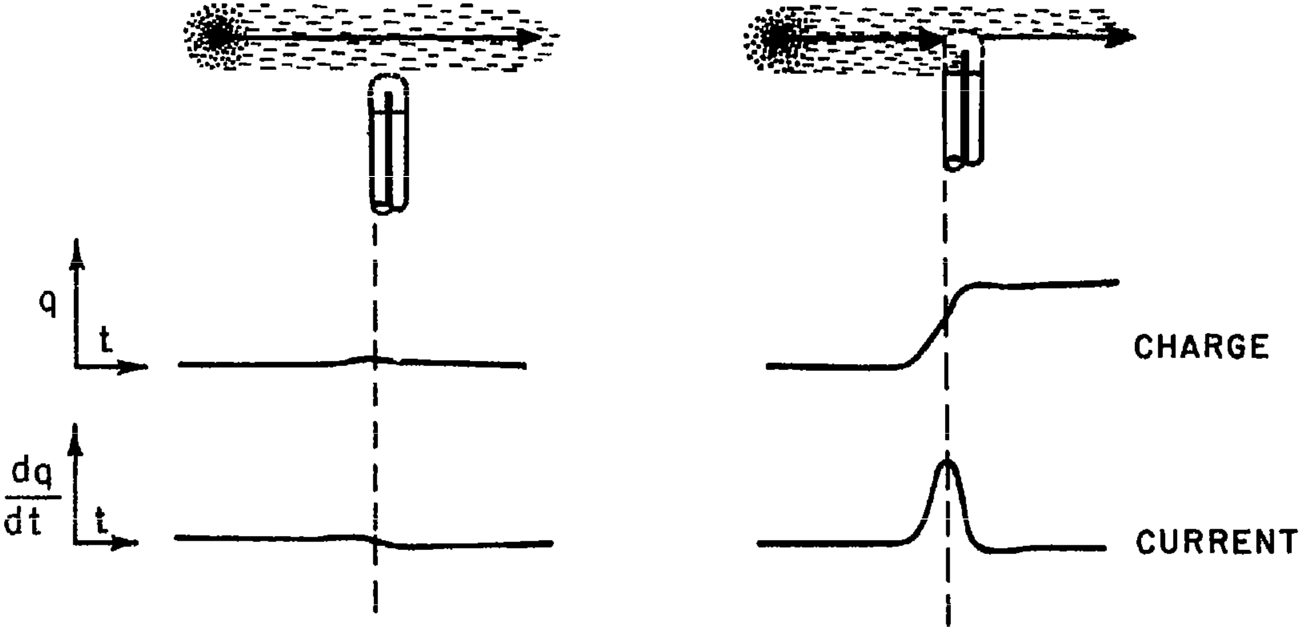
(b) Collection.

Figure 4.- Qualitative sketch of pulse shape received by unshielded probe from motion of a point charge q_0.



(a) Induction only. (b) Complete collection. (c) Partial collection.

Figure 5.- Qualitative sketch of pulse shape received by unshielded probe from motion of a charge packet of total charge q_o.



(a) Induction only. (b) Partial collection.

Figure 6.- Qualitative sketch of pulse shape received by shielded probe from motion of a charge packet.

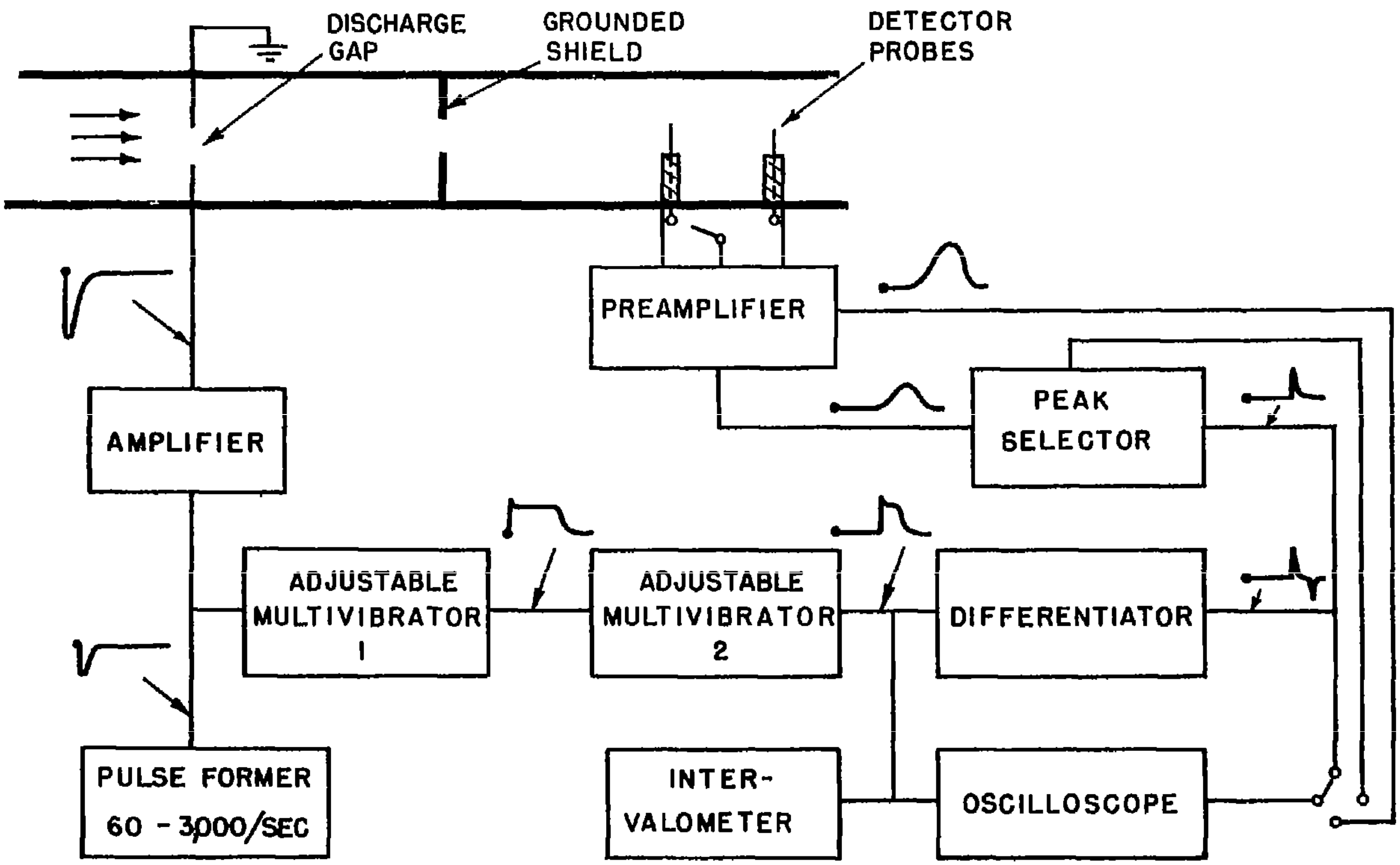


Figure 7.- Schematic diagram of original design of NACA ion-pulse true-airspeed indicator. Pulse shapes are indicated. Multivibrator 1 is adjusted to match delay; multivibrator 2 is adjusted to match interval between signals from the two probes.

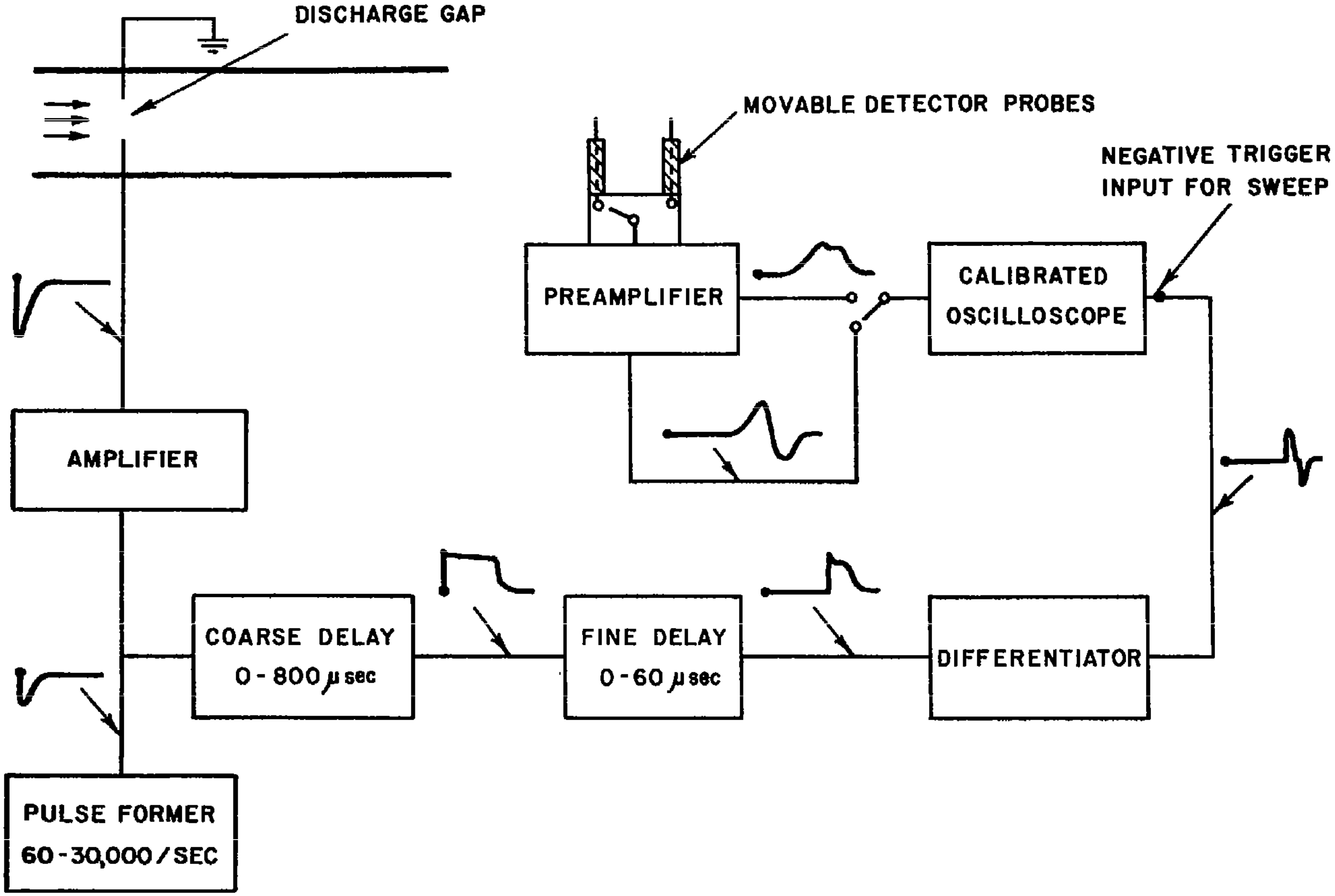


Figure 8.- Schematic diagram of modified circuit of NACA ion-pulse true-airspeed indicator as used in present tests.

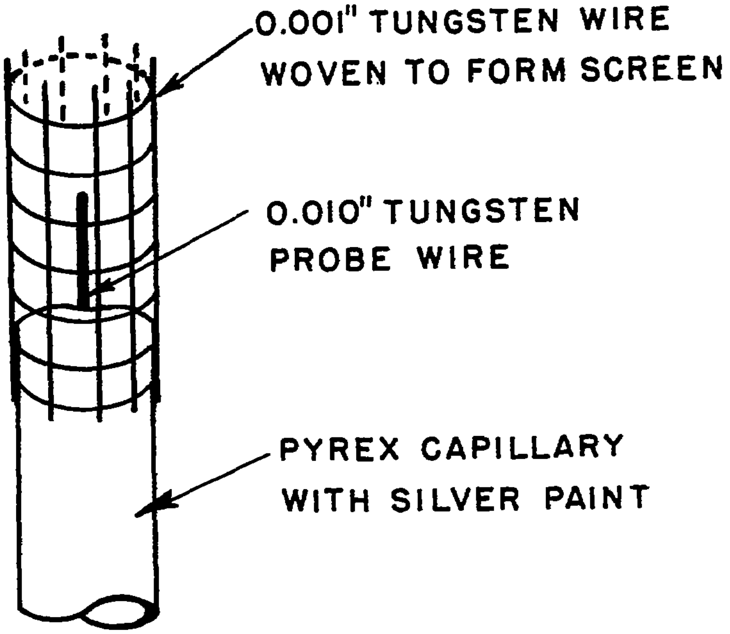
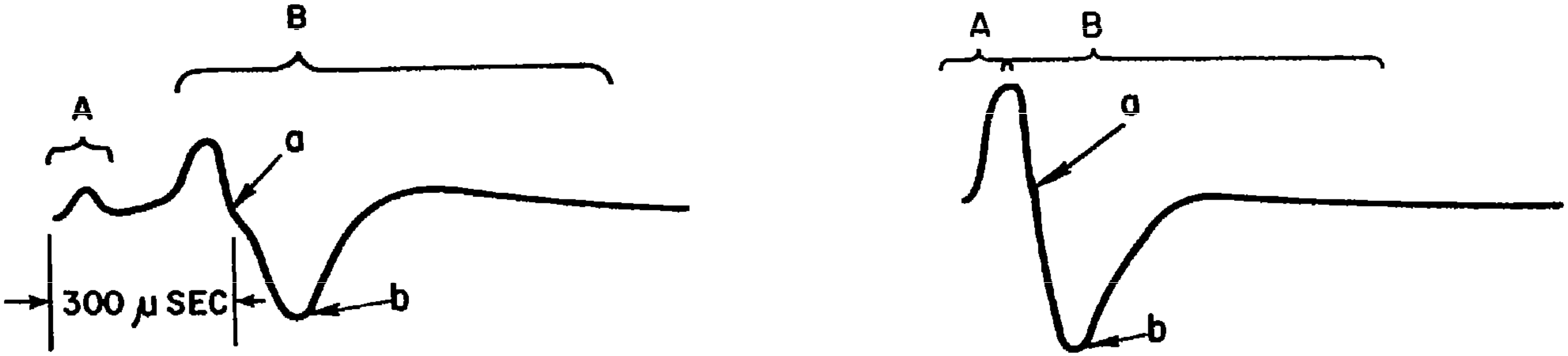


Figure 9.- Sketch of shielded probe tip.



7 INCHES FROM DISCHARGE

1 INCH FROM DISCHARGE

(a) Low-level output ("differentiated pulse").

7 INCHES FROM DISCHARGE

1 INCH FROM DISCHARGE

(b) High-level output ("total pulse").

Figure 10.- Sketch of signals received by shielded probe as amplified by NACA preamplifier.

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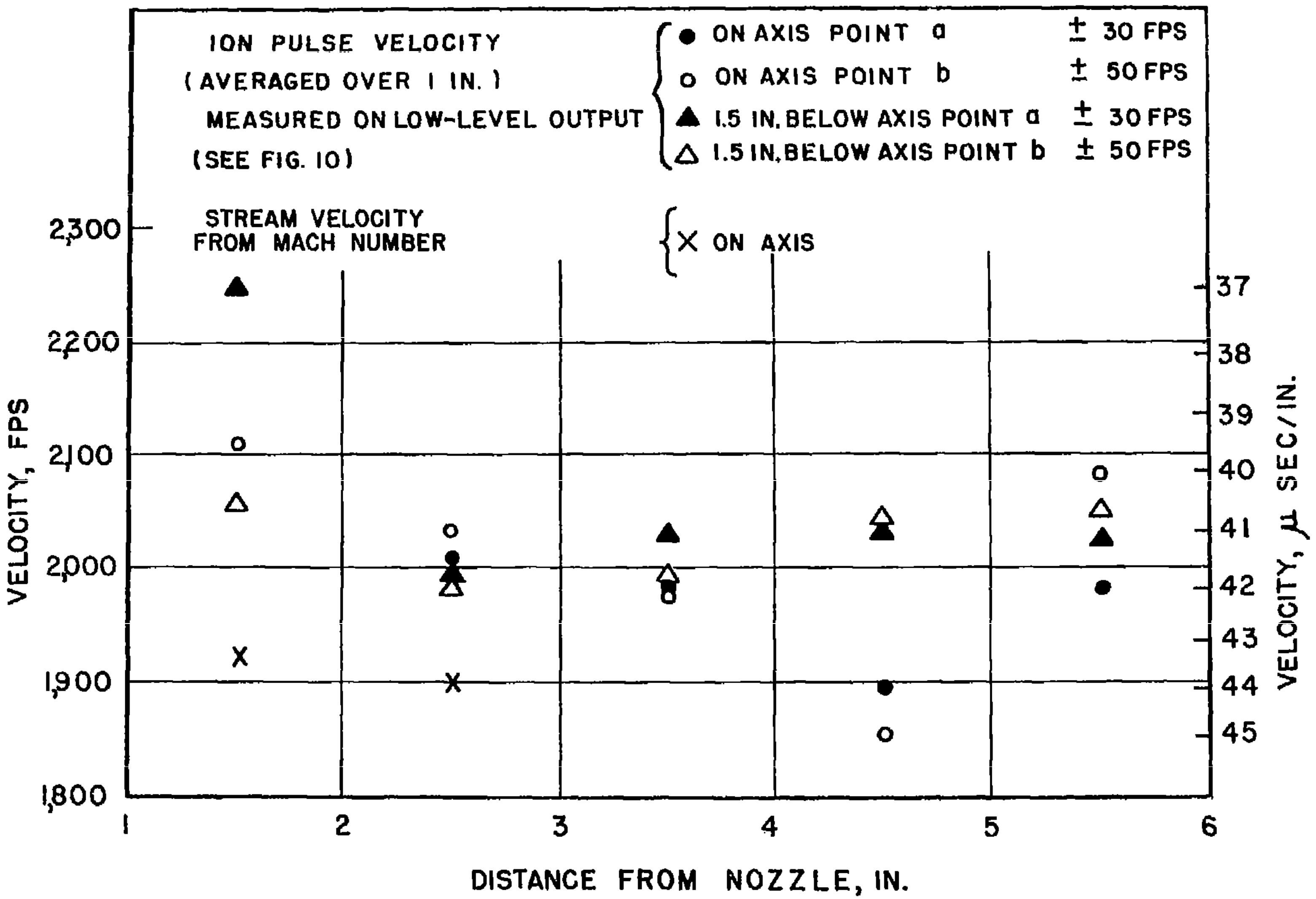

Figure 11.- Results of velocity measurements.