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EXPERIMENTAL STUDY OF STAGNATION ENTHALPY IN THE LANGLEY HOTSHOT TUNNEL

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SUMMARY

Three methods of determining stagnation-chamber enthalpy in the Langley hotshot tunnel have been investigated over a range of stagnation-chamber conditions. The experimental results were obtained at a Mach number of 20 with measured velocities in the range of 8000 ft/sec (2.4 km/sec). A description of the direct velocity-measuring system is presented in the text along with a history of its development in an appendix. The results of the investigation indicate that the assumption of uniform enthalpy in the arc chamber is not valid and leads to large errors in several flow parameters, such as Reynolds number and free-stream density. It is shown, however, that the validity of the assumption of uniform arc-chamber conditions improves with elapsed run time, and does so in a predictable manner. The application of a correction factor is now possible when direct enthalpy measurements are inconvenient. The discrepancy between calculated and measured enthalpy is shown to be a strong function of run time for the range of the investigation. The methods used to determine the enthalpy level should be applicable in a variety of facilities, although the results are probably not directly applicable to other arc-chamber configurations.

INTRODUCTION

Determination of the enthalpy level* in hypersonic test facilities has become increasingly difficult as demands for simulation of higher Mach numbers and velocities increase the required levels of stagnation-chamber temperatures and pressures. The temperature levels are frequently high enough to make direct measurement of the stagnation temperature impractical, and enthalpy levels must be determined by measurements of space-averaged pressure and density. Enthalpy can be determined from these measurements only with the assumption of uniform conditions throughout the stagnation chamber. A method of checking the validity of this assumption is to determine the velocity in

*It is assumed throughout this paper that the arc-chamber enthalpy is equal to one-half the free-stream velocity squared. The terms "enthalpy" and "velocity" will be used interchangeably.

the expanded flow since free-stream velocity and stagnation enthalpy can be simply related in a hypersonic facility. This determination has been made in a number of facilities (see refs. 1 to 5) both by direct measurement of the velocity and by inferring a velocity from stagnation-point heat-transfer measurements. In addition, this problem has been investigated by J. E. Bowman, of the Royal Armament Research and Development Establishment, Fort Halstead, Kent, England. It had always been anticipated that the assumption of uniform arc-chamber density would not be valid in the Langley hotshot tunnel. Therefore, an intensive program was undertaken to develop a technique to measure stream velocity. A history of this development is presented in appendix A, and a bibliography of supporting literature is included.

A comparison of results from the calculation of velocity from stagnation-chamber pressure and density measurements, direct velocity measurements, and velocities calculated from heat-transfer measurements in the Langley hotshot tunnel is presented to show the magnitude of discrepancies encountered at a tunnel Mach number of 20 and a velocity level of about 8000 ft/sec (2.4 km/sec). A consistent variation of this discrepancy with run time and the variation of the discrepancy with enthalpy level are described. The effect of these errors on test-section parameters is presented. From the results, a probable set of arc-chamber heating modes and a scheme of correcting the calculations of enthalpy from stagnation-chamber density and pressure are discussed.

SYMBOLS

Measurements for this investigation were taken in a mixed system of units. Equivalent values are indicated herein in both the U.S. Customary System of Units and the International System (SI) in the interest of promoting the use of the SI system in future NASA reports.

h	enthalpy, ft^2/sec^2 (J/kg)
M	free-stream Mach number
Pr	Prandtl number
p	free-stream pressure, lb/in^2 (N/m^2)
$p_{t,1}$	arc-chamber pressure, lb/in^2 (N/m^2)
$p_{t,2}$	pitot pressure, lb/in^2 (N/m^2)

p_w	pressure at model wall stagnation line, lb/in^2 (N/m^2)
q	free-stream dynamic pressure, $\frac{1}{2}\rho V^2$, lb/in^2 (N/m^2)
$\dot{q}$	heat-transfer rate, Btu/ft^2-sec (W/m^2)
R	Reynolds number, ft^{-1} (m^{-1})
r	nose radius, ft (m)
s	body coordinate, ft (m)
T	free-stream temperature, $^{\circ}K$
t	time, sec
u	velocity component, ft/sec (m/sec)
V	free-stream velocity, ft/sec (m/sec)
x	length along longitudinal axis of tunnel, ft (m)
α	angle measured on streak pictures, defined in figure 3(b)
μ	viscosity, slug/ft-sec ($N\text{-}sec/m^2$)
ρ	density, $slugs/ft^3$ (kg/m^3)
ξ	arbitrary test-section parameter

Subscripts:

c	conditions derived from calculated enthalpy
m	conditions derived from measured enthalpy
$\dot{q}$	conditions calculated from stagnation-line heat-transfer measurements

s stagnation conditions

w conditions in gas at model wall

TESTS AND APPARATUS

Tests

The present investigation was conducted in the Langley hotshot tunnel at a Mach number of approximately 20 for stagnation temperatures from 2000° K to 3000° K and stagnation-chamber pressures from 7000 lb/sq in. to 11 000 lb/sq in. (48.2 MN/m^2 to 75.8 MN/m^2). The resultant enthalpy varied from 25×10^6 ft^2/sec^2 to 38.5×10^6 ft^2/sec^2 (2.3 MJ/kg to 3.6 MJ/kg). Free-stream Reynolds numbers per foot (per 30.4 cm) encountered during the investigation ranged from approximately 500 000 to approximately 250 000.

Facility

For the present investigation, the Langley hotshot tunnel utilized a capacitor bank and a coaxial electrode system to heat and pressurize nitrogen to maximum values of 3000° K and 11 000 psi (75.8 MN/m^2). The gas was expanded in a 5° half-angle nozzle to a Mach number of 20. Tests were conducted in the conical nozzle at a median diameter of 22 inches (55.88 cm) and a nominal run time of 120 milliseconds. A more detailed description of the facility and a test-section calibration are presented in reference 6. The arc chamber used for these tests is shown in figure 1.

Pressure Instrumentation

The arc-chamber and test-section pitot pressures were routinely measured and recorded for each tunnel run during the present investigation. Arc-chamber pressures were measured by use of strain-gage pressure transducers. The location of the pressure-measuring port is shown in figure 1. These transducers were calibrated on a deadweight tester prior to each run. Test-section pitot pressures were monitored by variable-reluctance differential-pressure diaphragm transducers. The transducers were calibrated for each run by using a micromanometer as a standard. All the transducers were powered and their output amplified by a carrier amplifier system. The amplified output was recorded on an oscillograph at a paper speed of 60 inches per second (152.4 cm/sec).

Heat-Transfer Probe

A transverse cylinder (fig. 2) was used as a probe to obtain heat-transfer measurements. Stagnation heat-transfer rate and pressure were measured on the stagnation line. Two measurements were made of each quantity in order to check experimental scatter. Heat-transfer rate was also measured at the 90° or tangent-point station. A comparison of the tangent-point heat-transfer rates with stagnation-point heat-transfer rates was made to give an indication of any excess heat input due to stream contamination. The model was instrumented at both the 90° and -90° station to provide a check for flow symmetry. All instrumentation was located near the center of the model to minimize the effects of velocity gradients in the direction of the axis of the cylinder. The ends of the cylinder were closed to prevent flow in the interior of the model. Details of the thin-skin calorimeters used are shown in figure 2 and a description of construction techniques may be found in reference 7. The output of the thermocouple junctions was recorded without amplification by an oscillograph.

Velocity-Measuring Instrumentation

Velocity measurements were obtained with a system similar in principle to that used in reference 1, in which the travel of a disturbance created by a spark discharge in the test section was observed by means of a schlieren system and a streak camera. In the present investigation, velocity was determined by observing the progress of the plasma created by the spark discharge which eliminated the need for the schlieren system. The essential parts of the system were the cameras, the spark-disturbance generator, and the electrodes. A description of the system components and geometry is presented in the following sections.

Cameras.- Two types of cameras were used in conjunction with the velocity-measuring system. A high-speed (up to 7000 frames per second) framing camera was converted to a streak camera by removing the framing prism. Film velocity at the time of the test run was about 100 feet per second (30.48 m/sec). Total duration of film transport was about 4 seconds. The film velocity was determined by means of a millisecond timing light which exposed a small area at the edge of the film. Figure 3(a) is an example of a picture taken with this camera. Figure 3(b) shows a schematic diagram of the streak picture. Open-shutter time-integrated pictures of the sparks were taken with a standard camera using 3- by 5-inch (7.6- by 12.7-cm) film plates. A fine-grain film with a speed rating of ASA 160 was used with an aperture setting of f16 and an exposure time of about 100 microseconds (duration of the spark). The camera was alined obliquely with the flow direction in order to include the electrode tips in the picture (fig. 4 is an example). The pitot probes appear as an obstruction in the picture. The purpose of the open-shutter pictures was to define the initial path of the arc, since a common source of trouble with such electrode arrangements was a discharge around the tunnel-wall boundary layer rather than across the flow core.

Spark-disturbance generator.- The spark generator requirements for creating a flow disturbance were rapid recycling, high power output, good isolation of the electrode system from the tunnel walls, and ease of maintenance. The system used is shown schematically in figure 5. The system was designed to provide four sparks at any desired time within a tunnel test. The timing of each spark was independent of the others. To operate the system, the charging switch was closed before the run to connect the high-voltage power supply to the four 100-microfarad capacitors by means of the capacitor charging relay. The capacitors were typically charged to 1600 volts. When the desired charge voltage was reached, the charging relay was opened, leaving the capacitors charged and the entire circuit isolated or "floating" with respect to the tunnel walls and building ground. All events during the tunnel run were initiated by a central programer. Four channels of the programer were required to discharge the capacitors. At a preset time, one channel of the programer acted to close an internal relay which completed the 110-volt ac circuit to one capacitor discharge relay. Within 2 milliseconds of the time set in the programer, the current flowed through capacitor discharge relay contacts, one of the fuses, and the spark electrode gap. During the discharge, the fuse exploded and isolated the discharged capacitor from the rest of the circuit, thereby requiring the next capacitor to discharge across the electrodes rather than energize the discharged capacitor.

Electrodes and system geometry.- The electrodes were fabricated from 1/16-inch-diameter (0.159-cm) copper rods wrapped with fiber glass and machined to 1/4-inch (0.63-cm) diameter. A vacuum seal was maintained with an O-ring system which also positioned and alined the electrodes. The electrodes were normally set with a 10-inch (25.4-cm) gap (fig. 6) but could easily be adjusted to other values. As shown in figure 6, the electrodes were installed upstream of the viewing windows normal to the viewing path of the windows. One of the viewing windows was masked to provide a 1/2-inch (1.27-cm) horizontal viewing slit with vertical reference lines across the slit for use with the streak camera. As the cylindrical spark discharge progressed downstream, a portion of it was seen through the slit by the streak camera.

Data Recording

Figure 7 presents photographs of oscillograph records taken during this investigation. A trace from a solar cell mounted on the tunnel window, traces from two stagnation-pressure transducers which were located in the heat-transfer probe, traces from two pitot-pressure probes in the flow, and traces from two arc-chamber-pressure gages are presented in figure 7(a). The spikes on the solar-cell trace were made at the time of discharge of the velocity-measurement sparks. These spikes serve to correlate the time of velocity measurement with that of the measured pressures. The stagnation-pressure traces on the heat-transfer probe were used in obtaining the velocity from the measured heat-transfer rates. The pitot-pressure and arc-chamber-pressure traces were used to obtain the calculated test-section parameters. An indication of flow initiation and breakdown times as well as the actuation of the arc-chamber dump valve may be taken from this record. The traces from the heat-transfer gages in the heat-transfer probe are presented in figure 7(b) and represent the rate of change of temperature with time. There are two stagnation-line traces and two 90° radial station traces recorded in figure 7(b). Flow-initiation and breakdown times and electrical pickup from the velocity-measurement sparks are indicated.

DATA REDUCTION AND EXPERIMENTAL ACCURACY

Pressure Measurements

The measurements made at the stagnation line of the heat-transfer model agreed with the pitot-tube measurements within the experimental accuracy. Uncertainties are in the range of 4 to 6 percent for the pitot-pressure measurements and 3 percent for the arc-chamber-pressure measurements. The associated test-section-parameter data-reduction method may be found in references 6 and 8.

Heat-Transfer Measurements

The heat-transfer probe was initially at room temperature and the surface temperature increased approximately 100° F (56° K) in the thin-skin measuring sections. The effects of existing temperature gradients were not determined but are believed to be small. The uncertainty of the thermocouple temperature measurement is ± 2 percent. Overall system inaccuracy of heat-transfer rates is a maximum of ± 10 percent.

Velocity Measurements

Accurate velocity measurements by the spark method depended on knowledge of the film velocity and acceleration, the camera lens magnification, the alinement of the film with respect to the tunnel axis, the measurement of the tangent of the light streak on the film, the measurement of distance on the film, and the accuracy of magnifying and enlarging devices employed in data reduction. The accuracy of velocity determination lies within a maximum error of ± 3 percent.

Velocity derived from stagnation-line heat-transfer measurements had a maximum probable error of ±7 percent. Appendix B contains a more detailed account of instrumentation and data-reduction techniques and a subsequent discussion of errors.

RESULTS AND DISCUSSION

Enthalpy Measurement

Three methods were used to determine velocity in the Langley hotshot tunnel. The first method was to calculate the velocity as described in reference 6, for which it was necessary to assume that uniform thermodynamic conditions existed throughout the arc chamber and that the gas expanded isentropically from the arc chamber to the test section. The measured inputs to this program were arc-chamber density before the arc was fired and arc-chamber pressure during the run. The second method was to infer the velocity from a stagnation heat-transfer measurement on a cylinder. The assumptions involved were that the theory used to relate the heat-transfer rate and velocity were correct, and that the correct inputs to the theory were available. The experimental inputs are measured heat-transfer rate and measured pressure. The third and most direct method of determining velocity was to observe photographically the downstream travel of a plasmoid generated by an arc discharge in the test section. The only assumption required for this method was that the plasmoid was traveling at stream velocity. Figure 8 presents results from the three methods of determining the velocity for one tunnel run. This figure shows that the velocity derived from arc-chamber-pressure measurements is higher than the directly measured velocity and indicates that the validity of the assumption of uniform arc-chamber conditions is questionable. It may also be observed that the velocity derived from arc-chamber-pressure measurements decreases with elapsed run time. The direct velocity measurements show a scatter when compared with the other methods for any one run; however, this is the only system with enough resolution in time to see the short time-velocity perturbations that are believed to be occurring. Figure 9 presents the data over a range of arc-chamber conditions, including the data of figure 8, as a ratio of velocities directly measured and those inferred from heat-transfer measurements to velocities calculated from arc-chamber conditions. A straight-line least-mean-square-curve fit of the directly measured velocities shows good agreement with values inferred from heat-transfer measurements. Discrepancies on the order of 15 percent between the directly measured velocities and velocities determined from arc-chamber conditions are indicated. Figure 9 also shows a trend of decreasing discrepancy between measured and calculated velocity ratio with elapsed run time. The degree of scatter in the directly measured velocity is an indication of the short time departures from the time-averaged enthalpy that may occur at the nozzle entrance. It may also be observed that the magnitude of this scatter is decreasing with elapsed run time.

Figure 10 presents the discrepancy between measured and calculated enthalpy as a function of calculated enthalpy level. The time-dependent discrepancy presented in figure 9 appears here as scatter in the data for a particular run. It may be observed that there is no run which covers the entire enthalpy range of the investigation. It may also be seen that there is no well-defined trend of the scatter or the level of discrepancy as a function of calculated enthalpy level. From figures 9 and 10 it may be seen that the discrepancy between measured and calculated properties is a strong function of time. For the throat size used in the present investigation and a test gas of nitrogen, a time-dependent correction factor can be derived from figure 9 and can be applied to calculated flow parameters in order to improve the quality of the parameters over a range of tunnel operating conditions. Figure 11 presents the correction factors for the various parameters as a function of time. From this figure, it can be seen that if no enthalpy measurement is available and if flow conditions must be determined from measured arc-chamber and pitot pressures, the data taken at late run times will be more accurate. It may be observed from figure 11 that an accurate knowledge of the velocity or enthalpy is not necessary for the determination of dynamic pressure, but is vital in the calculation of Reynolds number. The existence of a correction factor is of particular value in tests for which an independent enthalpy indication would be inconvenient and where an accurate knowledge of the Reynolds number is important in interpreting the test results.

Heat-Transfer Modes

The basic problem of determining enthalpy level in hotshot-type tunnels arises because the mechanism by which the arc-chamber gas is heated is not completely understood. A number of heat-transfer modes can be postulated; these modes include radiation from the arc column, diffusion, movement of the arc itself, heating by the passage of a strong shock, direct conduction, and swirling or mixing of the arc processed gas. Only about 10 percent of the gas contained in the arc chamber passes through the test section during a 0.100-second run with a 0.100-inch-diameter (0.254-cm) throat. It is assumed that the gas which is used is at the furthest point from the electrodes and comes from a volume element near the throat (fig. 1). Thus, it is the enthalpy of this gas which is of interest and which is to be measured. The average enthalpy of the volume of gas in the entire arc chamber is calculated by measuring the arc-chamber pressure and the density prior to arc discharge. If the principal mode of heat transfer were radiation or movement of the arc, the small volume of gas near the throat would receive an initial burst of heat in the order of time of the arc discharge and then decay to a lower temperature. The data in figure 8 indicate that the actual test gas was heated less than the average of all the arc-chamber gas and only approaches this average in times that are long compared with arc discharge time, which is less than 1 millisecond. This result indicates that radiation and arc movement are not the dominant modes, but other modes of heat transfer such as direct conduction, shock heating, diffusion, or swirling of the test gas must be present as the dominant mode. In reference 9, it was tentatively concluded, after spectroscopic analysis of light bursts in the shock layer of a blunt model, that one of the heating modes is swirling of the gas. This spectroscopic analysis showed traces of material used only near the arc-chamber electrodes and indicated that some of the very hot gas from the vicinity of the arc column does enter the small test-gas volume at the downstream end of the arc chamber. Since the light bursts examined in reference 9 were not uniform in time and occurred only during a small part of the run time, it seems probable that swirling is not a dominant heat-transfer mode.

First-order approximations indicate insufficient conduction during run time to influence the measured enthalpy. Therefore, shock processing and diffusion may be the dominant heat-transfer modes with shock processing doing a larger part of the heating at early times, and diffusion contributing a major part at later times, with swirling contributing a smaller, sporadic part of the heating. Mechanical damage in the arc chamber itself has given evidence that a very strong shock wave exists and probably oscillates between the ends of the arc chamber.

CONCLUSIONS

A study of enthalpy levels in the Langley hotshot tunnel in which three methods of determining enthalpy were used has led to the following conclusions:

1. Measured velocities and velocities inferred from stagnation heat-transfer rates were in good agreement.

2. The discrepancy between velocities as determined from test-section measurements, and as determined from assumed uniform arc-chamber conditions was as large as 15 percent at early run times and decreased with increasing time. This trend was consistent over a number of runs and for a range of tunnel operating conditions.

3. Correction factors for test-section parameters have been derived from the experimental program which improve the test-section parameters calculated from assumed uniform arc-chamber properties.

4. Assuming the enthalpy level computed from arc-chamber measurements to be uniformly distributed can lead to large errors in free-stream density, temperature, viscosity, and Reynolds number, but the error in Mach number and dynamic pressure is small.

5. The most probable modes of transferring energy to the portion of gas to be expanded in the nozzle are shock heating and diffusion.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 28, 1965.

APPENDIX A

VELOCITY-MEASURING-SYSTEM DEVELOPMENT IN THE LANGLEY HOTSHOT TUNNEL AND ASSOCIATED PROBLEMS

Before the Langley hotshot tunnel was put into operation, it was recognized that measurements of parameters in addition to stagnation and pitot pressures would be needed to define the test flow accurately and that the high temperatures and pressures in the arc chamber and low density in the test section would present special instrumentation problems. Accordingly, a program was initiated to develop methods of measuring additional flow parameters. A desirable parameter to measure was free-stream velocity, and a high percentage of the total flow-parameter measurement program was directed toward velocity measurement. In general, it seemed there were two methods of obtaining a direct measurement of stream velocity: (1) measure the velocity of a disturbance in the flow or (2) measure the velocity of an object in the flow which had been accelerated to flow velocity. Both methods were tried and a chronologically oriented description of the efforts follows.

The first apparatus installed in the hotshot tunnel to generate a flow disturbance was a set of electrodes which fired across the flow core. Residual ionization from this first arc then resulted in the discharge of a set of electrodes further downstream, the voltage of which was just below the breakdown potential. The time between discharges and the separation between the upstream and downstream sets of electrodes was to allow the calculation of velocity. The problems encountered in this system were electrical insulation in relatively high vacuums and personnel safety resulting both from the high voltage and the requirement of isolating the system from ground. The problems encountered in the operation of the system were difficulty in confining the spark to the desired path, the curvature and nonrepeatability of the spark-channel shapes, premature firing of the secondary electrodes by induction or photoionization, and the design of a set of electrodes with minimum flow disturbance which were still rigid enough to avoid vibration. Many of these problems were aggravated by the electrical disturbance created by the arc discharge which energized the tunnel flow. The final problem which caused the rejection of this system of velocity measurement was the diffuse nature of the sparks. The secondary electrodes, in particular, suffered from this problem to such an extent that a picture of the sparks could not be used to determine spark locations well enough to give an acceptable accuracy to the measuring system.

Tests were made to investigate the feasibility of accelerating an object to flow velocity and then to measure the velocity of the object. A principal criterion for success of this type of system was to have an object with a very high drag-to-mass ratio in order to obtain a large acceleration. The configuration chosen for this experiment was a parachute. In order to have strength with low mass, the parachutes were constructed of 0.001-inch-thick (0.003-cm) mylar premolded into a parachute shape in order to avoid folds and attached to nylon thread for shroud lines. The parachute was supported as far upstream as was mechanically practical. When the flow started, the parachute was blown from its support and carried downstream. As it progressed downstream, it carried with it a tether line from a reservoir. In order to measure the velocity of the parachute, two aluminum-foil tabs were attached to the tether line a known distance apart. As the tether line pulled these tabs from between two closely spaced metal plates, they in succession broke two low-current contacts giving a voltage rise on an oscilloscope. Thus, distance was calculated from the distance between metal foil tabs, and elapsed time was calculated from the contact breaks and thus allowed calculation of velocity. This system did not prove satisfactory for measuring velocity in the Langley hotshot tunnel because the necessary drag-to-mass ratio was not achieved. The system could be applicable in a tunnel with a higher level of dynamic pressure.

The initial attempts to measure velocity allowed establishment of criteria for a velocity measuring system:

(1) The system must be easily maintained by tunnel technicians.

(2) The system should be built of readily available components.

(3) Capability must be provided for more than one measurement point per run.

(4) Components sensitive to the initial electrical disturbance of the arc chamber should be avoided.

(5) The system should not perturb the flow core or negate the possibility of running concurrent tunnel tests.

A survey of existing measuring systems showed that the system in reference 1 met many of the preceding requirements. This system used a pair of swept electrodes to discharge an arc across the stream in order to create a disturbance. A schlieren system and a streak camera were then used to take a picture of the expanding cylindrical shock wave generated by this disturbance. A system similar to this was constructed and tried in the Langley tunnel but the schlieren system proved to be inadequate for the density levels encountered. It was found that a streak picture could be taken of the plasma rather than the shock wave created by the disturbance. This modification gave legible but erratic records. The reason for the erratic records was that, although it would be advantageous with a schlieren system to view the cylindrical shock disturbance along its axis to obtain a larger effective change in refractive index and a more distinct streak picture, in photographing the plasma, the intense light left in the wake of the electrode caused difficulty in seeing the weaker light per unit time emitted from the stream center. For this reason, the electrode arrangement was rotated 90° with respect to the camera viewing axis, so that only light from the plasma in the center of the flow core would be recorded and the disturbance from the electrode tips would not be visible to the camera. For mechanical simplicity, the swept electrodes were made perpendicular to the tunnel axis. This modified system provided results of higher quality and was used to obtain the experimental results in this presentation. The most noticeable change was that nearly all the data from the previous system were higher than the calculated values, and had a very high scatter. The data from the second system gave results that were consistently lower than the calculated data and with an order of magnitude less scatter. Also, as expected, picture quality was improved and data reduction was made a lesser problem. The reasons for the differences in the data are not completely understood since a number of the system variables were changed simultaneously and there is not enough information to establish a cause and effect relationship. A possible explanation for the differences is that the plasma was accelerated by the electrodynamic forces, as suggested in reference 10, in the swept electrode case and not accelerated with the vertical electrodes. The differences in the data could be purely aerodynamic since the size and sweep angle of the disturbance in the tunnel boundary layer were changed.

In the development of a spark-disturbance generator for the hotshot tunnel, there were a number of persistent electrical problems to be dealt with. Most of these problems were encountered because of the low-density levels at which the sparks were to be discharged. At these pressures and for the electrodes used, Paschen curves predict that the path of least resistance for a spark becomes longer with decreasing pressure. Thus, when electrodes were installed in the tunnel test section with a 10-inch (25.4-cm) gap, if any part of the electrode circuit was common with the metal tunnel wall, the spark would leave one electrode and discharge to some part of the tunnel rather than the other electrode. To solve this problem the entire electrode discharge circuit was "floated" from the tunnel wall, which usually meant also that it could not be connected to building ground. This ungrounded circuit had peculiar problems of its own as well as additional hazard to personnel. Insulating a high-voltage circuit in a vacuum also had problems. A cable with insulation rated at 18 000 volts at atmospheric pressure gave a bright glow discharge through the insulation at 2000 volts at low pressures. All electrical joints in the vacuum system proved very hard to insulate. The most trouble-free electrode arrangement proved to be a small copper rod wrapped in fiber glass and then machined on a lathe to give a uniform 1/4-inch (0.64-cm) diameter with a smooth surface. This electrode was then inserted through the tunnel wall by means of a vacuum fitting with an O-ring seal. Thus, the spark-generator connection was made external to the tunnel at atmospheric pressure. The tendency of the spark to seek a longer path than that offered by the electrode gap eventually caused the fiber-glass insulation to break down and the electrodes began discharging at the base (close to the tunnel wall) rather than at the electrode tips.

APPENDIX A

Other problems involved were a preference of the spark to discharge around the boundary layer rather than through the flow core. This phenomenon was unexpected since the hotshot tunnel boundary layer is thought to be of lower density than the core. The answer may be that the high velocity in the core continually sweeps away ions caused by the advance microdischarge before the spark, and, in terms of generated ion and free-electron concentration, gives the core a lower effective density than the boundary layer as far as criteria for spark or glow discharge are concerned. The problem of obtaining a spark instead of a glow discharge seemed to depend on how well sharp corners (high field gradients) could be avoided in the electrode construction and how much energy was applied. It is suspected that the difference between a spark and a glow discharge is also a function of the voltage-rise time supplied by the spark generator, with the faster rise time more likely to result in a spark discharge. As the density is lowered, it is anticipated that the problem of obtaining a spark instead of a glow discharge will become more difficult.

APPENDIX B

DISCUSSION OF DATA REDUCTION TECHNIQUES

Velocity Derived From Heat-Transfer Measurements

In order to make an independent measurement to check the results given by the direct velocity measurements, a cylindrical heat-transfer model (fig. 2) was constructed having two measuring stations at the stagnation line and two at the shoulder. The heat-transfer gages used are described in reference 7. Two stagnation-pressure measurements were also made. All measurements were made near the center of the model to minimize end effects. The stagnation heat-transfer rate, pitot pressure, calculated stream properties, and Fay and Riddell's theory (ref. 11) were used to calculate a free-stream velocity. This system was subject to two systematic sources of error. The first error lay in the use of calculated values of density, viscosity, and temperatures behind the shock in the Fay and Riddell equation. Since the quantities were calculated from an assumed arc-chamber enthalpy, they were subject to error. The order of magnitude of the error in each quantity mentioned may be noted from figure 11. It can be shown that errors of this magnitude when used in the Fay and Riddell equation caused the velocity calculated from heat transfer to be in error a maximum of -5 percent.

The second source of error is the amount of stream contamination. Even a small particle is able to transmit large amounts of energy to the measuring surface at the high velocities being encountered. This error is seen to be only in the direction of making velocities inferred from heat-transfer measurements greater than measured velocities. The velocities calculated from the heat-transfer measurements never exceeded the velocity measurements and it appears that in the present investigation the Langley hotshot tunnel contamination level was low enough so that it did not cause appreciable heat-transfer error. The gages installed at the shoulder were intended for use in correcting the contamination-induced error, had it been large. However, the heat flux at the tangent point was very low and difficult to measure and it was believed that the inaccuracy in this measurement was more serious than any contamination-induced error.

The velocity inferred from heat-transfer measurements was calculated from stagnation-line heat-transfer measurements on a transverse cylinder by means of Fay and Riddell's theory (ref. 12). The inputs to the theory were the heat-transfer rate, model geometry, viscosity, density and temperatures behind the shock and at the wall, and stagnation pressure. The maximum error in measured heat-transfer rate is shown to be about ±10 in reference 7. The maximum discrepancies between the calculated and measured velocities are on the order of 15 percent. The equation used to relate velocity to heat-transfer rate is

$$\dot{q} = \frac{0.76(Pr)^{-0.6}}{\sqrt{2}}(\rho\mu)_w^{0.1}(\rho\mu)_s^{0.4}\left(\frac{V^2}{2}\right)\sqrt{\left(\frac{du}{ds}\right)_s}$$

which when solved for velocity yields

$$V = \left[\frac{2\sqrt{2}\dot{q}(Pr)^{0.6}(r)^{0.5}}{0.736(\rho\mu)_w^{0.1}(\rho\mu)_s^{0.4}\left(\frac{2p_s}{\rho_s}\right)^{0.25}}\right]^{0.5}$$

(A general discussion of methods of obtaining relationships between stagnation-point heat-transfer rates and associated flow properties may be found in ref. 12.) The order of error in the product of stagnation density and viscosity when raised to the 0.4 power gives a maximum error contribution of 5 percent in the calculation of velocity inferred from heat-transfer rates at early run time, defining the magnitude of error in the calculated inputs since this term contributed the major portion of the error. Stagnation pressure can be measured to an accuracy of ±4 percent. The model surface viscosity and density were calculated on the basis of the stagnation pressure and the surface temperature derived from the thermocouple measurements. The accuracy of the thermocouple-temperature measurement is ±2 percent. These errors together give a maximum error of ±10 percent in heat-transfer rate and a maximum probable error of ±7 percent in the velocity derived from heat-transfer measurements. Assumptions made were that the Prandtl number was 0.715, that the enthalpy contributed by molecular dissociation was zero, and that the free-stream enthalpy was negligible when compared with the velocity. It was also assumed that the contribution of contamination-transported energy was of negligible influence. An external energy contribution from contamination would tend to make the velocity inferred from the heat-transfer measurements higher than the measured velocity, which was not the case. Maximum error in free-stream velocity calculated from heat-transfer rates is estimated to be within ±10 percent at early run times, and ±6 percent at very late run times, since all discrepancies tend to converge with time.

Measured Velocity

A schematic of the velocity-measuring system is presented in figure 2. In this system, a spark is discharged from the electrodes across the test section to create a plasma cylinder. The cylinder then progresses downstream with the flow. The electrodes producing the discharge are buried in the boundary layer. The discharge itself is of a nebulous character and is in the regime between a glow discharge and a spark discharge. Since the electrodes are in the boundary layer, plasma generated near the electrodes flows in the boundary layer and the electrode wake at a much slower rate than the plasma generated in the free stream, resulting in a great deal more light being emitted from a unit viewing area per unit time in the boundary layer than in the free stream (fig. 4). For this reason, the flow of plasma is viewed transverse to rather than parallel with the electrodes.

The observation of the free-stream section of the discharge as it moves downstream is accomplished by the use of a slit parallel to the stream flow and a 16-mm streak camera (fig. 3(b)).

A typical picture obtained by this method is shown in figure 3(a). Scale markers across the viewing slit and time markers on the film allow the velocity to be calculated from the measured angle α (fig. 3(b)) on the film and the equation:

$$V = \frac{dx}{dt}$$

$$V = k \tan \alpha \qquad \text{where} \quad k = \frac{\dfrac{x \text{ real inches}}{x' \text{ film inches}}}{\dfrac{t \text{ real time}}{x' \text{ film inches}}}$$

and x' is reference distance measured on the film.

Considerable care must be exercised in the measurement of the angle α. In figure 3(a) it may be observed that the early time portion of the film was overexposed as a result of the intense light emitted by spark initiation. As the spark heated the column through which it was discharged, the column expanded rapidly in diameter until its internal pressure was equal to the free-stream static pressure. After a short time, the diameter (determined by the size the column emitted light) continued to increase by diffusion of ions from the center of the discharge column. Since the entire mass of gas which composes the column was originally moving at stream velocity, the center of the column continued to move at stream velocity while the upstream edge of the column moved with stream velocity minus pressure-driven expansion velocity plus diffusion velocity, and the downstream edge moved with stream velocity plus pressure-driven expansion velocity and diffusion velocity. Thus, it can be seen that a line drawn through the center of the streak picture (fig. 3(a)) is representative of the path an undisturbed flow particle would take.

APPENDIX B

The aberration which may be noticed in the spark-streak picture (fig. 3(a)) at late times is caused by the flow of the plasma in the stagnation region of the cylindrical heat-transfer probe which was located downstream of the velocity-measuring apparatus. Since the ions are trapped in the subsonic region behind the shock, they will become part of a low-velocity region of the flow.

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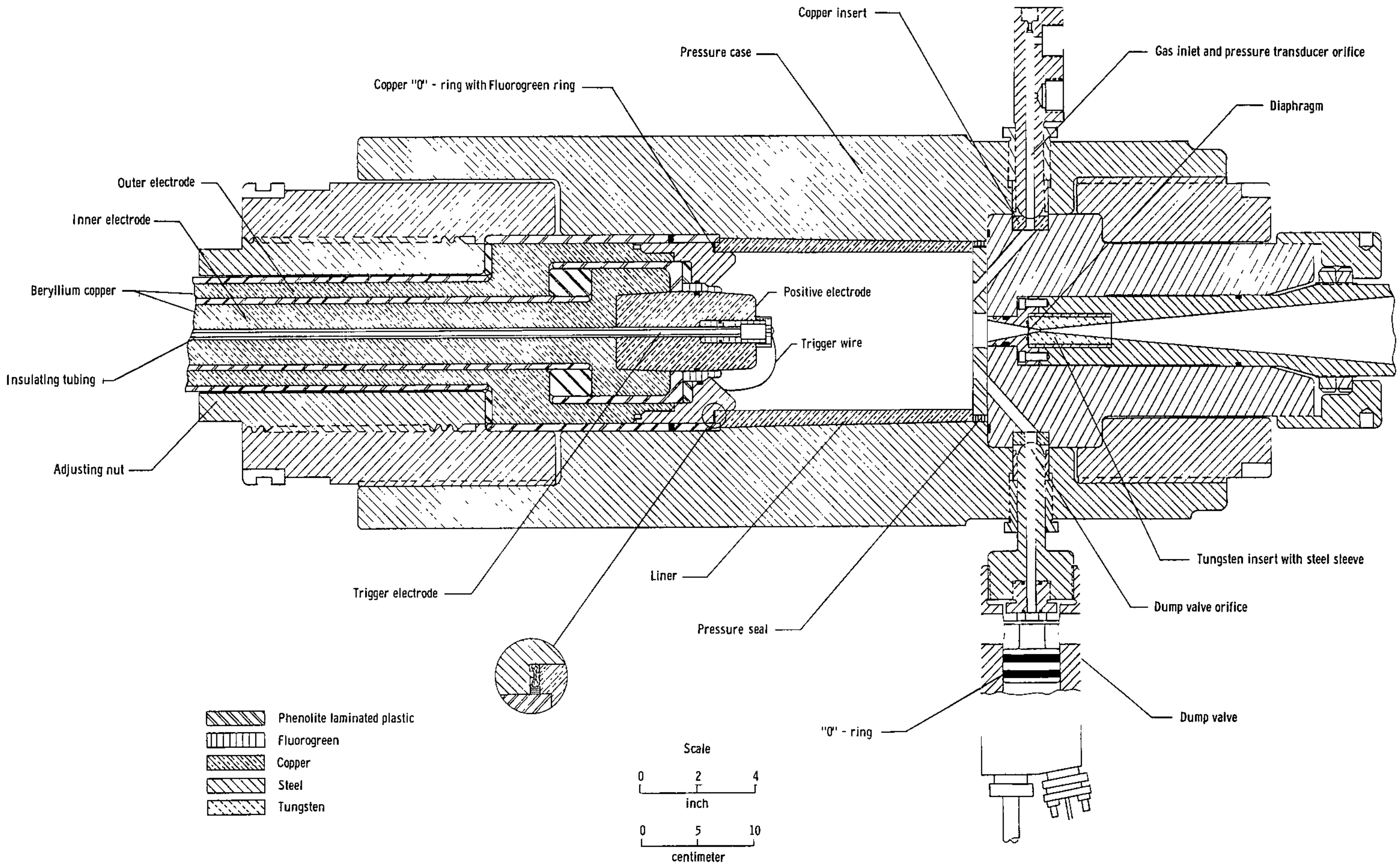


Figure 1.- Langley hotshot tunnel arc chamber.

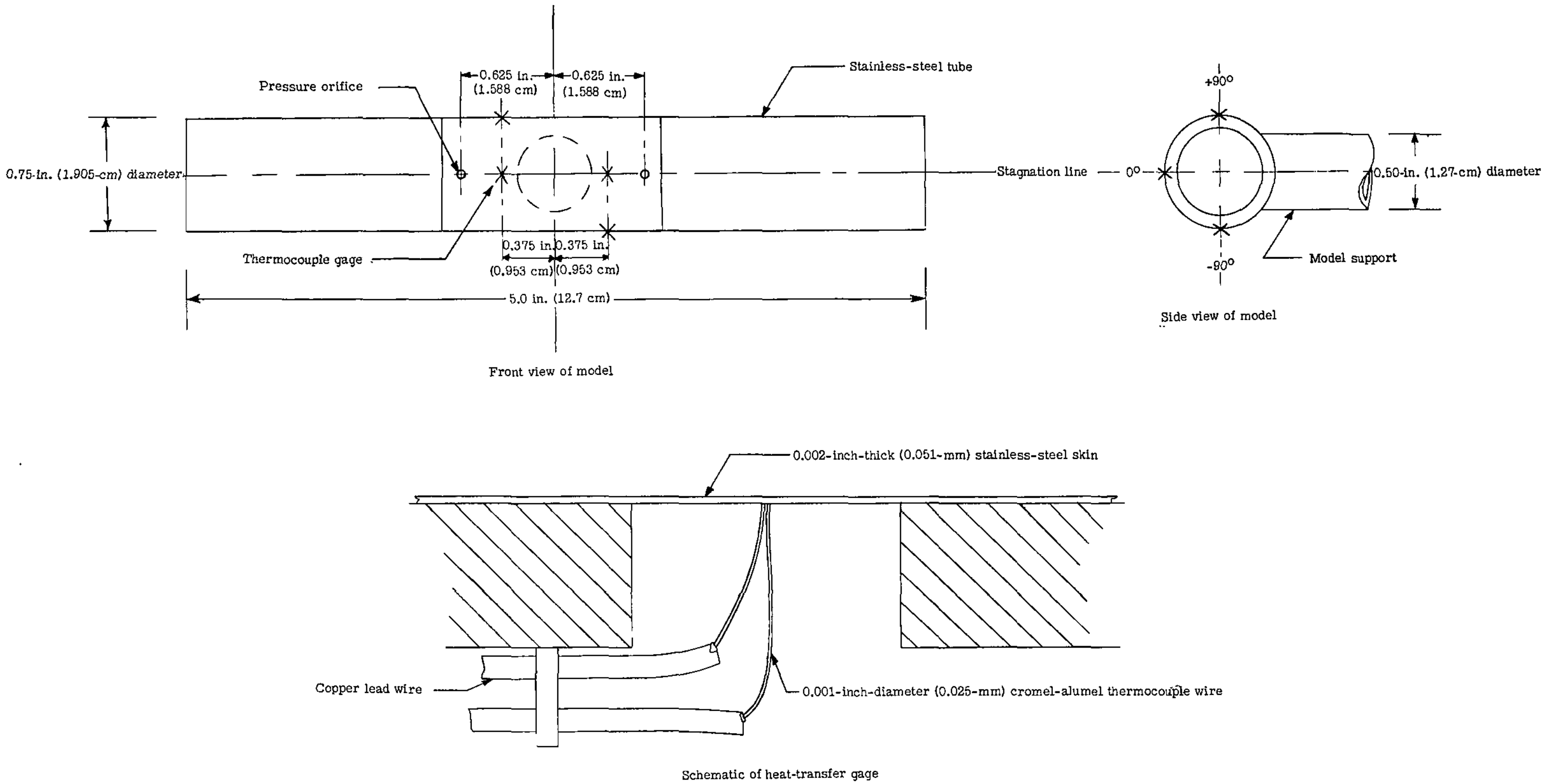
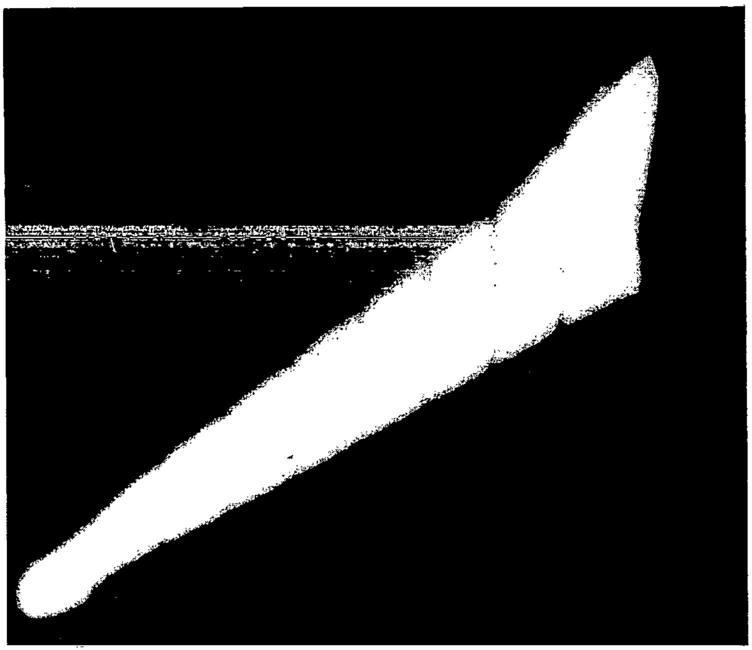
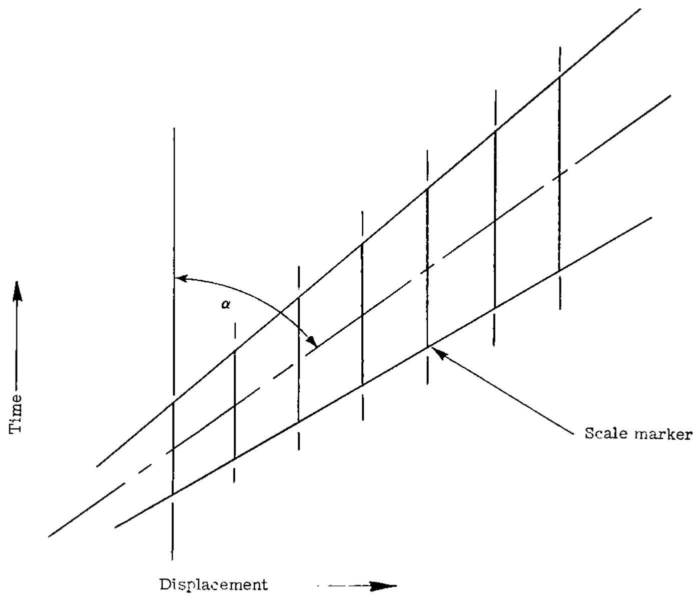


Figure 2.- Heat-transfer model.



L-65-7963

(a) Streak picture of spark.



(b) Schematic of streak picture.

Figure 3.- Travel of spark disturbance as recorded by streak camera.

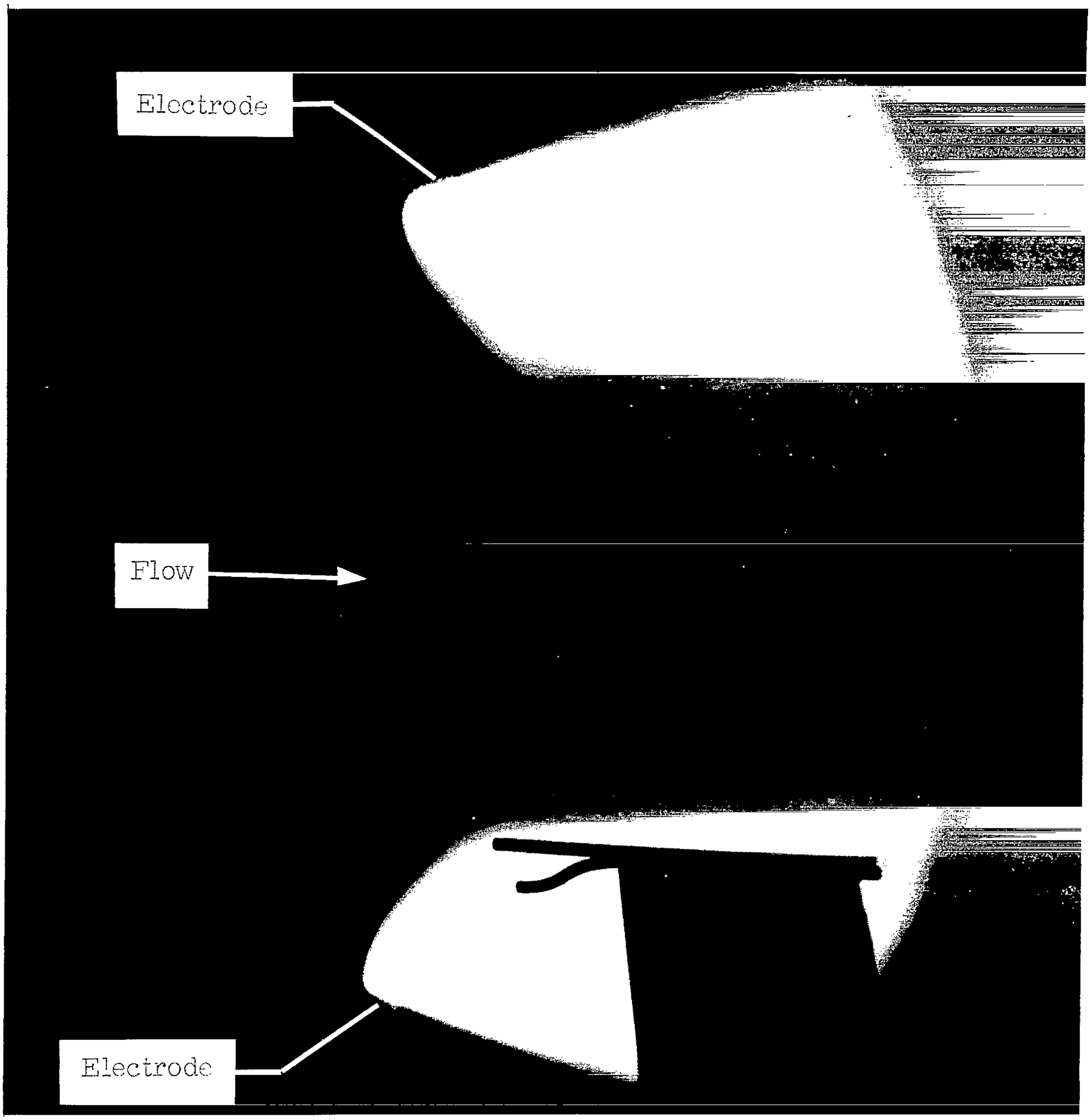


Figure 4.- Open-shutter picture of spark. L-65-7964

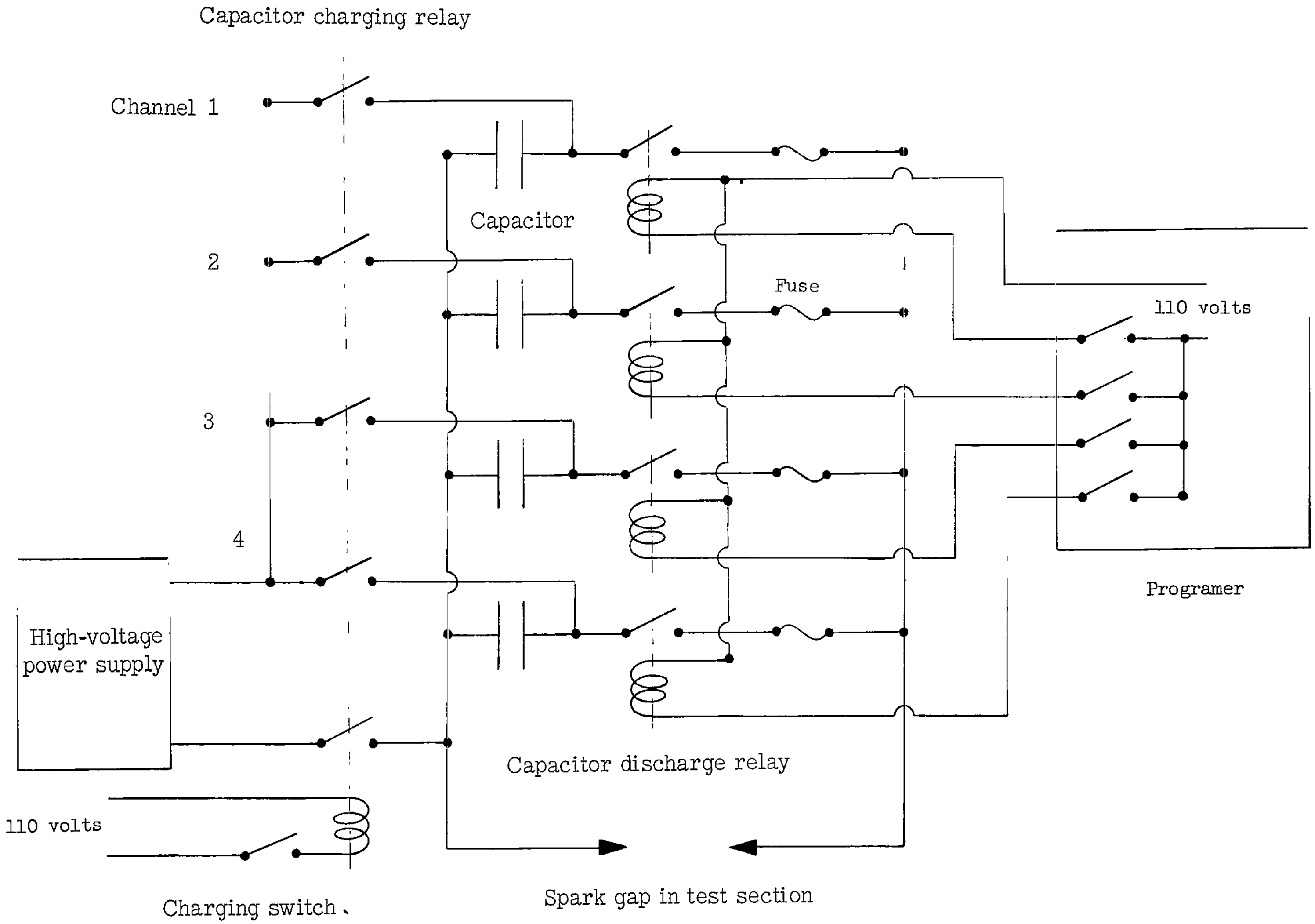


Figure 5.- Electrical schematic of spark-discharge apparatus.

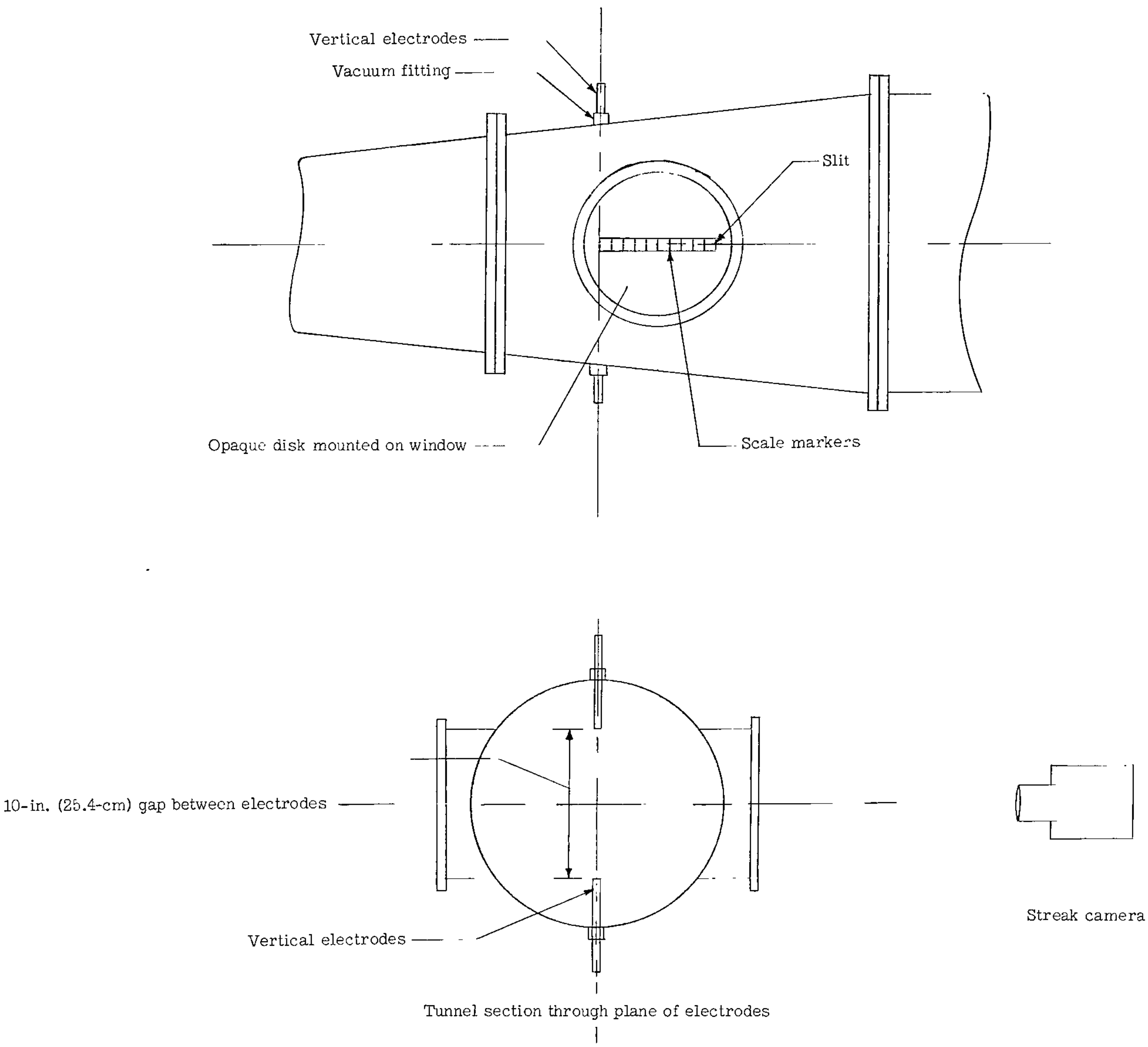
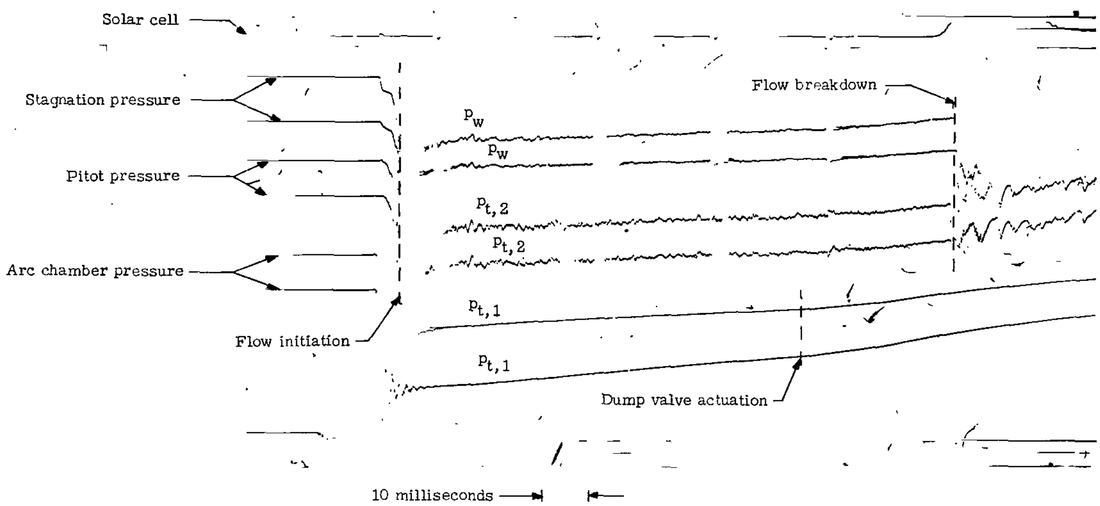
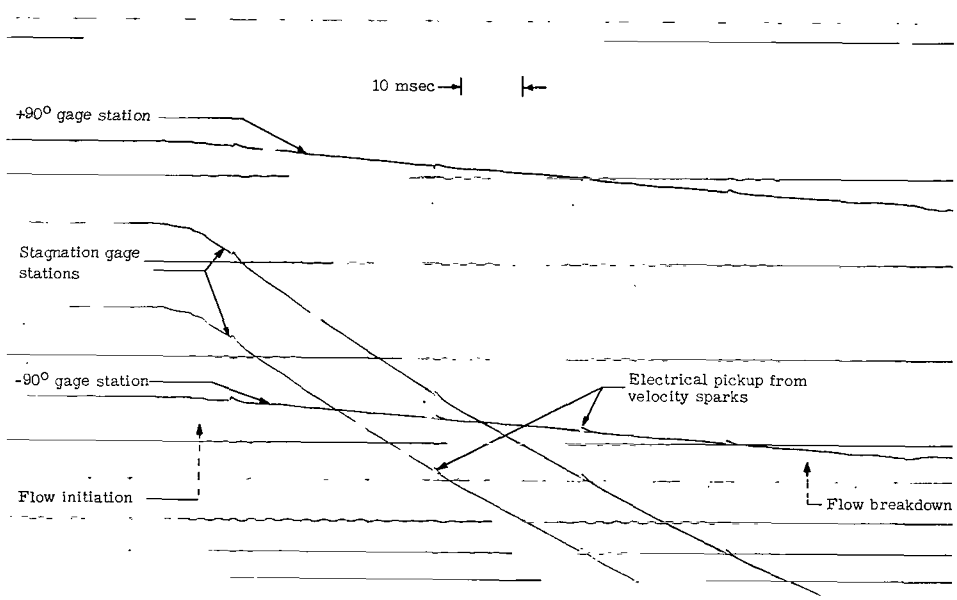


Figure 6.- Velocity-measuring system.



(a) Arc-chamber pressures, pitot pressures, and spark sensor.



(b) Outputs of heat-transfer gages.

Figure 7.- Oscillograph records from present investigation.

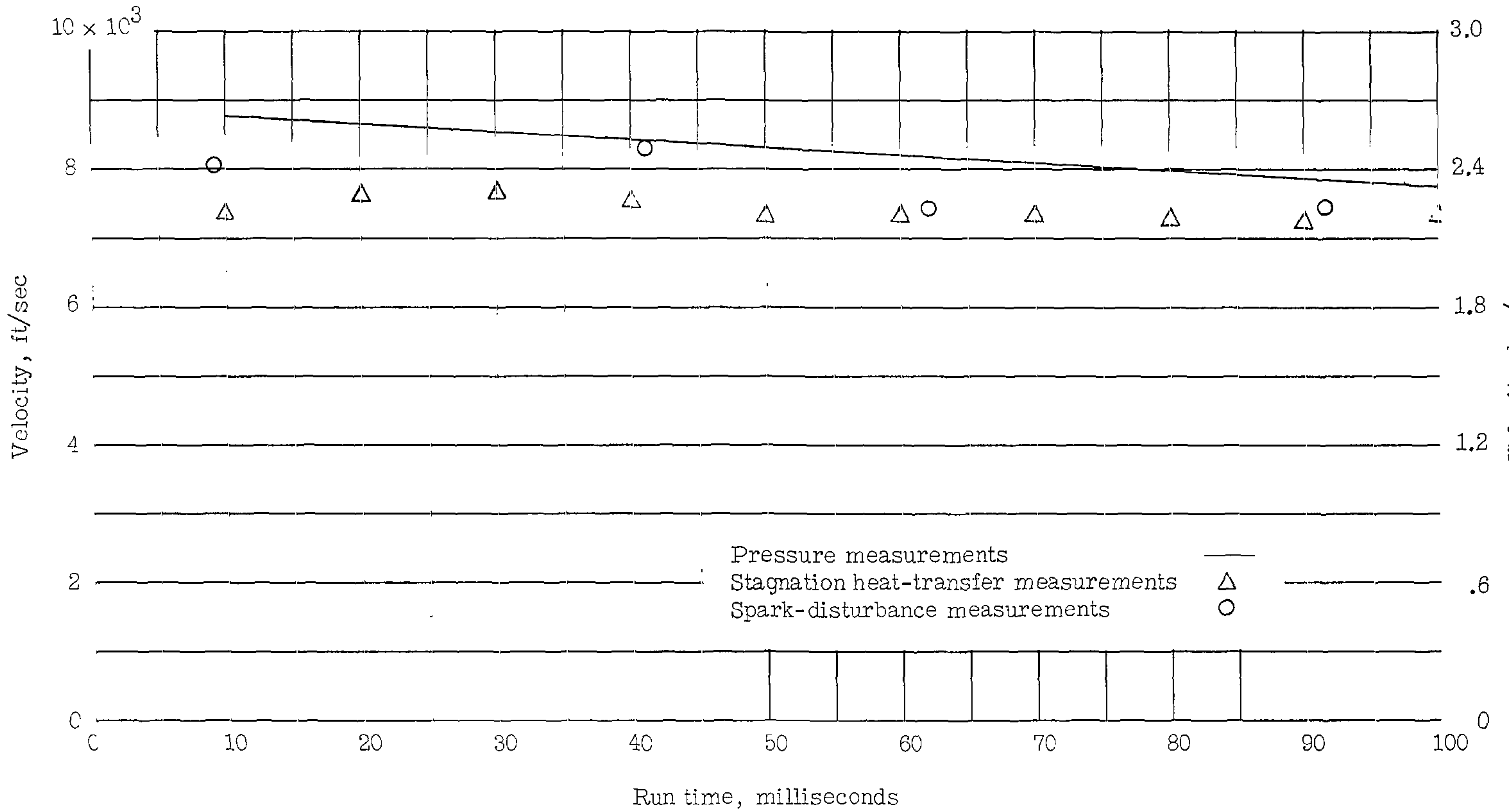


Figure 8.- Comparison of three methods of determining velocity for one run.

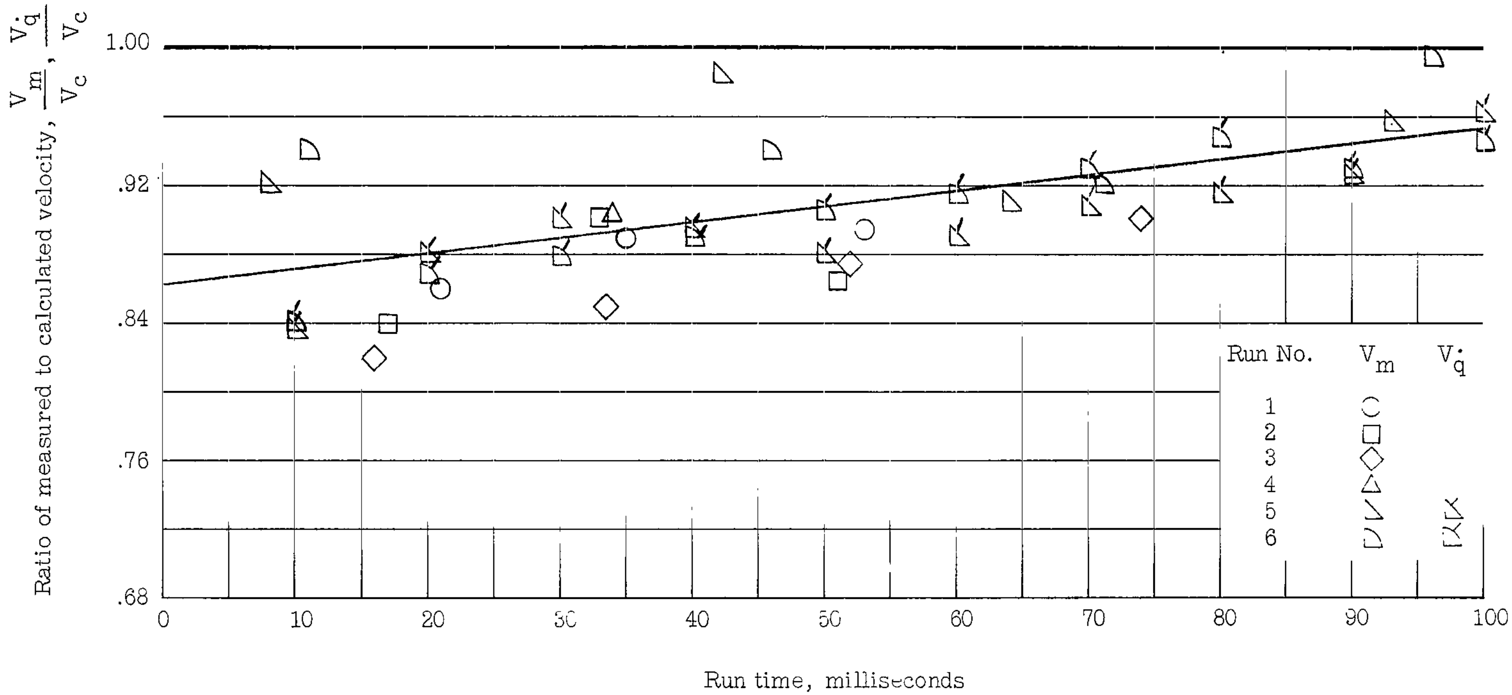


Figure 9.- Ratio of measured to calculated velocity as a function of run time.

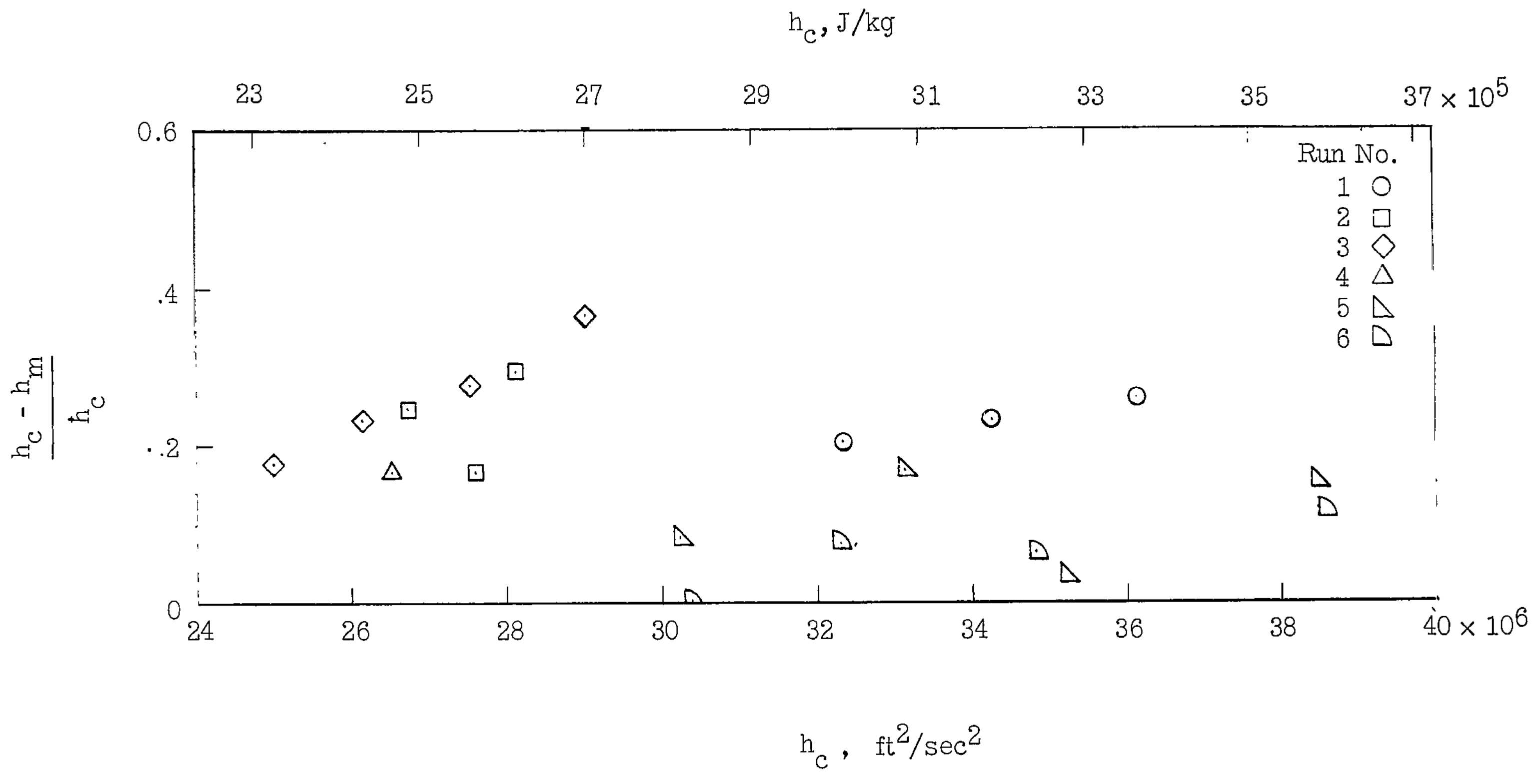


Figure 10.- Discrepancy between calculated and measured enthalpy as a function of enthalpy level.

NASA-Langley, 1966 L-4352

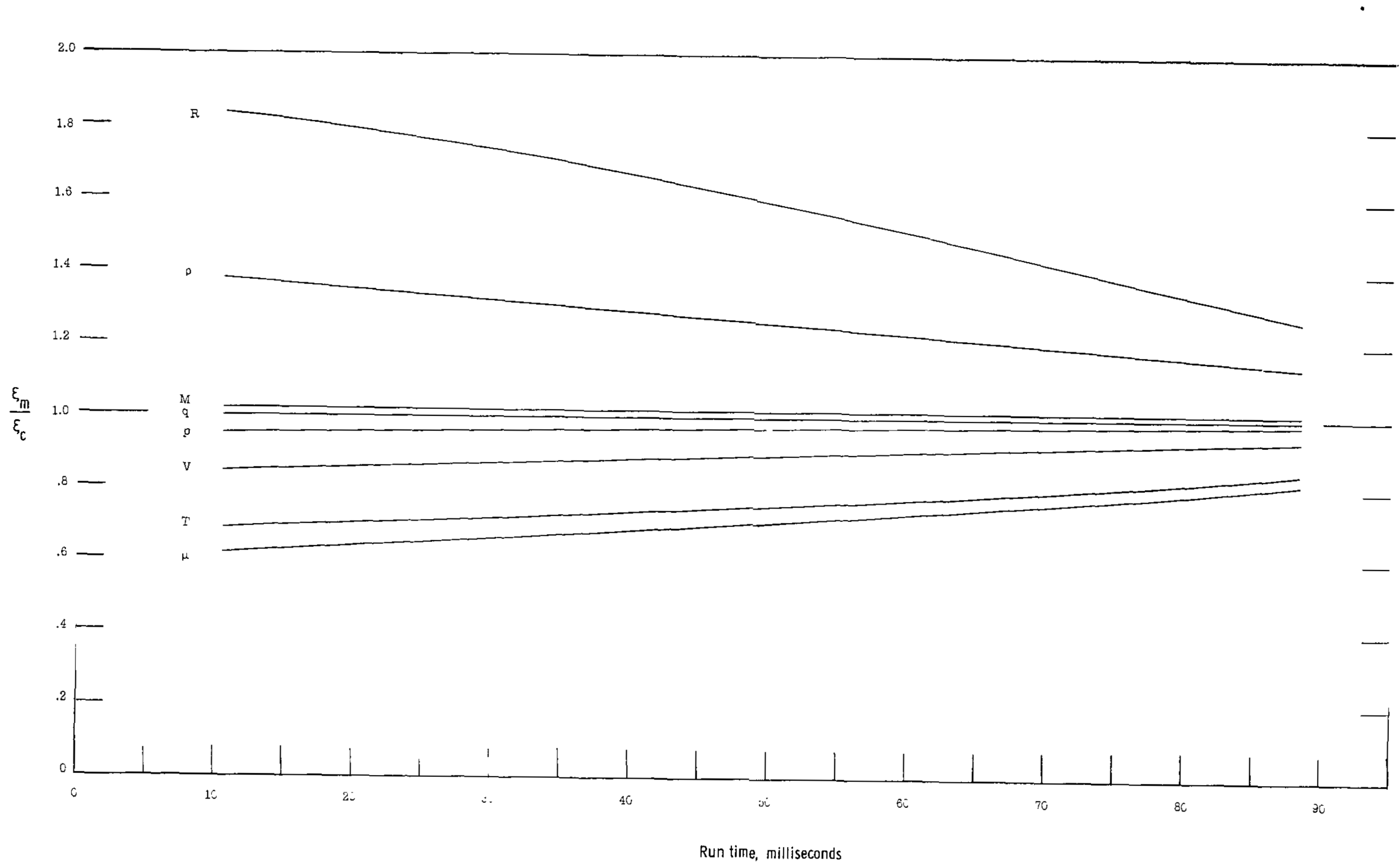


Figure 11.- Ratio of measured to calculated parameters as a function of run time.

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