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INVESTIGATION OF SPARK-OVER VOLTAGE - DENSITY RELATION FOR GAS-TEMPERATURE SENSING

By Robert J. Koenig and Richard S. Cesaro

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SUMMARY

The relation of spark-over voltage to gas density is considered as a basis for a possible gas-temperature-sensing method. The mechanism of the electric spark with practical considerations involved in applying this mechanism to gas-temperature sensing and the results of experimental work directed toward application of the spark-over voltage - density relation are discussed.

The investigation indicated that application of the spark-discharge mechanism to a gas-temperature-sensing method is feasible. For use with an automatic-control system, this sensing method would give a rapid response rate and provide a signal output that could be accommodated in the engine-control system. Experimental results indicated that gas velocity, electrode-surface finish, and a small static-pressure tap located on an electrode had no appreciable effect on reproducibility of spark-over voltage and that a small temperature-sensing probe could be used satisfactorily in a gas-turbine engine. An error of the order of ±2 percent was indicated in determining spark-over voltage. The error in the determination of gas temperature, however, must also include any error involved in determining gas pressure.

INTRODUCTION

Research on the effect of small variations in temperature on spark-over voltage was conducted as early as 1888 (reference 1) and 1889 (reference 2). In later years, the electric spark and its relation to gas density were extensively investigated and reported in references 3 to 17. The results of these investigations are used as background in the discussion of the mechanism of the electric spark and the practical considerations involved in applying this mechanism to a temperature-sensing method.

With the advent of new jet-propulsion systems, additional problems have arisen in gas-temperature sensing. Gas temperature-sensing methods in current use are considered unsatisfactory in the temperature and gas-velocity ranges encountered in such engines. An investigation of various gas-temperature-sensing and control methods is therefore being conducted at the NACA Lewis laboratory.

The principal requirements of a temperature-sensing system are accuracy, rapid response, reliability, long service life, and usable signal output. In addition to improving current methods of temperature sensing with respect to these requirements, consideration has been given to systems that show possibilities of meeting these requirements more fully than those available. Research was conducted on sensing systems based on those gas properties that vary in a known manner with the mean energy of the molecules.

The spark-discharge phenomenon and its relation to gas density as a possible temperature-sensing method and the application of this phenomenon to temperature sensing and control are presented herein. For many years, the spark-discharge phenomenon has been used to measure high voltages. For the application under consideration, the spark gap can be operated in a range in which voltage may be accurately determined by other means.

The preliminary experimental work reported herein includes the effect of gas velocity on spark-over voltage, the effects of electrode-surface finish and of a static-pressure tap in one of the electrodes on reproducibility of data, and the usefulness of a practical-size special probe in a gas-turbine engine.

MECHANISM OF ELECTRIC SPARK

Only in recent years has the mechanism of the electric spark been understood. The streamer theory of spark discharge, the present concept, was contributed by Loeb (reference 3) and Raether (reference 4). They arrived at a qualitative theory of the mechanism of sparking by streamer propagation from anode to cathode, the mechanism functioning by means of photo-ionization in the gas.

Sequence of Events

The sequence of events that leads to a spark is described in condensed form in reference 6. For the case of a discharge between two parallel plates, referring to figure 1 and following the sequence A through J, Loeb states: "The upper plate is positively charged; the lower plate, negatively. The field between them (A) has a strength of 30,000 volts per centimeter. At the lower left a random photon knocks a single electron from an atom. [At (B) is illustrated a secondary electron emitted from the cathode by a positive ion.] Moving towards the positive plate, the electron collides with other atoms to liberate an avalanche of electrons. In the wake of the electrons remain positively-charged atoms, or ions (C and D). These ions reinforce the charge of the positive plate, thus attracting new electrons (F) that have been liberated by radiation (E) during the previous events. The electrons, in turn, ionize more atoms so that a heavily ionized region (G) begins to extend [see tip at (H)] towards the negative plate. This process continues until there is a bridge of ions (J), called a streamer, between the two plates. It is this streamer that provides the channel for a spark or for lightning."

Photo-Ionization

The role of photo-ionization in the preceding sequence of events is described more fully in reference 3 as follows: "Accompanying the cumulative ionization there is produced by the electrons from four to ten times as many excited atoms and molecules. Some are excited to an energy exceeding the ionizing potential of some of the atoms and molecules present, either by excitation of an inner shell, by ionization and excitation, or in a mixed gas like air by the excitation of molecules of higher ionizing potential, e.g., N_2. These excited atoms or molecules emit radiations of very short wave length in some 10^{-8} second. This short ultraviolet radiation is highly absorbed in the gas and leads to ionization of the gas. In fact, the whole gas and the cathode as well are subjected to a shower of photons of all energies traveling from the region of dense ionization with the velocity of light. Thus nearly instantaneously in the whole gap and from the cathode new photoelectrons are liberated which almost at once begin to ionize cumulatively."

Statistical Factors

The sparking potential is not sharply defined because it depends upon ionization, which is a chance phenomenon. The sparking potential, however, is reproducible within ±3 percent and for certain conditions within 1 percent according to reference 3. A discussion of this chance phenomenon, including time factors involved in the spark mechanism, is given in reference 7. Experimental evidence of the actual sparking threshold is given in reference 8.

Spark-Over Voltage - Density Relation

The voltage required for spark-over for a uniform field in a gas is primarily a function of gap spacing and density of the gas (references 1 and 2). The following equation can be written to represent any particular range of the curve

$$E = A + B\rho l \tag{1}$$

where

E	spark-over voltage
A,B	constants
ρ	density of gas between electrodes
l	gap spacing

Gas density ρ can be expressed as

$$\rho = \frac{p}{RT} \tag{2}$$

where

p	absolute static gas pressure, (lb/sq ft)
R	gas constant
T	absolute temperature, $^{\circ}R$

Combining equations (1) and (2) and expressing them in terms of temperature give the following equation:

$$T = \frac{Bpl}{R(E-A)} \tag{3}$$

Equation (1) based on Paschen's law (reference 2) is not strictly correct. Deviations from this relation are encountered both at high vacuums (low densities) and at high pressures (high densities). For small gap spacings in air, such as those discussed in this paper, Paschen's law will be obeyed within the range of experimental accuracy at room temperatures over a pressure range from 1 to 150 pounds per square inch absolute. The limits at elevated temperatures are not given in any available literature. Paschen's law states that E is a function of ρl, the total number of molecules that an electron encounters in a linear path across the gap. The spark mechanism is not dependent on the total number of ions formed in a linear succession of processes but is dependent on the concentration of ions (reference 3). With the streamer mechanism, sparking potentials will follow different curves, depending upon whether ρ or l is varied (reference 7). For a given temperature-sensing probe, electrode design and gap spacing are fixed. Equation (3) can be simplified by combining B, l, and R into a single constant K to give

$$T = A + K \frac{p}{E} \tag{4}$$

Absolute gas temperature can thus be obtained from measurements of static pressure and of spark-over voltage.

DISCUSSION OF FACTORS AFFECTING SPARK-DISCHARGE MECHANISM

Types of Electrode and Effect of Humidity

The various electrodes used for the spark gap can be classified into three types as follows:

Needle gap. - The needle gap is sensitive to humidity, subject to rapid deterioration of the points, presents alinement and gap-spacing maintenance problems, requires a greater time to form a spark than other type electrodes, and gives appreciable deviations in spark-over voltage (reference 9). Because of these undesirable characteristics, the needle gap is unsatisfactory for use in a temperature-sensing probe.

Sphere gap. - The sphere gap, which has been widely used in electrical work, is insensitive to changes in humidity (references 9 and 10). Maintenance of a fixed gap dimension is much easier with a sphere gap than with a needle gap, the time of formation of a spark is shorter, spark-over voltages are more consistent, and burning of the electrode surface is reduced, giving a longer service life. These characteristics indicate that the sphere gap should be considered for use in a temperature-sensing probe.

Parallel plates. - Parallel-plate electrodes having well-rounded edges are superior to the other types of electrode discussed in that they provide a uniform electric field and require the least time to form a spark. This type of electrode is insensitive to changes in humidity, and reproducibility of spark-over voltages is better than for other types of gap. Maintenance of a uniform gap is more difficult with plate electrodes than with the sphere type of gap. If a uniform gap can be maintained, the parallel-plate gap is the best choice for a temperature-sensing probe.

Effect of Cathode Material

The different amounts of electron emission from various cathode materials may influence the spark-over voltage. According to Loeb (reference 11), "for longer sparks ($>$ 3 mm) [gaps greater than 0.118 in.] in air at atmospheric pressure it is impossible to detect with any certainty the effect of cathode material on V_s [spark-over voltage]." This statement implies that with small gaps there is an effect. At pressures less than atmospheric, appreciable changes in the spark-over voltages occurred when cathodes having widely different work functions were used (references 12 and 13). The term work function is related to the number of thermionically liberated electrons emitted from a material at a given temperature. Materials having a low work function will emit a greater number of electrons at a given temperature than materials having a high work function. Low-work-function materials (barium alloys) have been used for the electrodes of ignition spark plugs. The effect of these materials is to reduce the time of formation of the spark and to improve the reproducibility of spark-over voltage (references 3 and 14). The choice of cathode material for application of the spark-discharge mechanism to temperature sensing must therefore be made on the basis of experimental results.

Surface Roughness

Discontinuities on the surface of electrodes give low sparking potentials owing to local discharges. In the same way, dirt, impurities, moisture, and oil also lower the sparking potentials (reference 15); consequently, most experimenters have used highly polished electrodes. A case, however, is cited in reference 15 where more consistent results were obtained when the surface contained minute scratches. Effects of surface condition are also greatest at low pressures and small gap spacings. An experimental investigation of the effect of surface roughness was made and is reported in a subsequent section of this report.

Effect of Gas Velocity

From a survey of literature on the effect of gas velocity on spark discharges, a small effect of velocity on spark-over voltage for 1/16-inch-diameter blunt-end electrodes was found, and no effect for 3/16-inch-diameter electrodes (reference 16). The effect reported in reference 16 may possibly be avoided by using electrodes that give a more uniform field, such as spheres or parallel plates with rounded edges. For application of the spark-discharge mechanism to gas-temperature-sensing methods, consistent results irrespective of gas velocity would be desirable. If the time of forming a spark is sufficiently short, the mechanism of spark formation should not be appreciably affected by change in gas velocity over the velocity range from zero to sonic. For example, if the time of formation of a spark is 10^{-7} second, a molecule of the gas would travel, during spark formation, only 10^{-4} foot in a direction normal to the gap at a gas velocity of 1000 feet per second; a small spark-formation time is therefore desirable. The results of a preliminary investigation of the effect of gas velocity on spark-over voltage are discussed in a subsequent section of this report.

Effect of Radiant Energy

Ionization by either alpha or gamma rays in the volume of the gap is sometimes employed to improve reproducibility of sparking potential and to reduce spark-formation time. For sphere gaps, satisfactory results have been obtained with small gap spacings by placing 3 to 5 milligrams of radium inside the sphere in a hole drilled nearly to the surface of the sphere; the radium and the gap are separated by only a thin layer of metal (reference 17). Radiation obtained with radium improves ionization without distorting the field. With radium, the ionization is not distributed uniformly in time as with light; that is, one alpha particle will liberate only a limited number of ions and no more ions will be liberated until the next particle arrives. The effective ionization is thus dependent upon the number of alpha or gamma rays per second.

The effect of the presence of photoelectric emission on a spark-gap discharge is one of reducing the time of formation of the spark except for very intense illumination, which serves to lower slightly the sparking potential. Illumination of a gap by an adjacent spark has been found to reduce spark-over potential 5 to 10 percent (reference 18). The effect of ultraviolet light on the cathode is explained in reference 3 as follows: "Illumination of the cathode with ultraviolet light furnishes a photocurrent i_0 from the cathode. For plane-parallel gaps under 10 centimeters in air at atmospheric pressure and for smaller-sphere gaps, this source of current furnishes the most satisfactory arrangement." Over-voltages of as much as 50 percent were required for small gaps in air without the use of ultraviolet light (reference 10). These deviations as well as the formation time can be reduced if a photoelectric current is supplied from the cathode by use of ultraviolet light.

Gas Composition

Although most of the data in the literature are for spark-over in air, the effect of gases other than air on spark-over voltage is discussed in reference 15, which states that, on the whole, the higher the molecular weight of a gas the higher the spark-over voltage. In the application of the spark-discharge mechanism to temperature sensing, it would often be desirable to sense the temperature of a gas composed of air plus the products of combustion of a hydrocarbon fuel. The gas composition in this case is a function of fuel-air ratio and combustion efficiency. Further experimental study is required to determine the spark-over voltage for different gas compositions encountered in various exhaust gases. In general, the effect of varying combustion efficiency on gas composition appears to be a serious limitation on the use of the spark-discharge mechanism for temperature sensing. For the case of the gas-turbine engine, however, the changes in gas composition are quite small because these engines operate at very low fuel-air ratios. Variations in the combustion efficiency at a fuel-air ratio corresponding to the approximate maximum allowable gas temperature would probably be insignificant.

Particles of foreign material in the gas, such as might exist in the products of combustion, will appreciably affect the spark-over voltage (references 10 and 12). The effect is one of lowering the spark-over voltage from that of the uncontaminated gas and also of causing erratic spark-over voltages.

Effect of Thermal Expansion

The effect of thermal expansion on a spark-gap temperature-sensing probe need be considered only when the probe is used to indicate rapid changes in gas temperature. Any gradual change in gap spacing due to thermal expansion would be accounted for in the probe calibration. For use where the gas-temperature change is rapid, the effect of thermal expansion must be given careful consideration in the probe design so as to have a minimum change in gap spacing with change in temperature.

Preliminary design calculations indicate that a probe with Inconel as the electrode material designed for a 1000° F instantaneous change in gas temperature would give an indication accurate to ±100° F. The mass of metal subject to the temperature change would determine the time required for the metal to reach the new gas temperature. If a probe were so designed that the gap spacing increased with temperature, the effect of temperature lag of the metal would be to cause the gas-temperature indication to be higher than the actual gas temperature. Thus, if the temperature probe were used in conjunction with a temperature-limiting control, the limit temperature would not be exceeded.

Miscellaneous Effects

Such factors as polarity, the effect of a grounded electrode, rate of voltage increase, and any effects of alternating current are not discussed herein because these effects would be included in the calibration of the probe.

Reproducibility of Spark-Over Voltage

Consideration of the results of previous investigators with respect to values of spark-over voltage indicates that it should be possible under controlled laboratory conditions to reproduce values of spark-over voltage within ±2 percent. The various available values of spark-over voltage for plane-parallel gaps and spherical gaps agree within ±3 percent. An accuracy of ±1.5 percent is claimed for the sphere spark-gap voltage data presented in reference 10. These data represent average values of a number of spark-overs for any given condition. In reference 3, it is stated that observed values of sparking threshold need not vary more than 1 percent for a wide range of values of photoelectric current or for considerable changes in spark-formation time. The accuracy with which gas temperatures may be determined by measurement of spark-over voltage will be depreciated by any error in determining the required pressure measurement.

EXPERIMENTAL STUDY

An investigation was made to determine experimentally the effect of gas velocity on spark-over voltage, the effects of electrode-surface finish and of the presence of a static-pressure tap in one of the electrodes on reproducibility of data, and the usefulness of a special probe of a size practical for use in a gas-turbine engine.

Curves, calculated using an empirical equation developed in reference 9, served as a guide in the experimental work reported herein. For sphere gaps the empirical equation, which covers a limited range of conditions of spark-over voltage, is

$$E = g \frac{l}{f_o} \tag{5}$$

where

g average voltage gradient between limits of separation of $l = 0.54\sqrt{r}$ and $l = 2r$; where $g = 27.28\left(1 + \frac{0.54}{\sqrt{\sigma r}}\right)$, kilovolts per centimeter

l gap spacing, centimeters

f_o function of l/r for one sphere grounded. For 1-inch-diameter spheres: 1/4-inch gap (0.635 cm), $f_o = 1.18$
3/8-inch gap (0.9525 cm), $f_o = 1.29$

r radius of sphere, centimeters

σ relative air density, ρ/ρ_o

ρ density, pounds per cubic foot

ρ_o density of 0.0739 pound per cubic foot

The average error for curves calculated from equation (5) for spheres having diameters greater than 0.787 inch (2 cm) should not be greater than 2 percent (reference 9).

Apparatus

A diagram of the electric circuit used is shown in figure 2, and a sketch of the ducting and electrode mount is shown in figure 3. Most runs were made using 1-inch-diameter spherical electrodes. For part of these runs, the grounded sphere was provided with a 1/32-inch static-pressure tap. This tap consisted of a drilled hole concentric with the sphere and on the axis of the gap, as shown in figure 3. The special temperature-sensing probe (fig. 4) consisted of a 1/4-inch-diameter sphere welded to the center electrode of a spark plug and was concentrically located within a 3/8-inch-inner-diameter tube welded to the shell of the spark plug.

Measurements

Voltage was measured using a d'Arsonval type instrument and calibrated resistances, the combination being rated by the manufacturer at 0.5-percent instrument accuracy at full scale. Air velocity was determined from manometer measurements of the total and static pressure. Air temperature was determined by thermocouples, located as shown in figure 3, with a correction to static temperature.

Procedure

For static runs, density was varied by changing the pressure over a range from 5 to 100 inches of mercury absolute. Runs were made over the density range for gap settings of 1/32 (0.0794 cm), 1/16 (0.1588 cm), 1/8 (0.3176 cm), 1/4 (0.6352 cm), and 3/8 (0.9528 cm) inch with all gaps held to a tolerance of ±0.001 inch. The voltage was slowly increased from a value of approximately 5 kilovolts below the calculated spark-over voltage until sparking occurred. Several spark-overs were taken at each condition, and all runs were repeated as a check. Spheres having surface finishes of 4, 32, and 64 microinches rms were used. The same procedure was followed for the velocity runs, with the exception that data were taken only for spheres having a surface finish of 32 microinches rms and 1/32- and 1/8-inch gap spacings. The temperature-sensing probe (fig. 4) had a fixed gap of 1/16 inch and a surface roughness of approximately 32 microinches rms. Data were taken only at static conditions for this probe. In all the experimental work air was drawn directly from the atmosphere, compressed, and cooled to approximately 80° F. No effort was made to dry the air or filter the impurities from it.

Results of Experimental Study

Comparison with calculated results. - The results of the static runs for the 1-inch-diameter spheres are compared in figure 5 with curves calculated from equation (5). The experimental results agree very closely with the calculated curves. Calculated curves are given only for 1/4- and 3/8-inch gap spacings. (See limits of separation given with average voltage gradient g in equation (5).) The scatter of data is attributed to momentary variations in supply voltage, inaccuracies in measurements, and impurities in the air.

Effect of static-pressure tap. - Results of static runs for 1-inch-diameter spheres with one of the spheres having a 1/32-inch static-pressure tap are presented in figure 6. The curves of figure 5 are superimposed on the data of figure 6 to show the effect of the 1/32-inch static-pressure tap on the cathode. Three curves are identical and the lowering effect of the static-pressure tap on spark-over voltage for a gap spacing of 1/16 inch is attributed to flux concentration at the sharp edge of the tap.

Surface finish. - Data taken to study the importance of sphere roughness are presented in figure 7. The sphere used as the cathode in these studies was provided with a 1/32-inch static-pressure tap. The spheres having a surface finish of 32 and 64 microinches rms (fig. 7) gave approximately the same degree of scatter, whereas the spheres with a finish of 4 microinches rms (fig. 6) gave a slightly greater scatter of data. These results indicate that the magnitude of the effect of surface conditions over the range investigated is small, particularly for the spheres having a surface of 32 and 64 microinches rms. Any differences between these two surface conditions were obliterated by data scatter. In order to facilitate comparison, the curve for spheres having a surface finish of 4 microinches rms (fig. 6) are superimposed in figure 7. For the 1/16-inch gap spacing, the data for spheres having a surface finish of 32 and 64 microinches rms are, in general, lower than for the spheres having a finish of 4 microinches rms. For further investigation of this deviation, data were taken for a spark-gap spacing of 1/32 inch (fig. 7(a)). The curve obtained is almost a straight line with a very small scatter of data and offers no explanation for the trend shown for 1/16-inch spark-gap spacing.

Temperature-sensing probe. - The results obtained using the temperature-sensing probe (fig. 4) at static conditions are shown in figure 8. The curve obtained is almost a straight line and the data are reasonably consistent, indicating the feasibility of using a probe of this general type and size for temperature sensing.

Effect of gas velocity. - The results of the velocity runs using 1-inch-diameter spheres are shown in figure 9. The curves shown are from the static runs with the velocity data plotted as individual points. The gas velocity was calculated using the static pressure measured at the sphere gap. The scatter of data is no greater for the velocity runs than for the static runs, indicating that velocity has no appreciable effect on spark-over voltage. It is rather common knowledge that an arc can be distorted by a moving gas stream and under certain conditions it may even be blown out. The case of a spark-over, however, is not the same. Figure 10 is a photograph of a spark-over taken at a velocity of 350 feet per second, using 1-inch-diameter spheres with 3/8-inch gap spacing. Several sparks appear due to limitations of the photographic equipment used. These and other photographic data obtained show that the spark travels directly across the gap. Further work, however, is required to determine whether velocity or possibly Mach number is a limiting factor in the application of the spark-over principle. The type and the location of the static-pressure tap also requires further study with regard to its accuracy at the higher Mach numbers.

SUMMARY OF RESULTS

The investigation of the spark-over voltage - density relation indicated that application of the spark-discharge mechanism to a gas-temperature-sensing method is feasible. For use with an automatic-control system, this sensing method should give a rapid response rate and provide a signal output that can be accommodated in the engine-control system. Experimental results indicated that gas velocity, electrode-surface finish, and a small static-pressure tap located on an electrode have no appreciable effect on reproducibility of spark-over voltage and that a small temperature-sensing probe could be used satisfactorily in a gas-turbine engine. An error of the order of ± 2 percent was indicated in determining spark-over voltage. The error in determination of gas temperature, however, must also include any error involved in determining gas pressure.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio, September 26, 1949.

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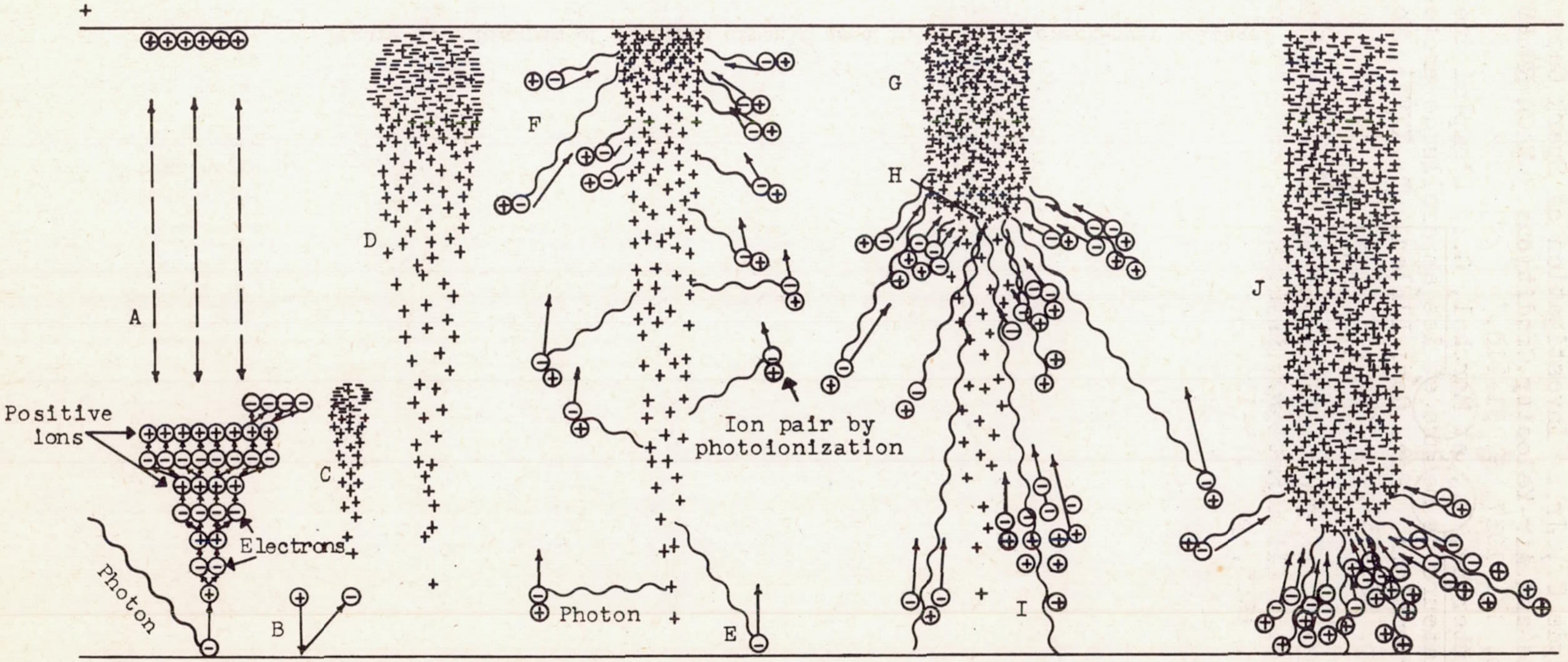


Figure 1. - Sequence of events in a spark discharge between two parallel plates. Upper plate is positively charged; lower plate, negatively. Field between them (A) has strength of 30,000 volts per centimeter. (From reference 6, pp. 24-25.)

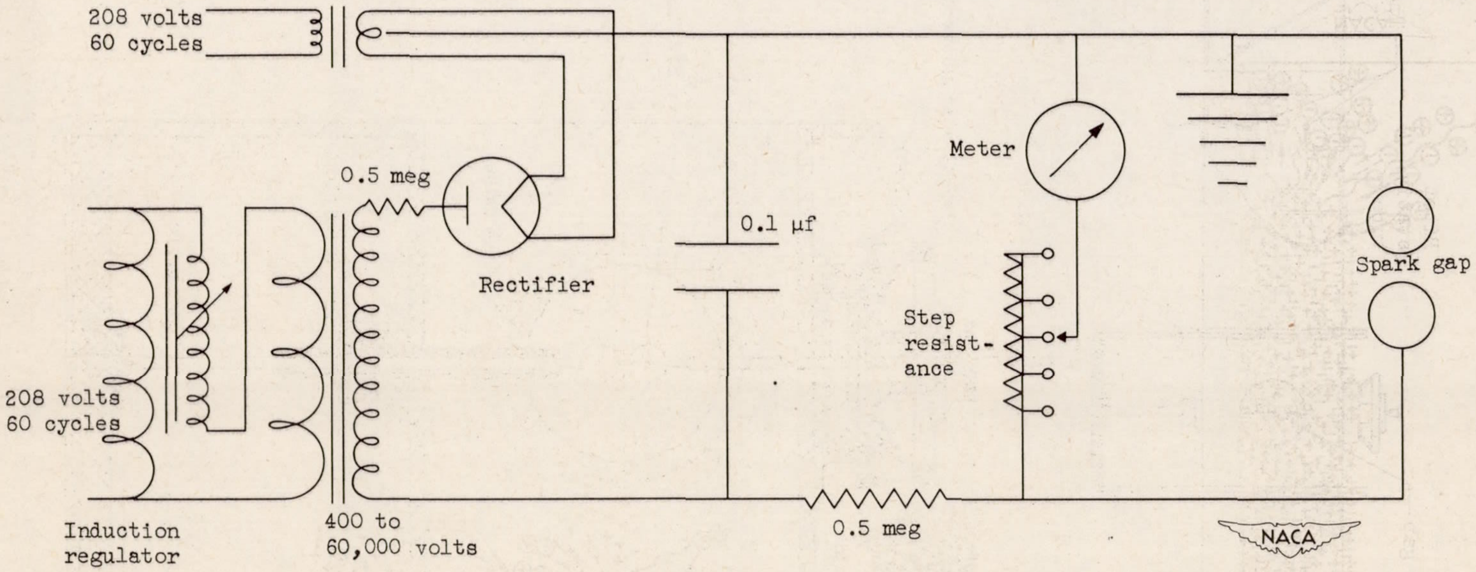


Figure 2. - Diagram of electric circuit used in study of spark-over voltage.

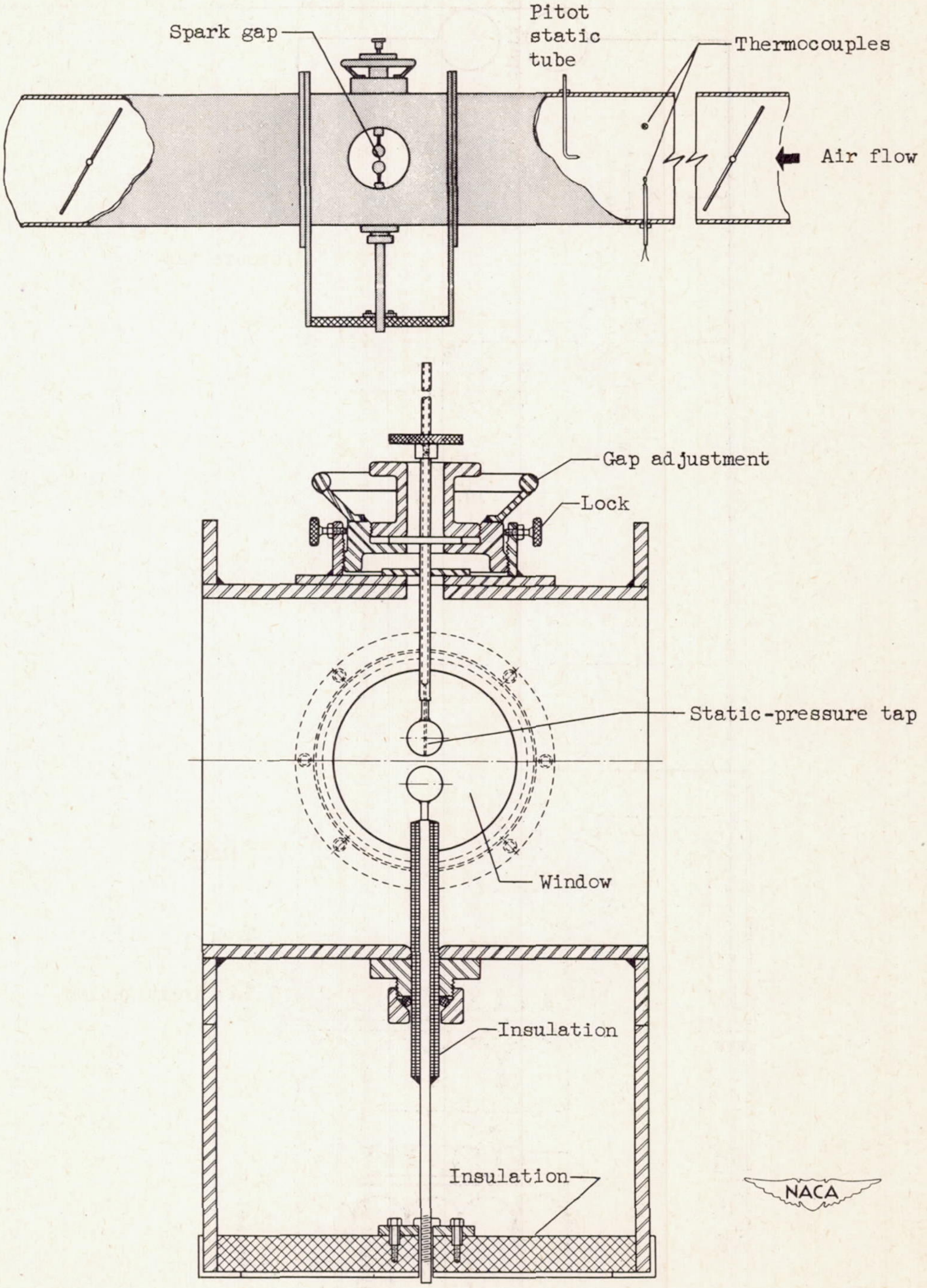


Figure 3. - Schematic diagram of equipment used in study of spark-over voltage.

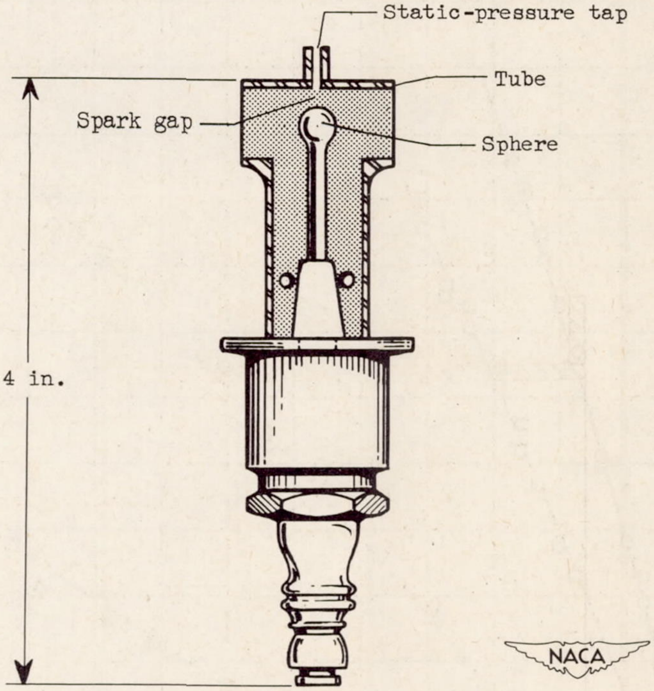


Figure 4. - Spark-gap temperature-sensing probe used in investigation.

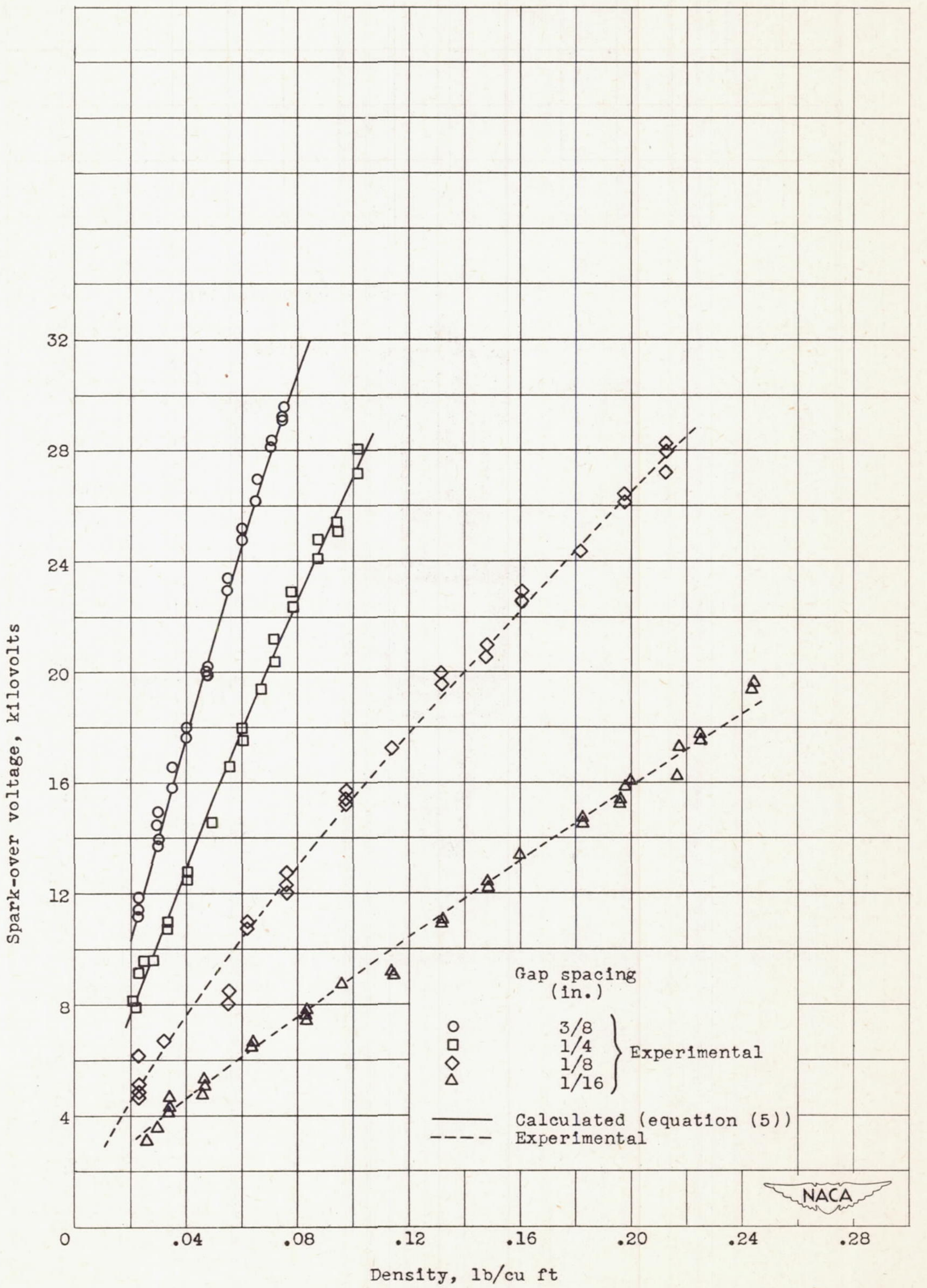


Figure 5. - Comparison of experimental and calculated data on spark-over voltage - density relation in air for 1-inch-diameter spheres with surface finish of 4 microinches rms.

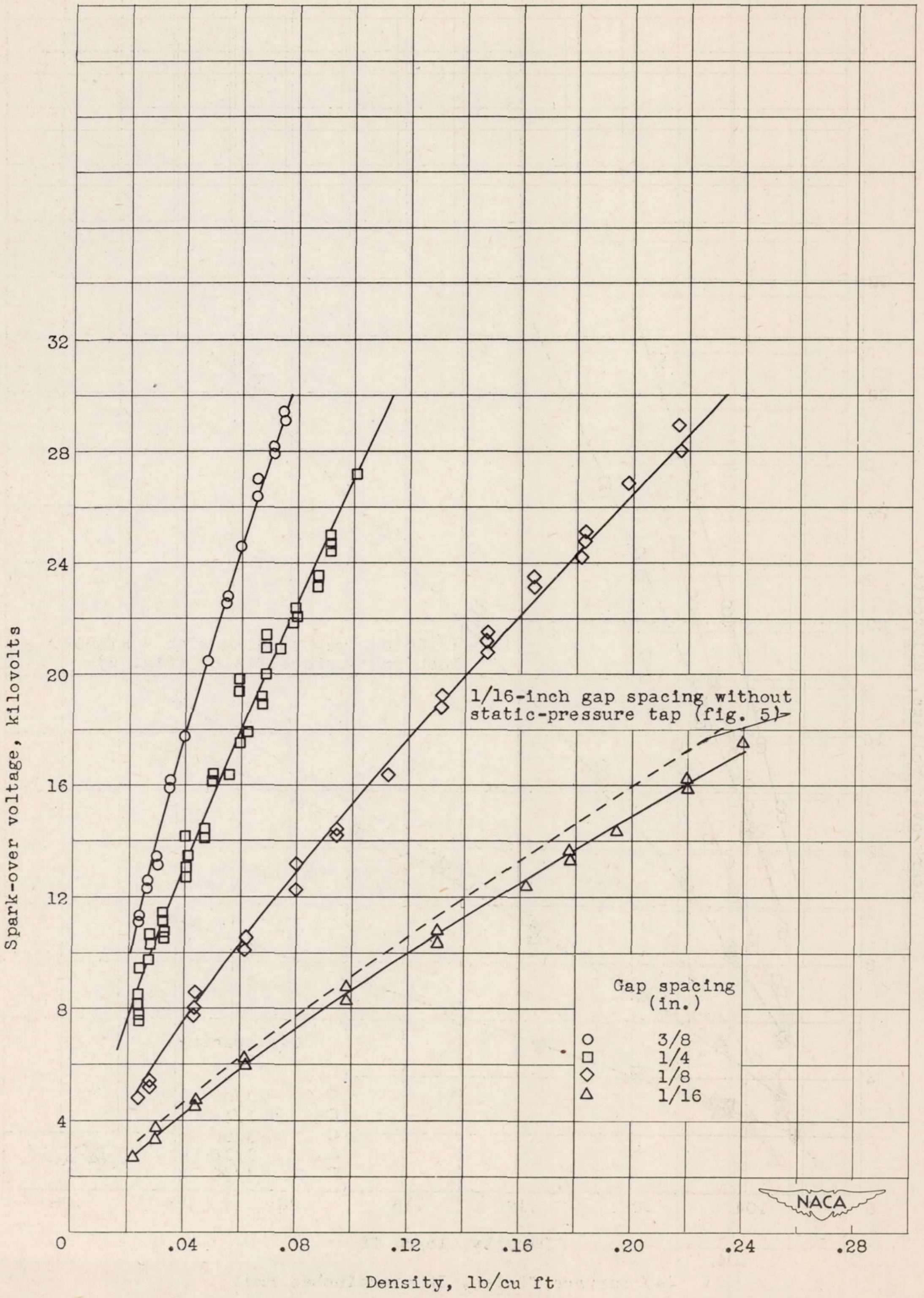
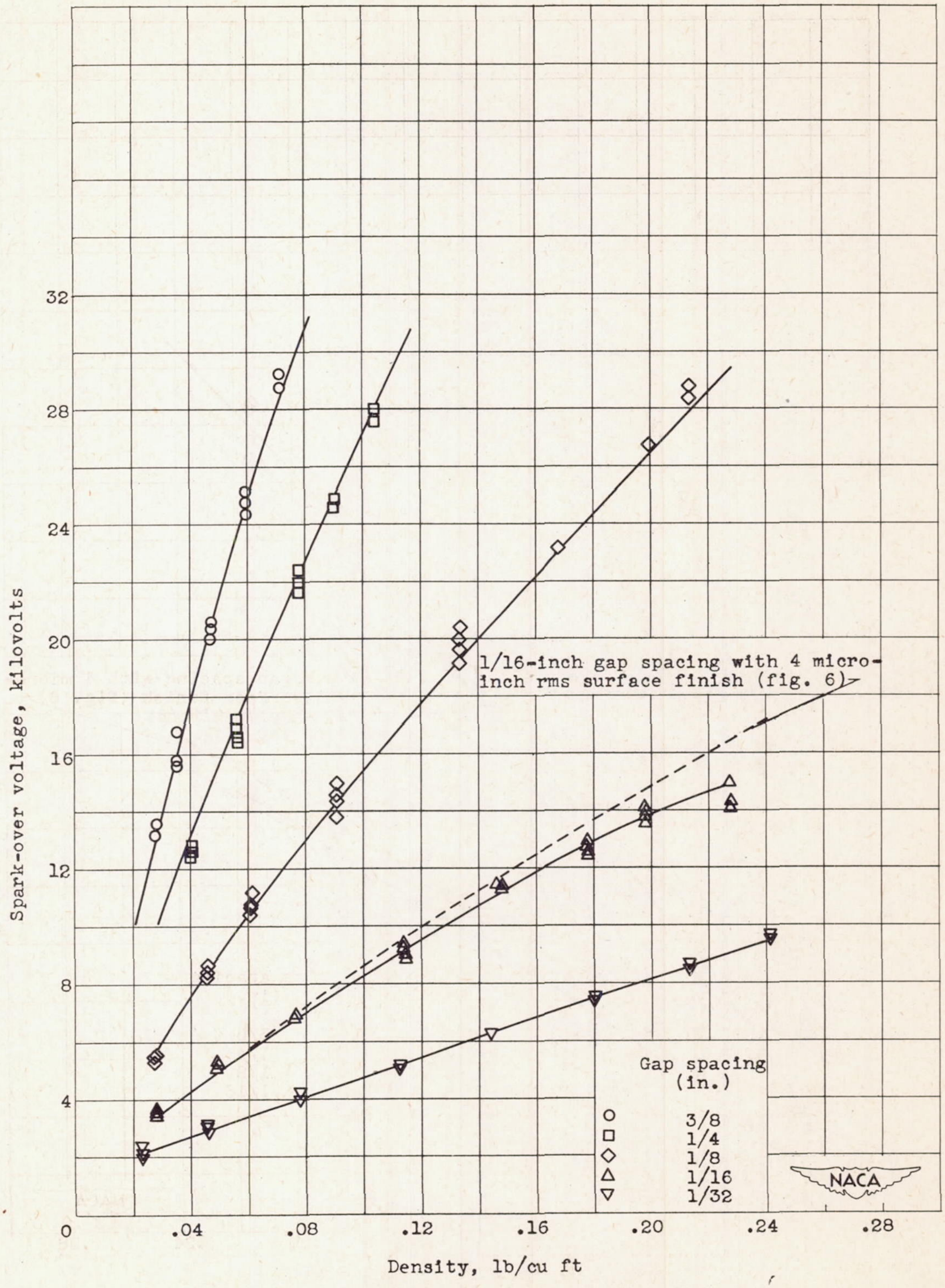
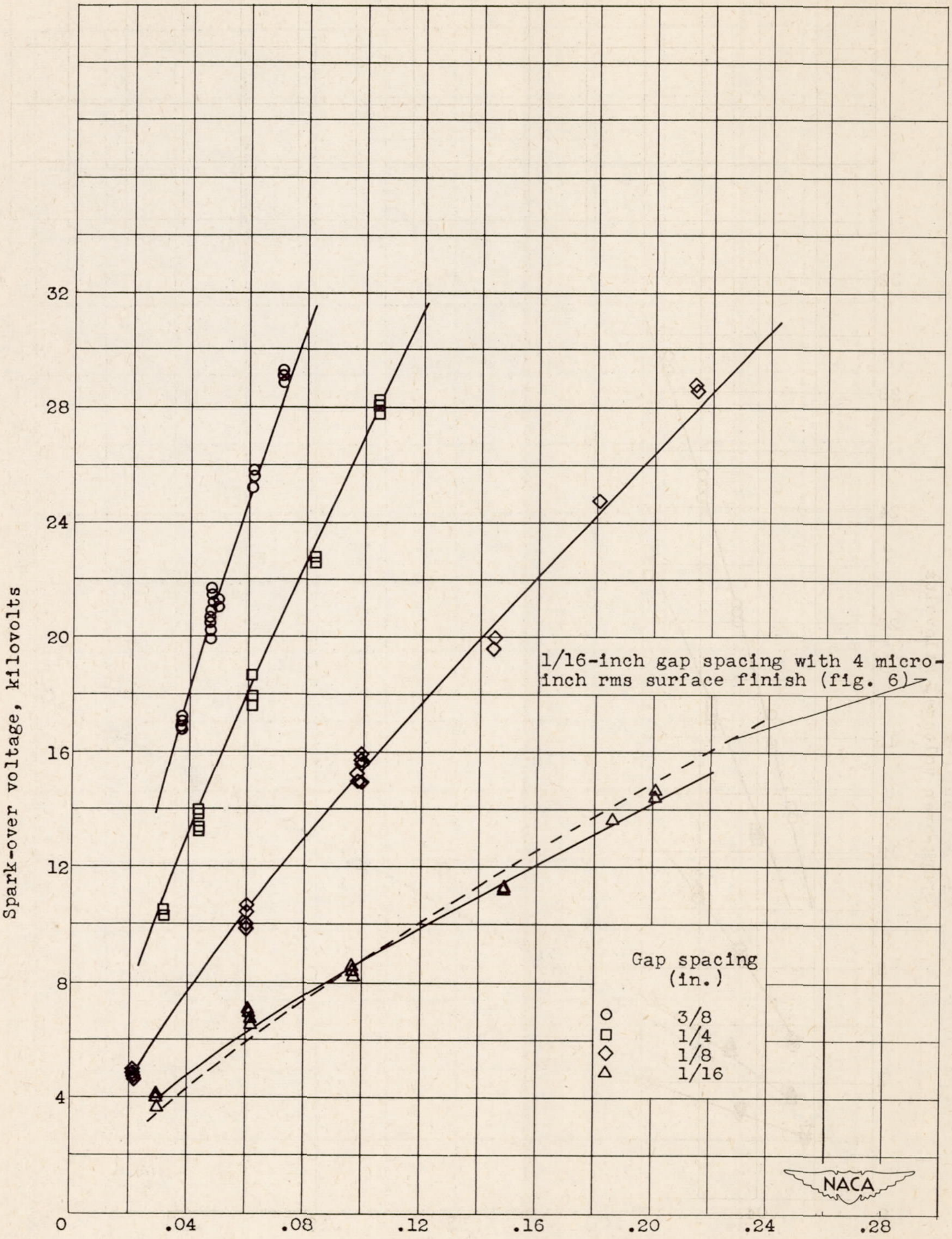


Figure 6. - Spark-over voltage - density relation in air for 1-inch-diameter spheres with 1/32-inch static-pressure tap on cathode and with surface finish of 4 microinches rms.



(a) Surface finish, 32 microinches rms.

Figure 7. - Effect of sphere surface roughness on spark-over voltage - density relation for 1-inch-diameter spheres with 1/32-inch static-pressure tap on cathode.



(b) Surface finish, 64 microinches rms.

Figure 7. - Concluded. Effect of sphere surface roughness on spark-over voltage - density relation for 1-inch-diameter spheres with 1/32-inch static-pressure tap on cathode.

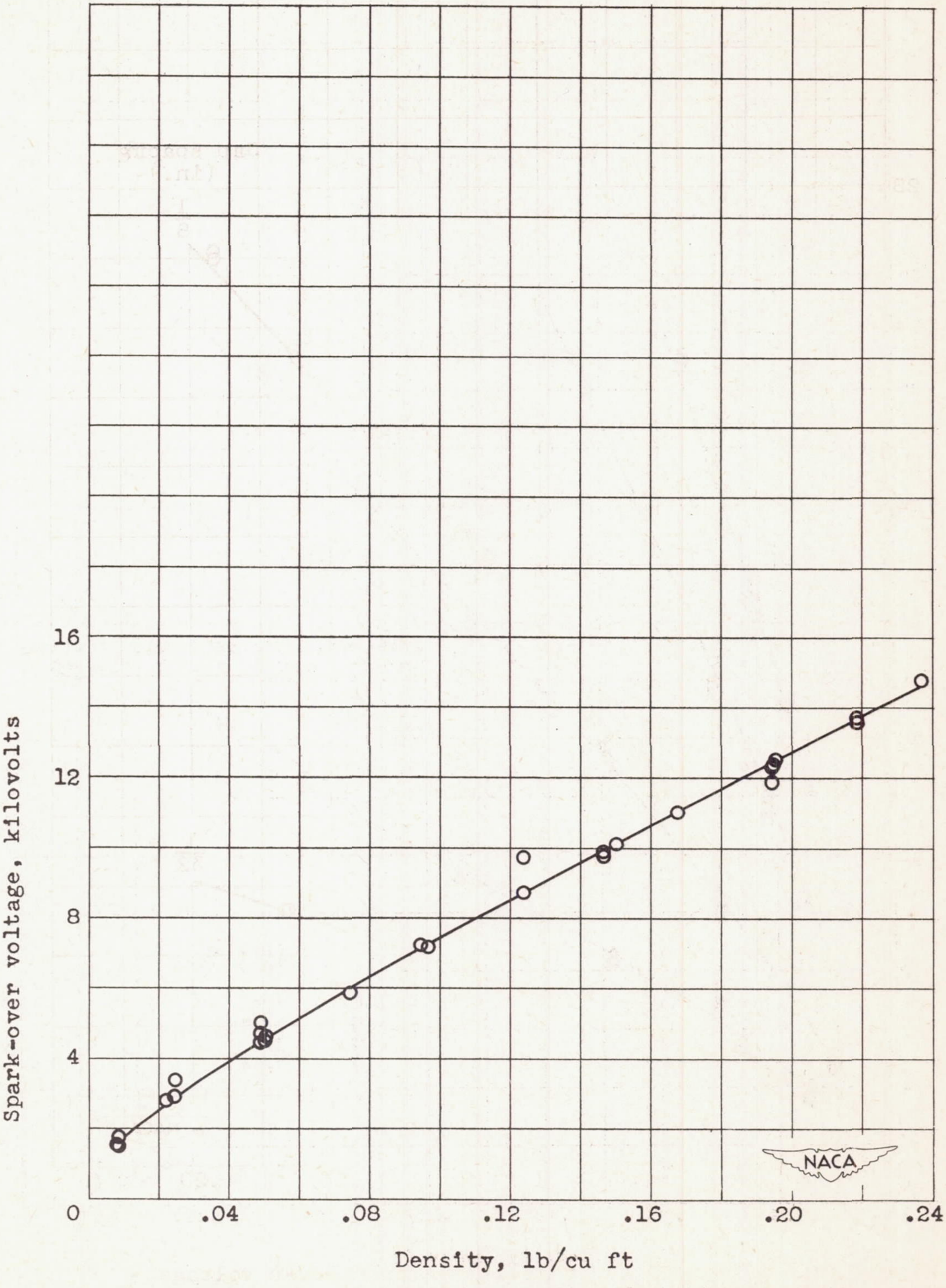


Figure 8. - Spark-over voltage - density relation for temperature-sensing probe shown in figure 4.

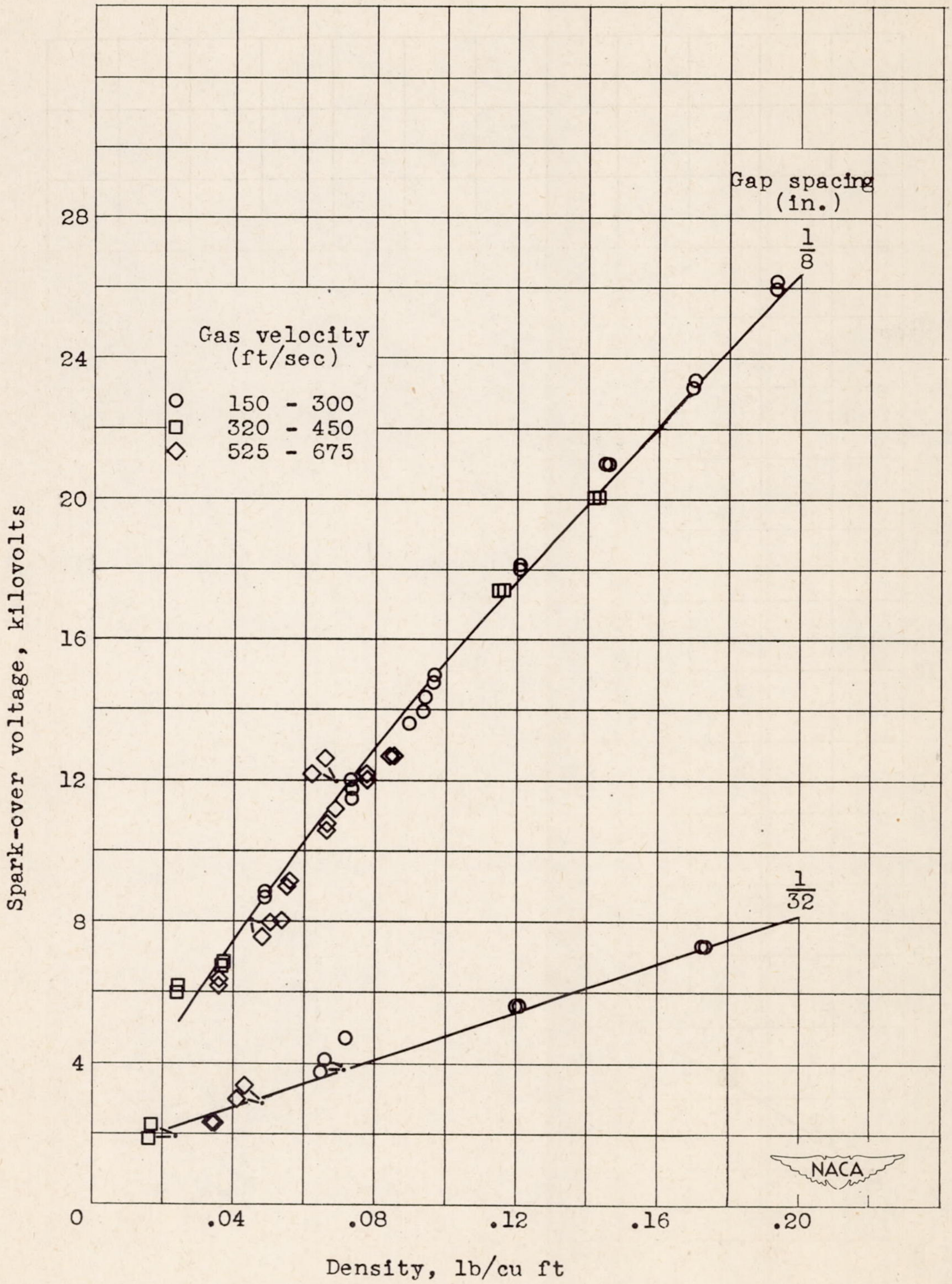


Figure 9. - Effect of gas velocity on spark-over voltage - density relation. Gas velocity, 150 to 675 feet per second; 1-inch-diameter spheres with 1/32-inch static-pressure tap on cathode; surface finish, 32 microinches rms.

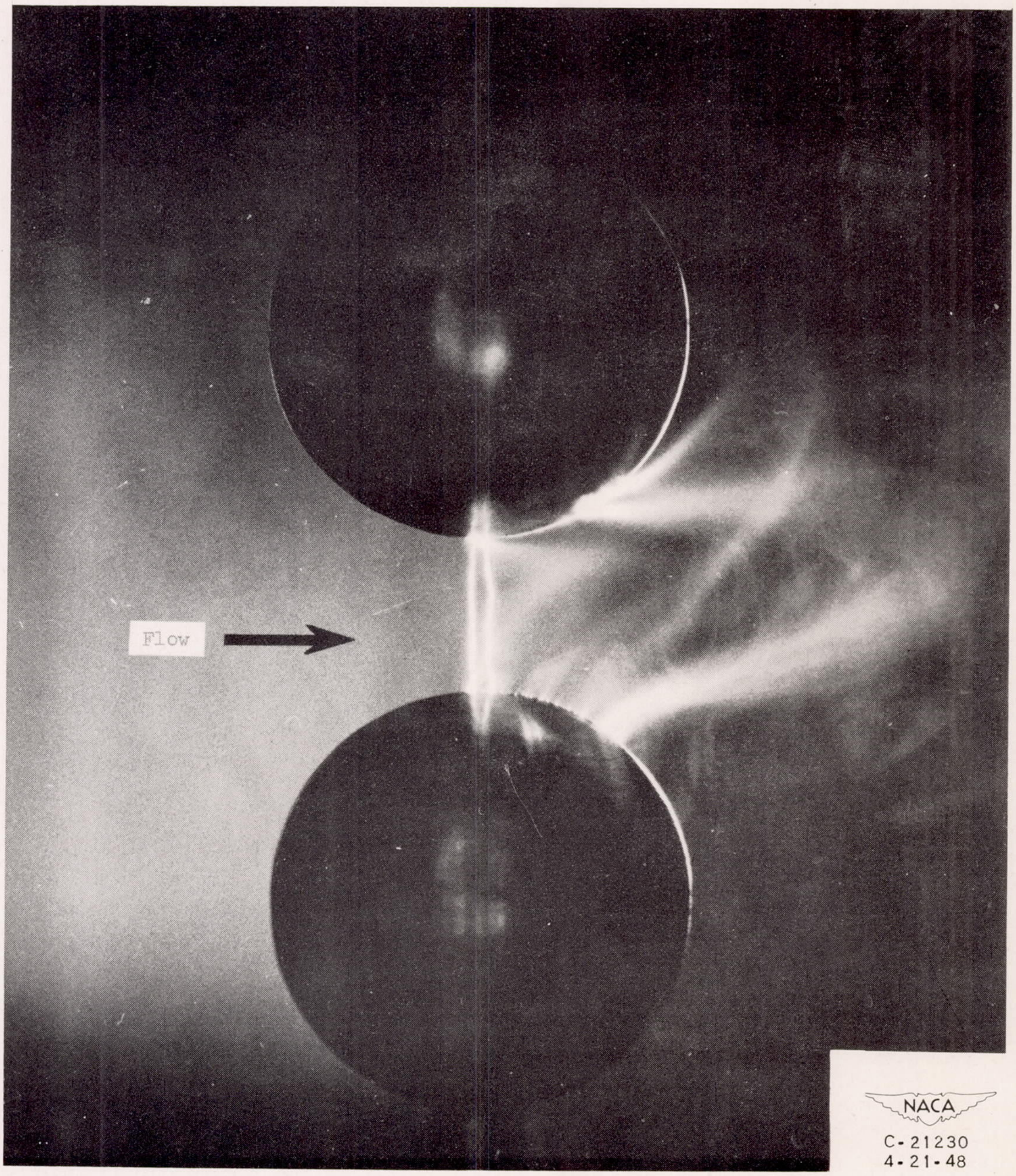


Figure 10. - Spark-over voltage between 1-inch-diameter spheres. Surface finish, 32 microinches rms; gap spacing, 3/8 inch; gas velocity, 350 feet per second; static pressure, 25 inches mercury absolute; temperature, 80° F.

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