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RESEARCH MEMORANDUM

INVESTIGATION OF SPARK GAPS SUBJECTED TO ALTITUDE AND AIR-VELOCITY CONDITIONS

By Clyde C. Swett, Jr.

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Cleveland, Ohio

REVIEWED BUT NOT
EDITED

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
November 24, 1948

31998/13

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RESEARCH MEMORANDUM

INVESTIGATION OF SPARK GAPS SUBJECTED TO ALTITUDE AND AIR-VELOCITY CONDITIONS

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SUMMARY

With the use of a constant ignition source, a study was made of the effects of air velocity on the energy and the power of the spark and the duration of the spark discharge in the spark gap for various conditions of electrode spacing, electrode diameter, air temperature, and pressure. An oscillographic method was developed and used to measure energy, average power, and time. It was found that energy and average power increased with pressure, velocity, and electrode spacing and that electrode diameter and air temperature had negligible effect. Air velocity caused the discharge to be blown downstream and to exist for a shorter time and sometimes caused a number of successive sparks to be formed. The first spark of the discharge contained more energy than following ones.

INTRODUCTION

Various new types of aircraft jet-propulsion engine that are currently in use and under development utilize spark gaps to ignite a moving combustible gas. In some cases, especially at high altitudes, difficulties have been experienced in obtaining ignition. These difficulties indicate the need for electrical ignition studies of flowing gases.

The subject of electrical ignition of flowing gases has not received much attention, chiefly because there has been little practical use for such information. The work that has been done was concerned with showing that turbulence makes a gas more difficult to ignite; however, no measurement of the gas flow is made (reference 1). Consequently, few experimental data are available from which ignition studies of flowing gases can proceed.

A program was therefore undertaken at the NACA **Lewis** laboratory to study electrical ignition of flowing gases. The first part of the program was an investigation to obtain fundamental information about spark gaps subjected to altitude and air-velocity conditions and is reported herein.

It was realized at the start of the investigation that air velocity would complicate matters by blowing the spark downstream. It was therefore decided to develop an oscillographic method that would give the following information:

(1) Energy in spark

(2) Duration of spark

(3) Average power of spark

(4) Knowledge of rate at which spark was extinguished

(5) Knowledge of whether spark is reestablished after having been extinguished

This information affords a fairly complete picture of the behavior of the spark under air-flow conditions.

APPARATUS AND PROCEDURE

Ignition System

The ignition, or spark-producing, system includes a condenser that can be charged and then discharged through a combination of resistors to produce in the spark gap a discharge somewhat similar (insofar as energy, voltage, and duration of the spark discharge are concerned) to that of the usual ignition system on aircraft. The following conditions were produced:

Peak voltage, volts	14,000
Spark energy (varies with gap conditions), joules	0.05-0.25
Duration of discharge (varies with gap conditions), microseconds	200-700

This type of system was used because of its facility of operation and because its current wave is free from oscillations, such as those found in coil systems, that would complicate the measurements.

The ignition and measuring systems used in the investigation are shown in figure 1. Condenser C was charged to 14,000 volts by means of a high-voltage rectifier consisting of transformers T_1 and T_2 and an 8013 rectifier tube. The voltage was indicated on an electrostatic voltmeter. After attainment of the correct voltage, the high-voltage source was removed by opening switch S_1. The condenser was discharged by means of S_2 mainly through two paths: (1) resistor R_1, and (2) the path consisting of R_2, spark gap G, and R_3 in series. A small current passed through R_4, R_5, and R_6.

The spark-gap electrodes were made of Inconel and two different sizes were used, 1/16-inch and 3/16-inch diameter. The electrodes had blunt ends and the center line of the electrodes was perpendicular to the direction of flow. This type of electrode was used because of its simplicity.

Measuring System

Measurement of the energy of the discharge was made by causing a voltage-current characteristic of the discharge to appear as a trace on the screen of an oscillograph tube with timing spots superimposed on the trace. The discharge current was obtained by placing the voltage that it produces across R_3 on the horizontal plates of the tube. The horizontal deflection of the electron beam of the oscillograph tube is directly proportional to the current and can be calibrated to give current directly. The voltage of the discharge was reduced by means of the voltage divider consisting of R_4, R_5, and R_6 and placed on the vertical plates. Vertical deflection can be calibrated in terms of the voltage of the discharge. Switch S_3 was closed at conditions requiring smaller deflections of the beam.

Calibrations of the voltage and the current were obtained by applying known voltages and currents and observing the deflections of the beam. Some slight current passes through the voltage divider and R_3, which results in some horizontal deflection. Consequently, in all measurements, the current passing through the divider must be subtracted from the total current (as indicated by the oscillograph tube) in order to obtain the current through the spark gap. The divider current is actually so small that its inclusion caused only 2 to 3 percent error in results; however, it was subtracted in all cases in order to obtain as accurate results as possible.

Timing spots were placed on the resulting trace by cutting off the electron beam at predetermined intervals with an audio oscillator connected to the Z-axis amplifier. The amplifier cut off the electron beam only on positive peaks of the audio-oscillator voltage waves.

The reproducibility of results was determined by inserting a 0.0483-microfarad condenser in place of the spark gap and then obtaining a number of oscillograms of the voltage-current-time trace. The oscillograms were analyzed to determine the energy going into the condenser and the results revealed an average deviation of 2 percent from the mean value. This deviation included all errors in measuring the voltage, current, and time values on the oscillograms, in plotting instantaneous power-time curves, and in measuring areas.

Air-Flow Apparatus

Room-temperature investigation. - The apparatus used to produce air flow at room temperature through the spark gap is shown in figure 2. A large-capacity exhaust system was used to produce air flow through the test section. The pressure and the velocity of the flowing air was controlled by means of two valves. The 3-inch valve opened into the room so that room air was used throughout the investigation. Air velocity was increased at the test section by reduction in flow area. The test section consisted of a $1\frac{1}{4}$-inch-inside-diameter polystyrene tube with an electrode assembly designed to eliminate air leakage that might affect the flow through the test section. An ultraviolet lamp was placed close to the 3-inch valve so that some of the air being taken into the apparatus was ionized in order to reduce the time lag of the spark gap to a negligible amount.

Air flows were determined by means of pressure taps and connections were made to an absolute and a differential manometer. Calibration was made against a pitot-static tube inserted in the test section. All velocities given are therefore peak velocities at the center of the tube.

Low-temperature investigation. - Low-temperature measurements were made by using an altitude chamber shown in figure 3. Temperature and pressure were controlled by means of refrigeration and vacuum-pump units. The temperature could be varied over a range from 80° to -70° F. Air at the desired temperature and pressure was circulated through the test section by means of a blower, the speed of which was controlled to give various air velocities. A wooden nozzle was used to increase the air velocity. A thermocouple was placed upstream of the nozzle for temperature measurements. The temperature at the electrodes was calculated by assuming adiabatic expansion between the two points. Air velocity was measured by means of a pitot tube inserted in the end of the test section, but located far enough downstream so as not to interfere with the spark nor its movement.

In an attempt to eliminate some of the time lag that was encountered, it was found that the ultraviolet lamp was unsatisfactory at low temperatures. Consequently, a spark plug was located, as shown in figure 3, and connected to a 60-cycle ignition transformer in order to provide sufficient ionization. This arrangement was satisfactory and was used throughout the low-temperature investigation.

Analysis of Oscillograms

The method used to determine energy and average power is shown in figure 4. With the assumption that the voltage-current characteristic of a spark discharge is a function of time, as in figure 4(a), each value of time t_0, t_1, t_2, . . . has a corresponding current i_0, i_1, i_2, . . . and voltage e_0, e_1, e_2, . . . ; or at instant t_0 there is an instantaneous value of power that is found as the product $e_0 i_0$. The instantaneous power can similarly be obtained at any time and can be plotted as a function of time, as shown in figure 4(b). The area under this curve can be measured by some means, such as a planimeter, and represents energy because it is determined by the product watt-seconds, or joules. The average power is the energy divided by the time base and is shown as a dashed line in figures 4(b) and 4(d). Average power is usually unimportant, but is considered herein for reasons that are subsequently discussed. If the discharge should consist of more than one spark (for example three sparks) the characteristic appears as in figure 4(c), which can be resolved into the instantaneous power-time curve in figure 4(d). Because there are three separate sparks in the whole discharge, there can be more than one value of voltage for certain values of current.

Determination of Breakdown Voltages

Breakdown voltages of the electrodes used throughout the investigation at 0.250-inch spacing were determined with a direct-current-voltage source. The voltage was gradually increased until spark-over occurred. Breakdown voltages are shown in figure 5 for various conditions of pressure, electrode diameter, and air velocity. Data for 0.125-inch spacing would be approximately 50 percent lower than these data.

DISCUSSION OF METHOD AND APPARATUS

Probably the most important advantage of the oscillographic method of study is that it shows what is happening at all times to the spark. That is, this method shows when the spark is extinguished, the rate of voltage rise, and the rate of decay of current, energy, and instantaneous power. The method is accurate enough for most purposes.

The oscillographic method has a number of disadvantages, the greatest of which is the length of time (15 to 25 min) necessary to analyze each oscillogram. Measurements made at zero velocity were inaccurate because the voltage across the spark gap during the discharge time was low. The deflection of the beam was small because the divider ratio could not be increased without danger of damaging the oscillograph tube if the spark gap failed to spark because of time lag. Because the timing oscillator was not timed with the initiating circuit, the recording of time by means of the timing spots was difficult. At some conditions at which the rate of voltage rise or current decay was rapid, the intensity of the trace was low, which made the film difficult to read.

The ignition apparatus described is limited to fairly long electrode spacings and higher pressures, such as those used herein. At shorter spacings the spark is extinguished and reignited too often to make measurements practical.

This oscillographic method may have fairly wide application in ignition studies. If the values of C, R_1, and R_2, are varied, the ignition apparatus can be made to deliver a wide range of energies and peak currents. The divider constants and current-measuring resistor would, of course, have to be changed accordingly. Sparks of short duration would probably require that a capacitance voltage divider be used. There would be a limitation as to how short a discharge could be used because the intensity of the trace decreases as the spark duration is shortened.

In applying this method to ignition work, one factor that is neglected in this method should be mentioned. This factor is the energy in the initial breakdown of the spark gap, that is, the energy stored in the capacity of the spark gap and leads. This energy is estimated to be less than 0.002 joule for this apparatus and is negligible herein. In ignition work, some conditions might be encountered where this amount would be an appreciable part of the total energy.

RESULTS AND DISCUSSION

The numerical values presented apply only to this particular ignition system with circuit constants as specified, because any change in the values of C, R_1, R_2 or the voltage changes the spark energy. Other types of ignition system give different numerical results, but the qualitative trends should be the same with the possible exception of systems that produce very short-duration sparks.

The results are presented for only one electrode diameter because it was found that changing the diameter from 3/16 to 1/16 inch had negligible effect.

The action of the spark when subjected to a moving air stream is indicated in figure 6, which shows oscillograms that are illustrative of all the results. Voltage appears as ordinates and current as abscissas in the oscillograms. Figure 6(a) shows results for different air velocities at constant pressure and figure 6(b) shows results for different pressures at constant air velocity. As soon as the spark was established in a moving air stream, it began to move downstream as indicated by visual observations and by a rate of current decrease and voltage increase much greater than that at zero velocity. Voltage and current as functions of time are shown in figure 7. Figure 7(a) shows results for a constant pressure of 11.36 inches of mercury absolute and figure 7(b) shows results for a constant velocity of 200 feet per second. As the velocity was increased, the spark moved farther downstream, thereby increasing the rate of current decay so that the discharge duration was shortened. Increasing pressure also increased the rate of current decay and shortened the discharge duration.

The values of instantaneous power as a function of time are shown in figure 8 for the same series of data shown by the oscillograms of figure 6. The rates of change of the instantaneous power were greater at higher velocities, as indicated by the slopes of the curves in figure 8(a), and at higher pressures, as indicated by the slopes of the curves in figure 8(b).

At the higher velocities investigated (400 and 500 ft/sec), another phenomenon occurred; the current decreased at such a rapid rate resulting in such a large voltage rise that an additional spark was established between the electrodes, as indicated by the fourth and fifth oscillograms of figure 6(a) and by the curves in figures 7(a) and 8(a). The number of additional sparks that were formed after the first spark for various operating conditions is shown in table I. The peak current, maximum instantaneous power, and energy of the first spark were greater than those of the following sparks in all cases where multiple sparks occurred. In almost all cases, the voltage at which the second spark occurred was less than the direct-current breakdown voltage for the electrodes. With few exceptions, the first spark still existed at the time the second spark was established.

The effect of air velocity on the energy dissipated in the spark at various pressures is shown in figure 9 for 0.125-inch and 0.250-inch electrode spacings. For the 0.125-inch spacing (fig. 9(a)), energy increased with increasing velocity and with increasing pressure. For the 0.250-inch spacing (fig. 9(b)), energy generally increased with increasing velocity, but no consistent trend was indicated with variation in pressure. Much of the deviation must be attributed to the erratic nature of the spark; no such deviations were found in checking the accuracy of the equipment.

The effect of air velocity on the duration of the discharge at various pressures is shown in figure 10. For both electrode spacings, the time decreased with increasing air velocity and with increasing pressure.

The effect of temperature on the energy dissipated in the spark and on the duration of the spark for various pressures is presented in figures 11 and 12, respectively, for the 0.250-inch electrode spacing. Temperature had little effect on either the energy or the duration of the spark. Figure 11 indicates no consistent trend for variation of energy with pressure for the 0.250-inch spacing, which parallels the results of figure 9(b). The duration of the spark decreased with increasing pressure (fig. 12), as in the case of figure 10.

In check runs at given operating conditions, the duration of the spark varied somewhat and, in general, the longer times gave greater energies. For this reason, average power (energy divided by time) was determined and these data, shown in figures 13 and 14 plotted against air velocity and temperature, respectively, show more consistent trends. The average power increased with increasing velocity, with increasing pressure, and slightly with increasing temperature. The increase of power (although slight) with increase in temperature was unexpected inasmuch as an increase in temperature results in a decrease in density. With a decrease in pressure (and density) the average power decreased. Comparison of figures 13(a) and 13(b) indicates that average power increases with electrode spacing.

No attempt was made to photograph the spark, but measurements were made of the farthest distance downstream that traces of the spark could be seen by the eye. These measurements are shown in figure 15. At a velocity of 565 feet per second, traces of the discharge could be seen as far as 1.1 inches downstream. The determination of the rate at which the spark is blown downstream would require high-speed photography and is beyond the scope of this investigation.

SUMMARY OF RESULTS

With the use of a constant ignition source, a study was made of the effects of air velocity on the energy and the power of the spark and duration of the spark discharge in the spark gap for various conditions of electrode spacing, electrode diameter, air temperature, and pressure. The following results were obtained:

1. Energy and average power in the discharge increased with air velocity, pressure, and electrode spacing.

2. An increase in air velocity caused the discharge to exist for a shorter time; if the velocity were sufficiently high the discharge existed as several sparks rather than as one spark. The energy in the first of a number of successive sparks was always greater than those following it.

3. Air velocity caused the discharge to be blown downstream of the electrodes. At a velocity of 565 feet per second, traces of the discharge could be seen as far as 1.1 inches downstream.

4. The effect of electrode diameter and air temperature on energy and on average power in the discharge was negligible.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCE

1. Wheeler, Richard Vernon: The Inflammation of Mixtures of Ethane and Air in a Closed Vessel: The Effects of Turbulence. Jour. Chem. Soc. Trans. (British), vol. CXV, pt. I, art. VIII, 1919, pp. 81-94.

TABLE I - NUMBER OF SPARKS AFTER FIRST SPARK FOR VARIOUS CONDITIONS OF AIR VELOCITY, ELECTRODE SPACING, ELECTRODE DIAMETER, AND PRESSURE

Electrode spacing, 0.250 in.						Electrode spacing, 0.125 in.					
Air velocity (ft/sec)	Pressure (in. Hg abs.)					Air velocity (ft/sec)	Pressure (in. Hg abs.)				
	5.26	11.36	15.36	19.36	25.36		5.26	11.36	15.36	19.36	25.36
Electrode diameter, $\frac{1}{16}$ in.											
0	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	200	2	1	0	0	0
300	1	0	0	0	0	300	3	2	1	1	0
400	2	1	0	0	0	400	5	3	2	1	1
450	----	-----	-----	--------	0	450	----	-----	-----	-----	1
480	----	-----	-----	--------	0	485	----	-----	-----	-----	1
500	2	1	0	0	-----	500	7	5	3	2	-----
550	3	1	1	0	-----	550	8	5	4	2	-----
Electrode diameter, $\frac{3}{16}$ in.											
0	0	0	0	[a]0,0	-----	0	0	0	0	0	0
200	0	0	0	0	0	200	2	2	1	1	1,0
250	----	-----	-----	0	-----	300	4	2	2	1	1
300	[a]1,1	0	0	[a]0,0	0	400	7	4	3	[a]3,2	1
400	1	1	0	0	[a]0,0,0	450	----	-----	-----	-----	1
485	----	-----	-----	--------	[a]0,0,0	480	----	-----	-----	-----	3
500	[a]3,3	1	0	[a]0,1,0,0	-----	500	9	4	3	3	-----
560	3	1	-----	--------	-----	550	----	[a]6,6	4	-----	-----
565	----	-----	[a]1,0	[a]0,0,0,0	-----	555	----	-----	5	-----	-----
570	----	-----	-----	0	-----	565	----	-----	-----	3	-----
--------	----	-----	-----	--------	-----	575	9	-----	-----	-----	-----

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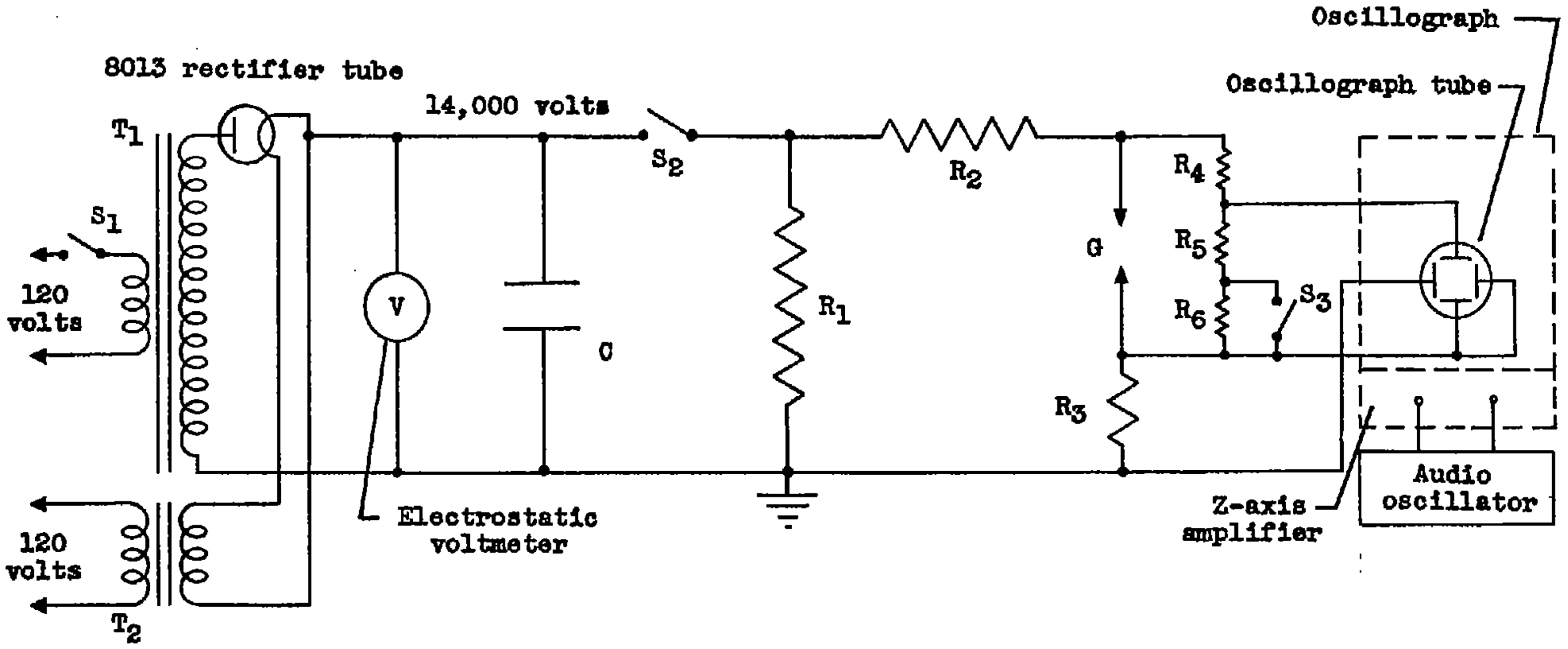
[a] More than one observation made at this condition.



C	Condenser	S	Switch
G	Spark gap	T	Transformer
R	Resistor		

Figure 1. - Ignition and measuring systems. C, 0.52 microfarad; R_1, 513 ohms; R_2, 10,170 ohms; R_3, 243 ohms; R_4, 92,400 ohms; R_5, 2,790 ohms; R_6, 5,210 ohms.

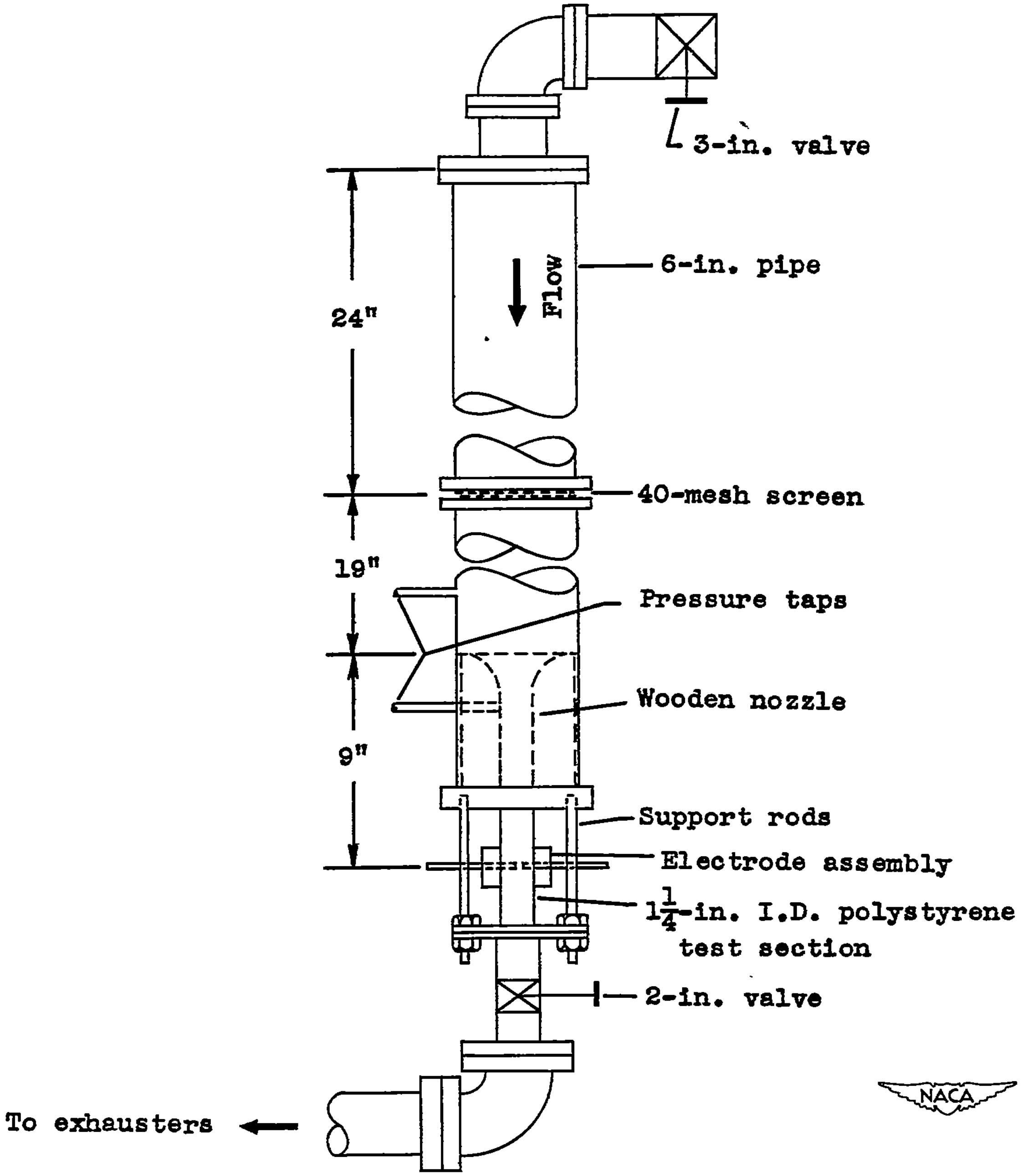


Figure 2. - Apparatus for room-temperature investigation.

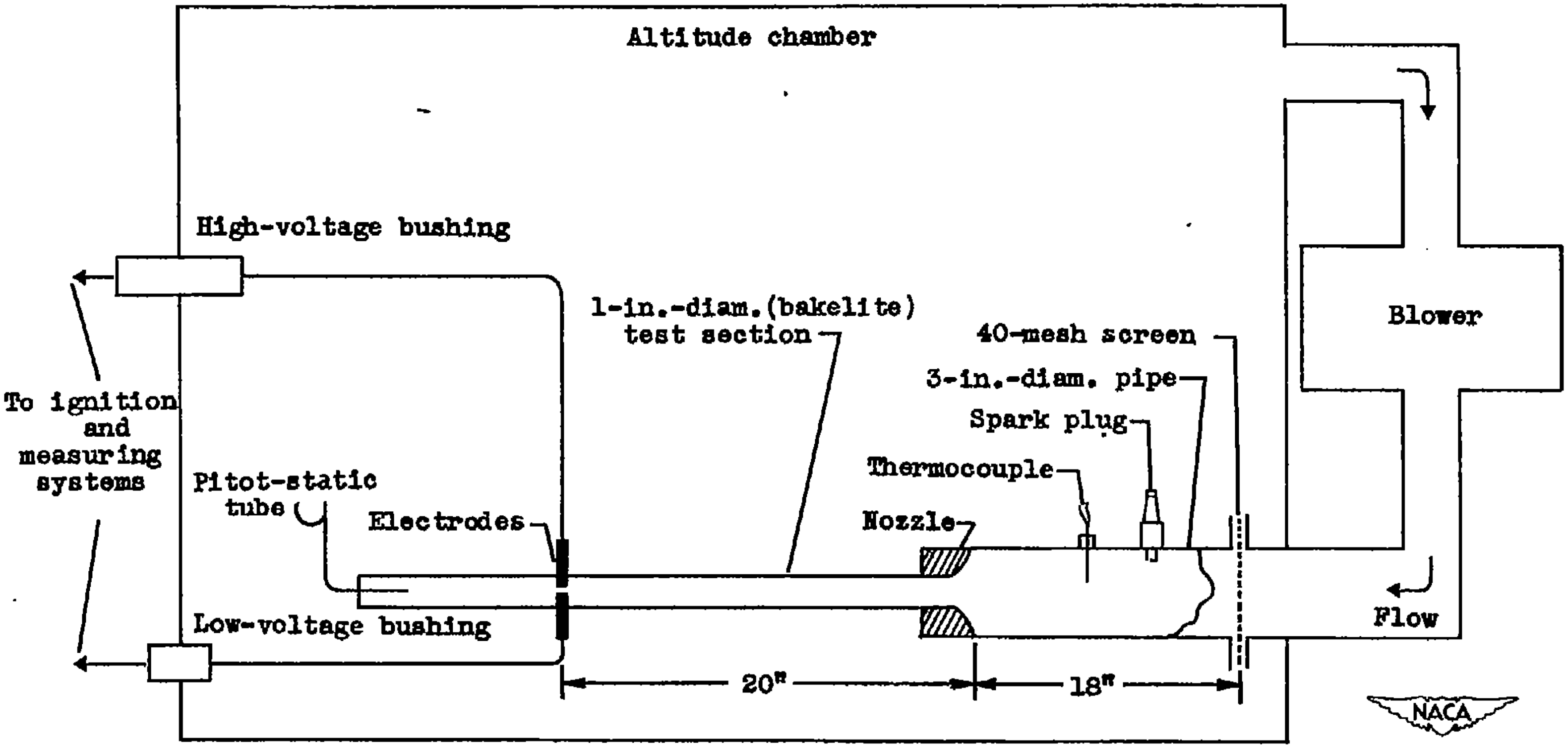
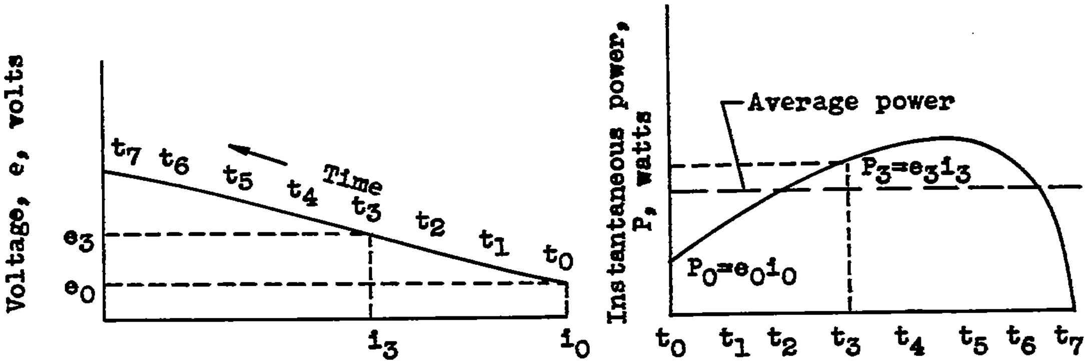
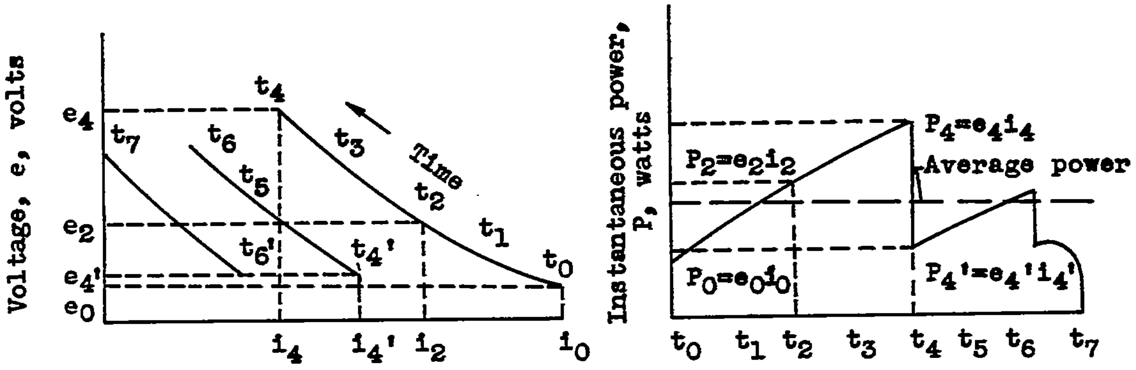


Figure 3. - Apparatus for low-temperature investigation.



(a) Voltage-current characteristic of discharge as function of time.

(b) Instantaneous power as function of time for figure 4(a).



(c) Voltage-current characteristic of discharge consisting of three sparks as function of time.

(d) Instantaneous power as function of time for figure 4(c).

Figure 4. - Method used to obtain energy and average power in discharge.

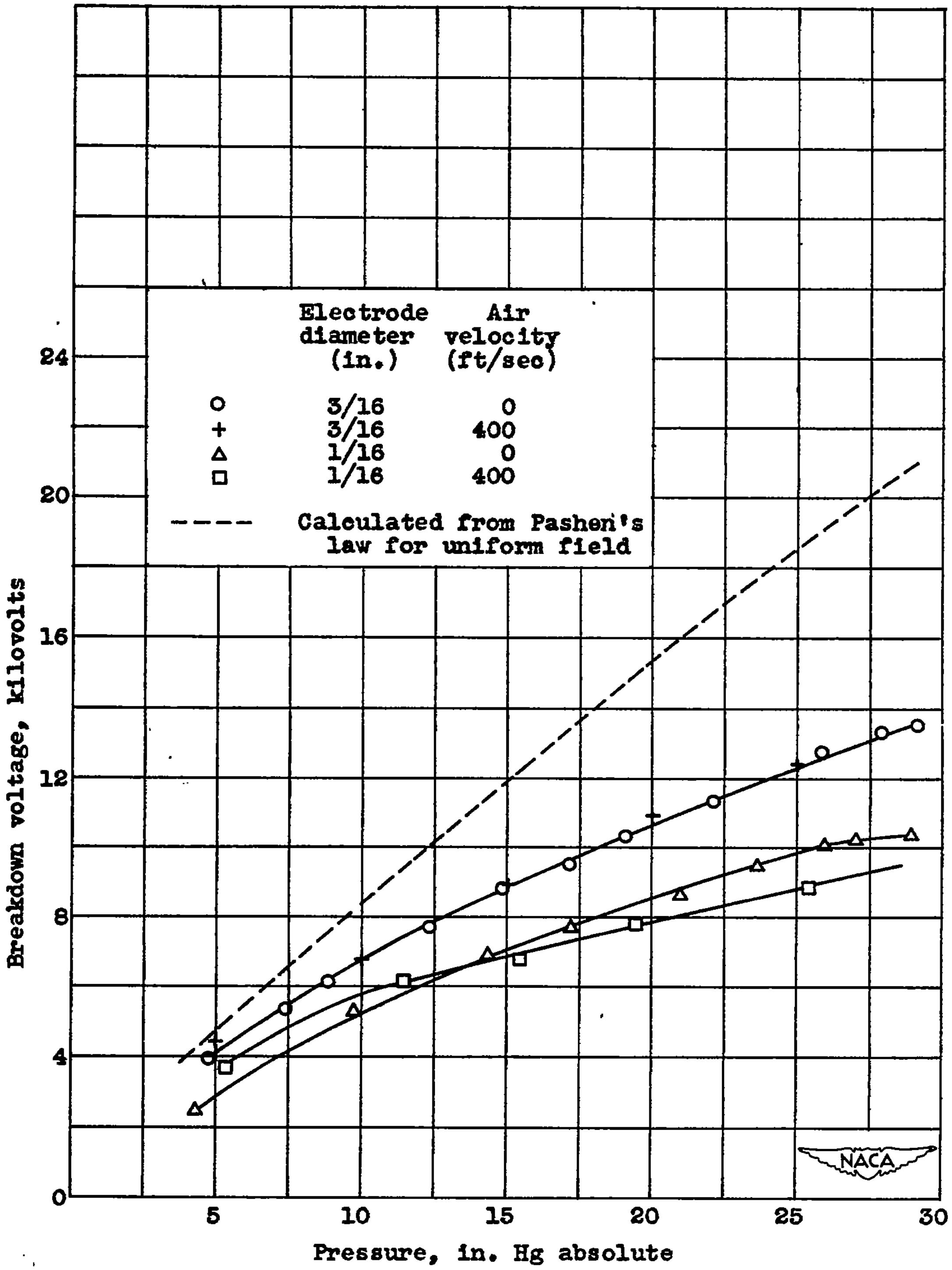
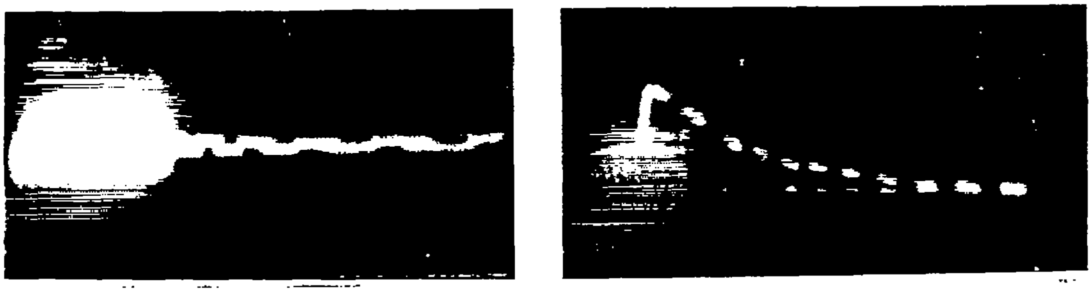
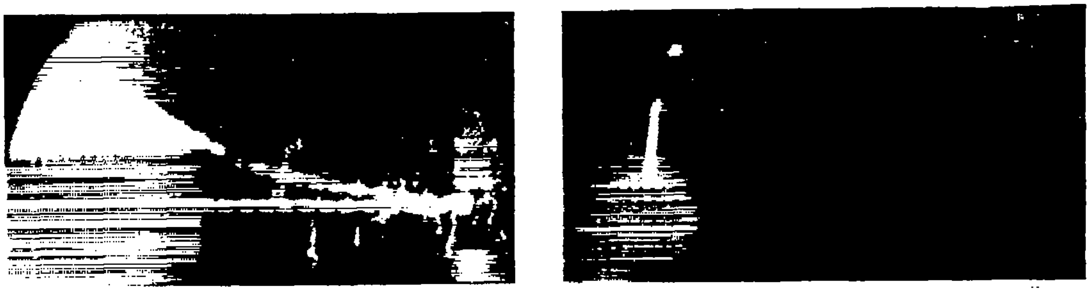


Figure 5. - Effect of pressure on breakdown voltage of spark gap. Electrode spacing, 0.250 inch; temperature, 80° F; type of voltage, direct current.



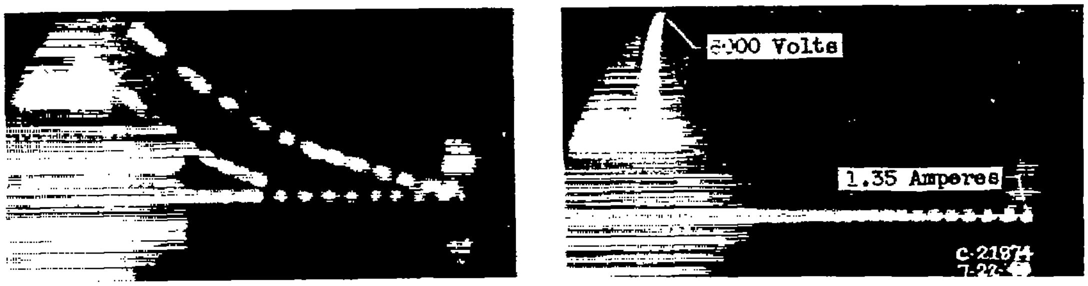
Air velocity, 0 feet per second; oscillator frequency, 12,000 cycles per second.

Air velocity, 200 feet per second; oscillator frequency, 30,000 cycles per second.



Air velocity, 300 feet per second; oscillator frequency, 60,000 cycles per second.

Air velocity, 400 feet per second; oscillator frequency, 70,000 cycles per second.



Air velocity, 500 feet per second; oscillator frequency, 70,000 cycles per second.

Calibration

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(a) Constant pressure, 11.36 inches mercury absolute.

Figure 6. - Typical oscillograms representing cross section of all results. Electrode spacing, 0.250 inch; electrode diameter, 3/16 inch; temperature, 80° F.

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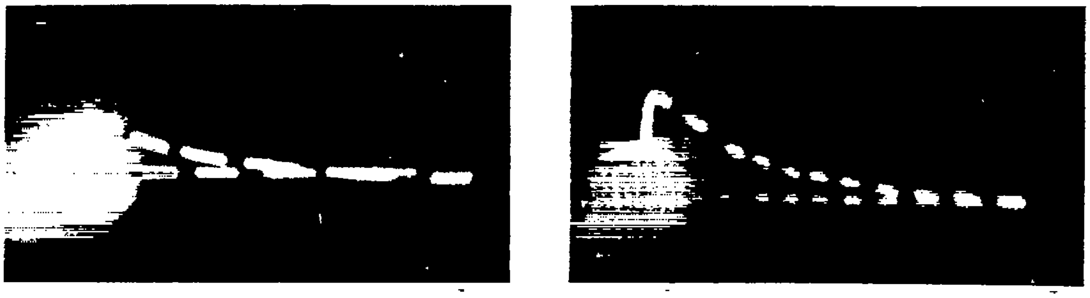
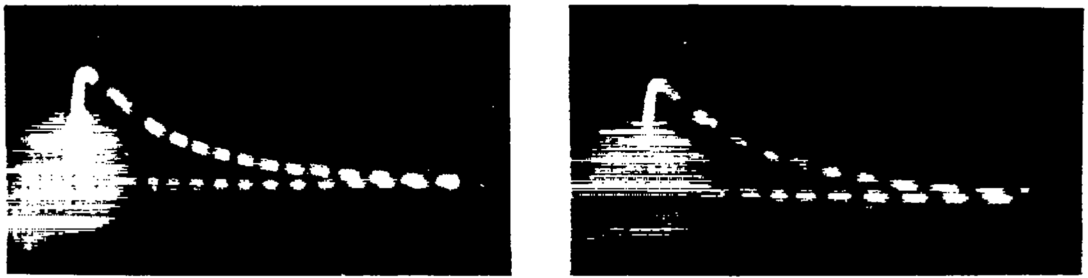


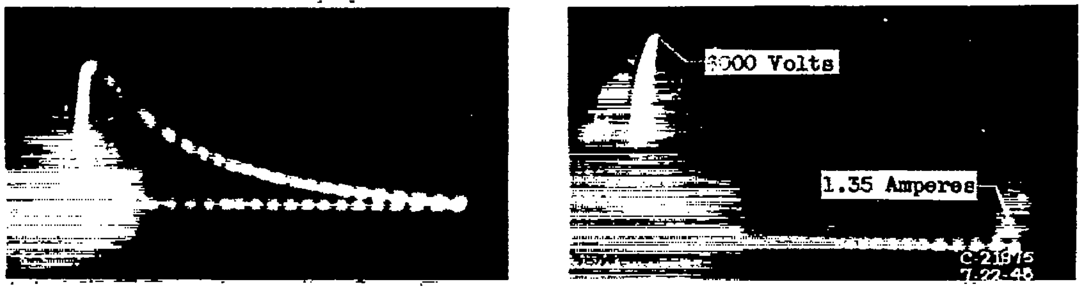
Pressure, 5.26 inches mercury absolute; oscillator frequency, 12,000 cycles per second.

Pressure, 11.36 inches mercury absolute; oscillator frequency, 30,000 cycles per second.



Pressure, 15.36 inches mercury absolute; oscillator frequency, 40,000 cycles per second.

Pressure, 19.36 inches mercury absolute, oscillator frequency, 30,000 cycles per second.



Pressure, 25.36 inches mercury absolute; oscillator frequency, 70,000 cycles per second.

Calibration

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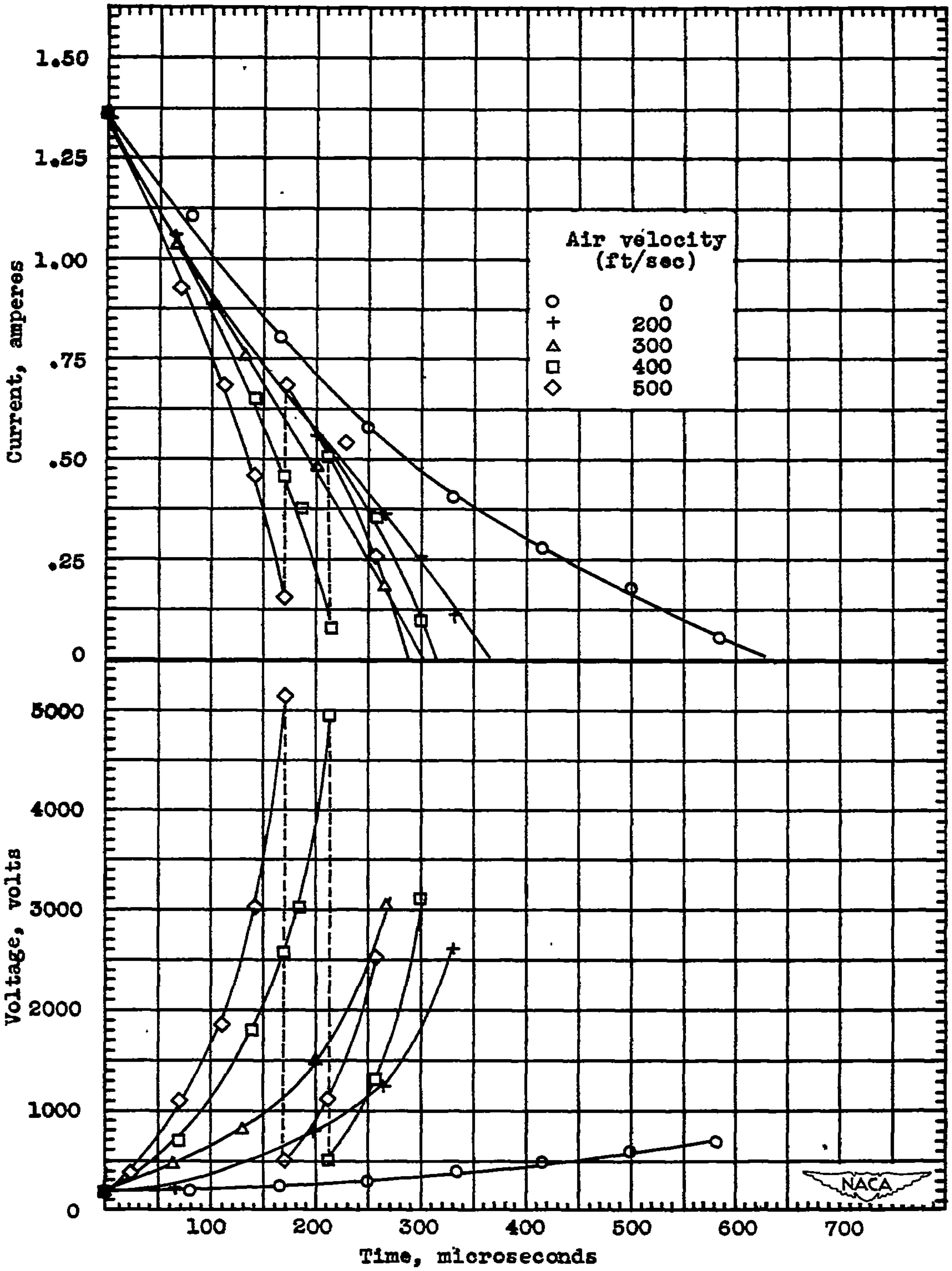
7-22-48

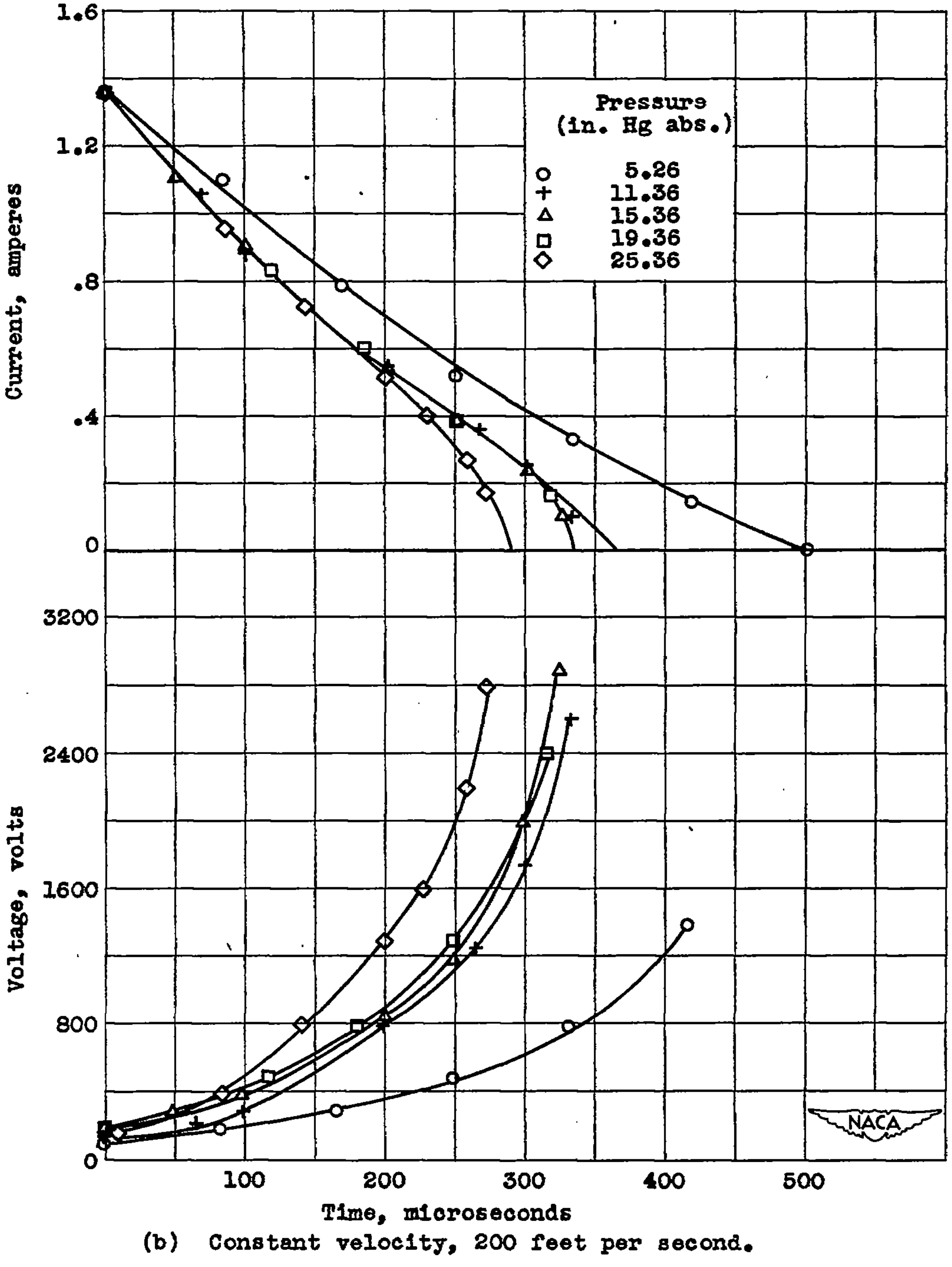
(b) Constant air velocity, 200 feet per second.

Figure 6. - Concluded. Typical oscillograms representing cross section of all results. Electrode spacing, 0.250 inch; electrode diameter, 3/16 inch; temperature, 80° F.



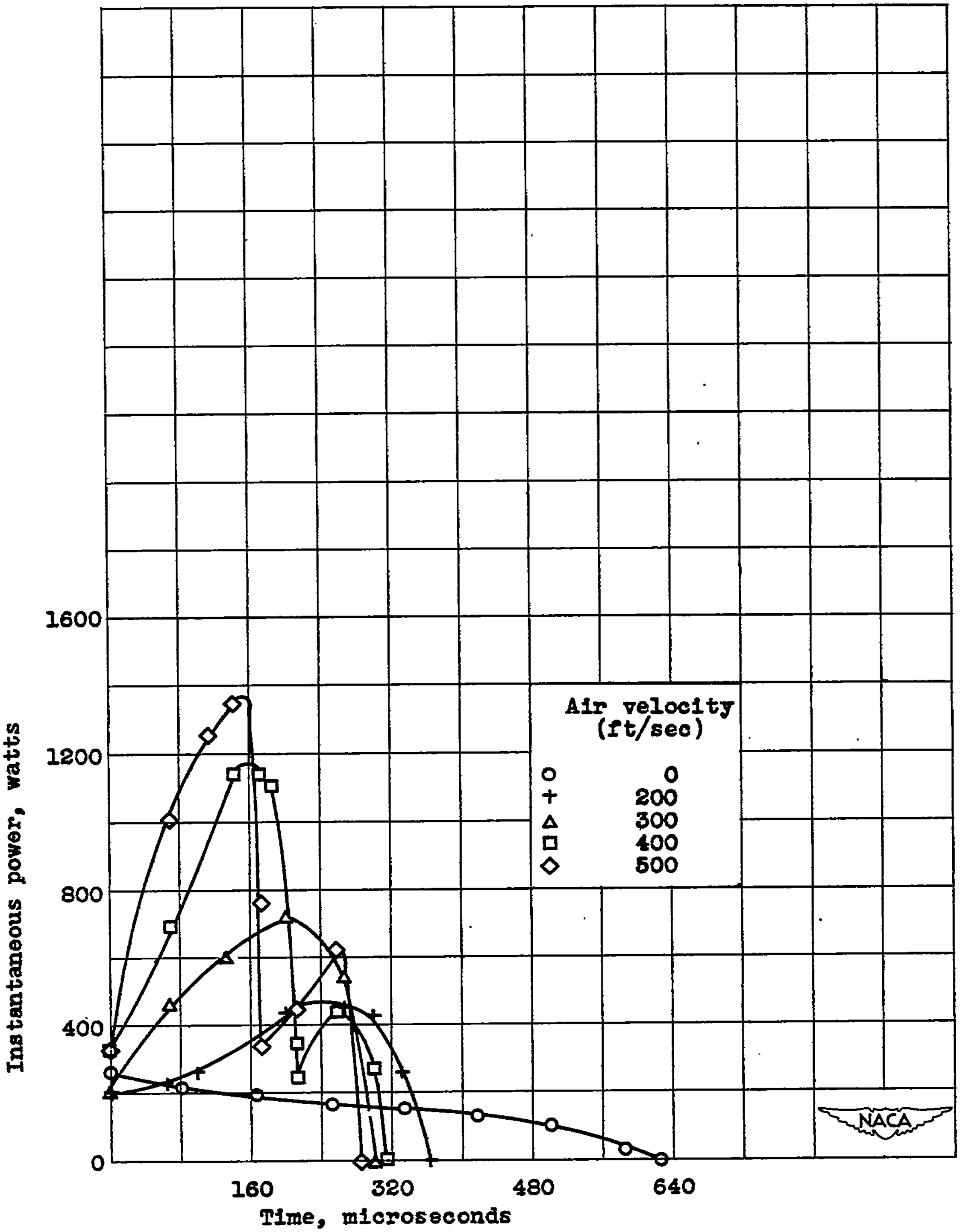
(a) Constant pressure, 11.36 inches mercury absolute.

Figure 7. - Variation of voltage and current with time for various air velocities and pressures. Electrode spacing, 0.250 inch; electrode diameter, 3/16 inch; temperature, 80° F.



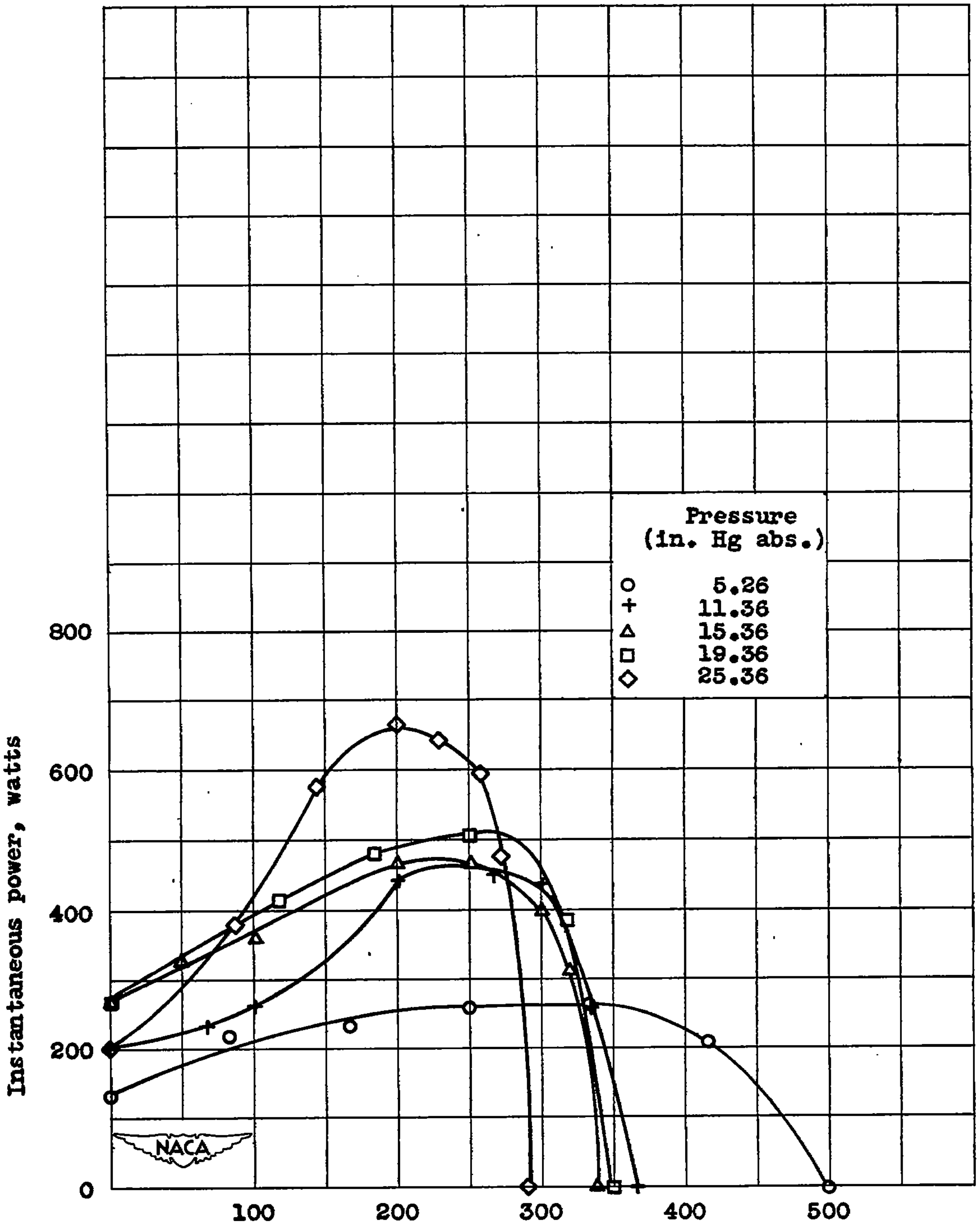
(b) Constant velocity, 200 feet per second.

Figure 7. - Concluded. Variation of voltage and current with time for various air velocities and pressures. Electrode spacing, 0.250 inch; electrode diameter, 3/16 inch; temperature, 80° F.



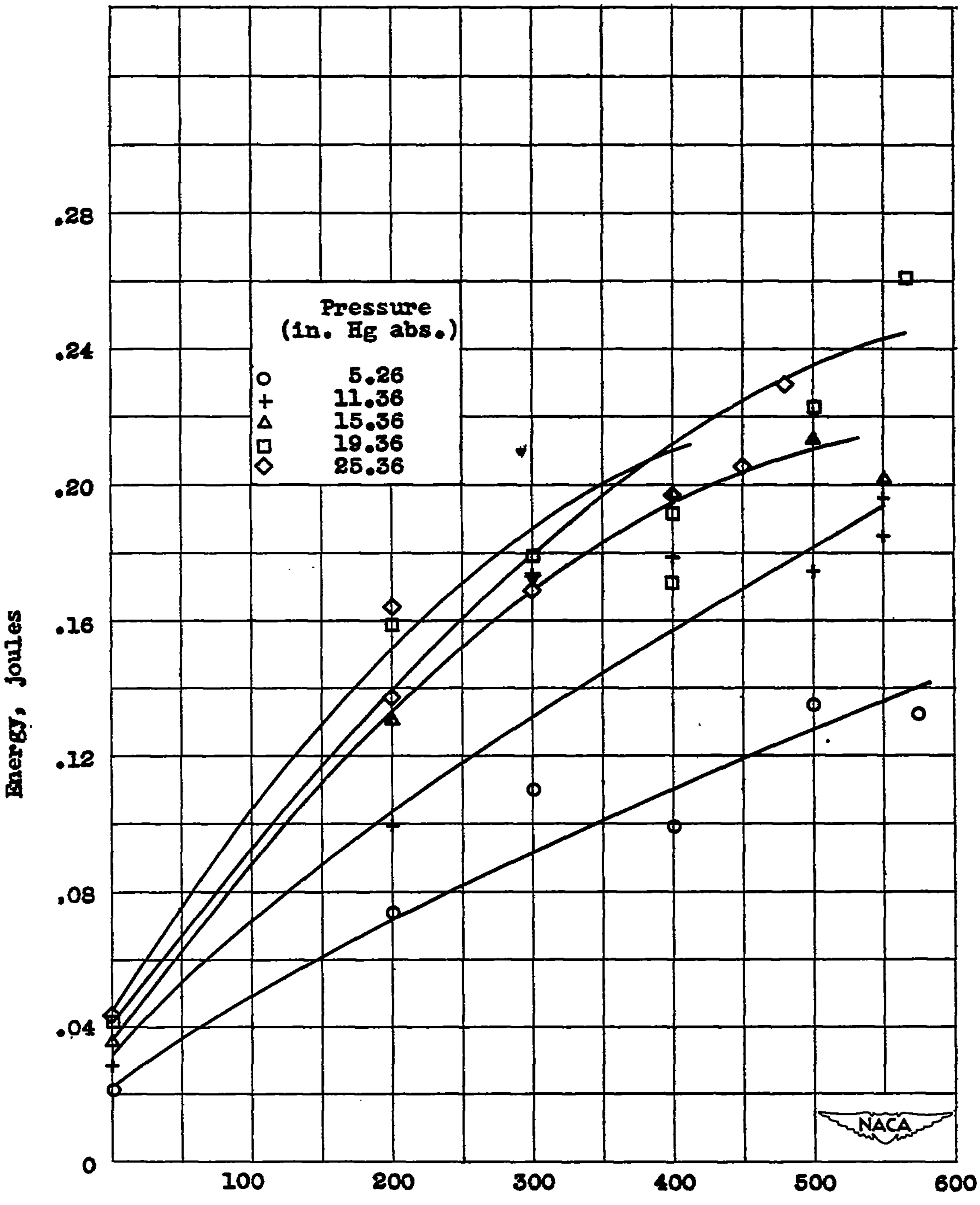
(a) Constant pressure, 11.36 inches mercury absolute.

Figure 8. - Variation of instantaneous power with time at various air velocities and pressures. Electrode spacing, 0.250 inch; electrode diameter, 3/16 inch; temperature, 80° F.



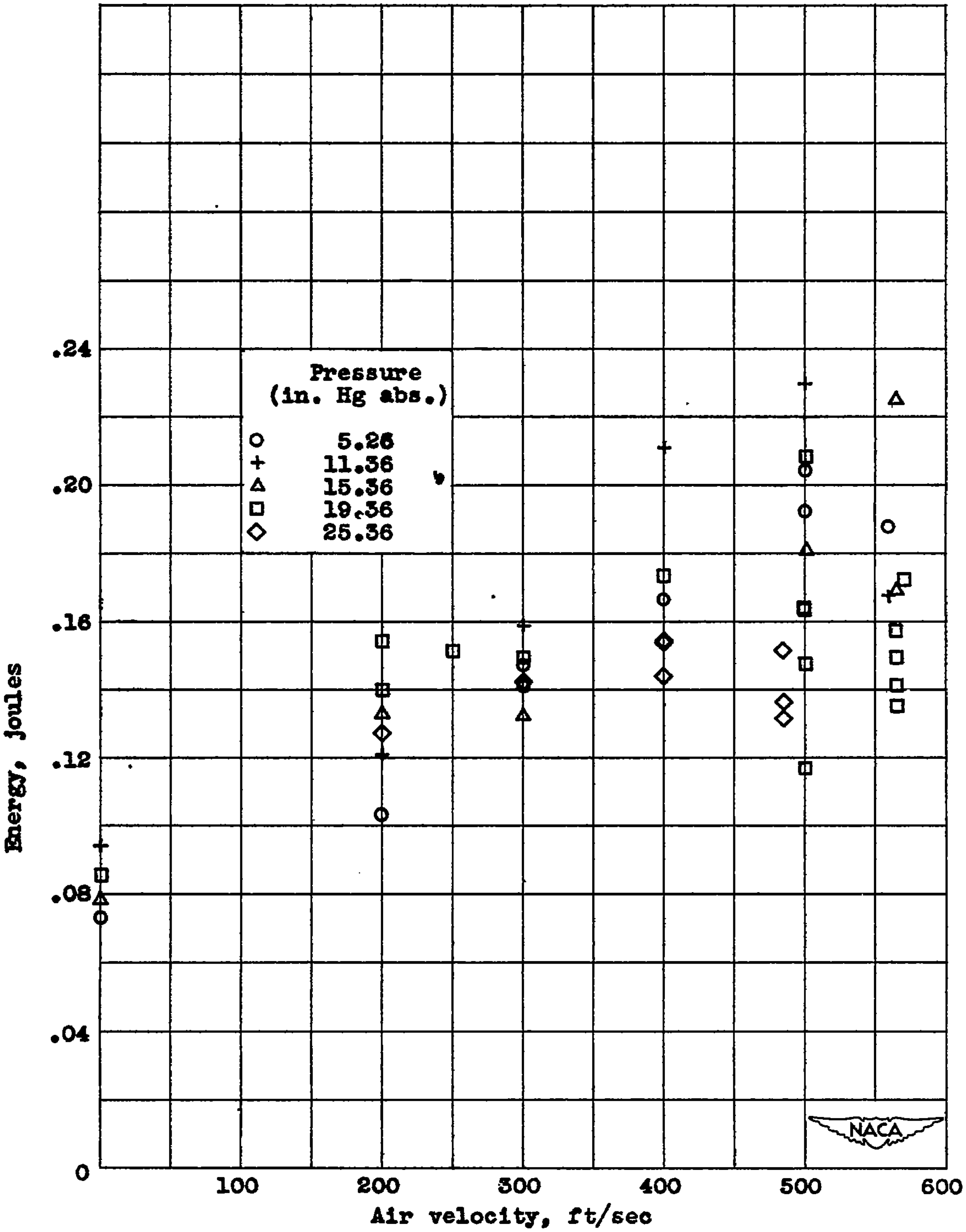
(b) Constant air velocity, 200 feet per second.

Figure 8. - Concluded. Variation of instantaneous power with time at various air velocities and pressures. Electrode spacing, 0.250 inch; electrode diameter, 3/16 inch; temperature, 80° F.



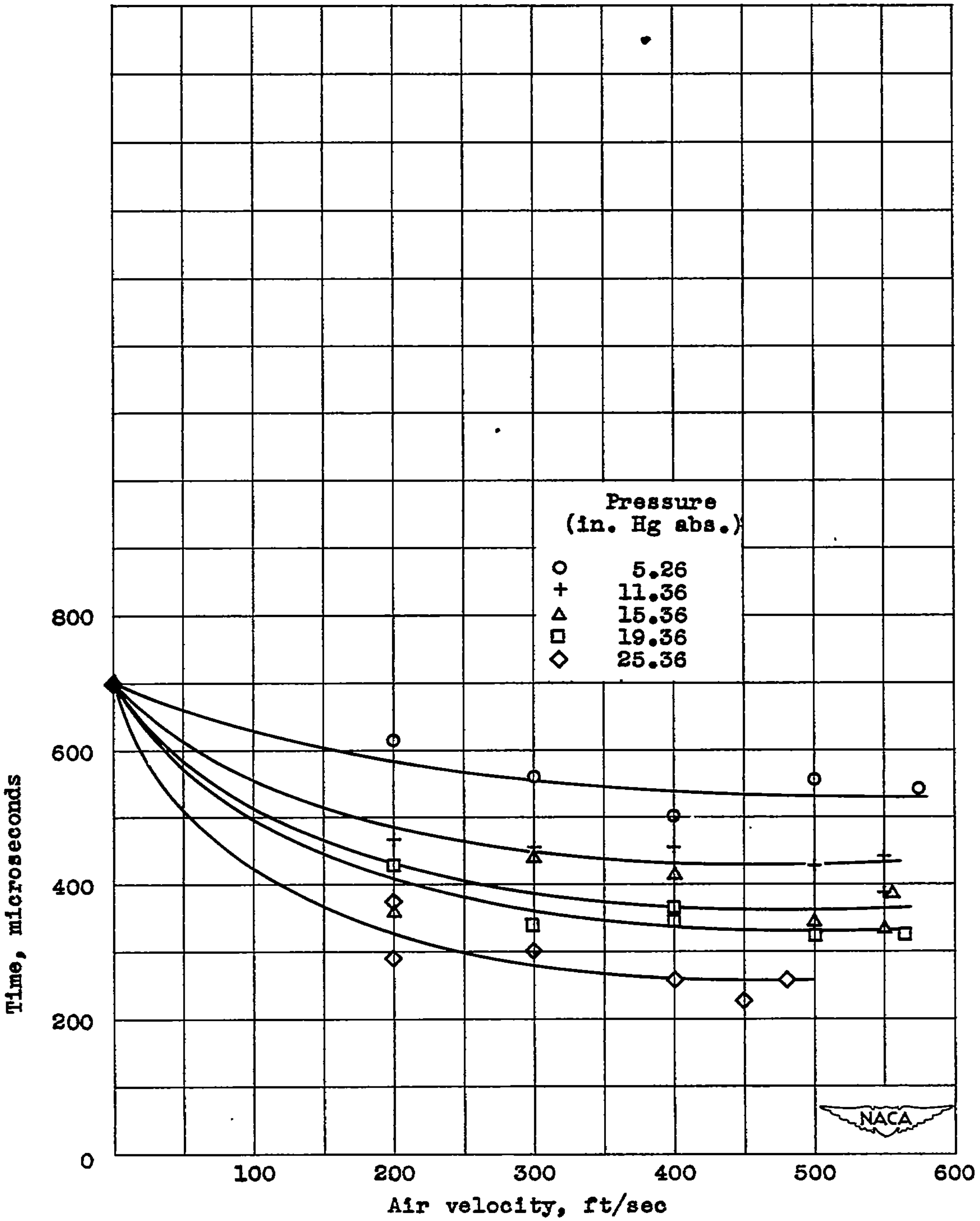
(a) Electrode spacing, 0.125 inch.

Figure 9. - Effect of air velocity on energy in discharge at various pressures. Electrode diameter, 3/16 inch; temperature, 80° F.



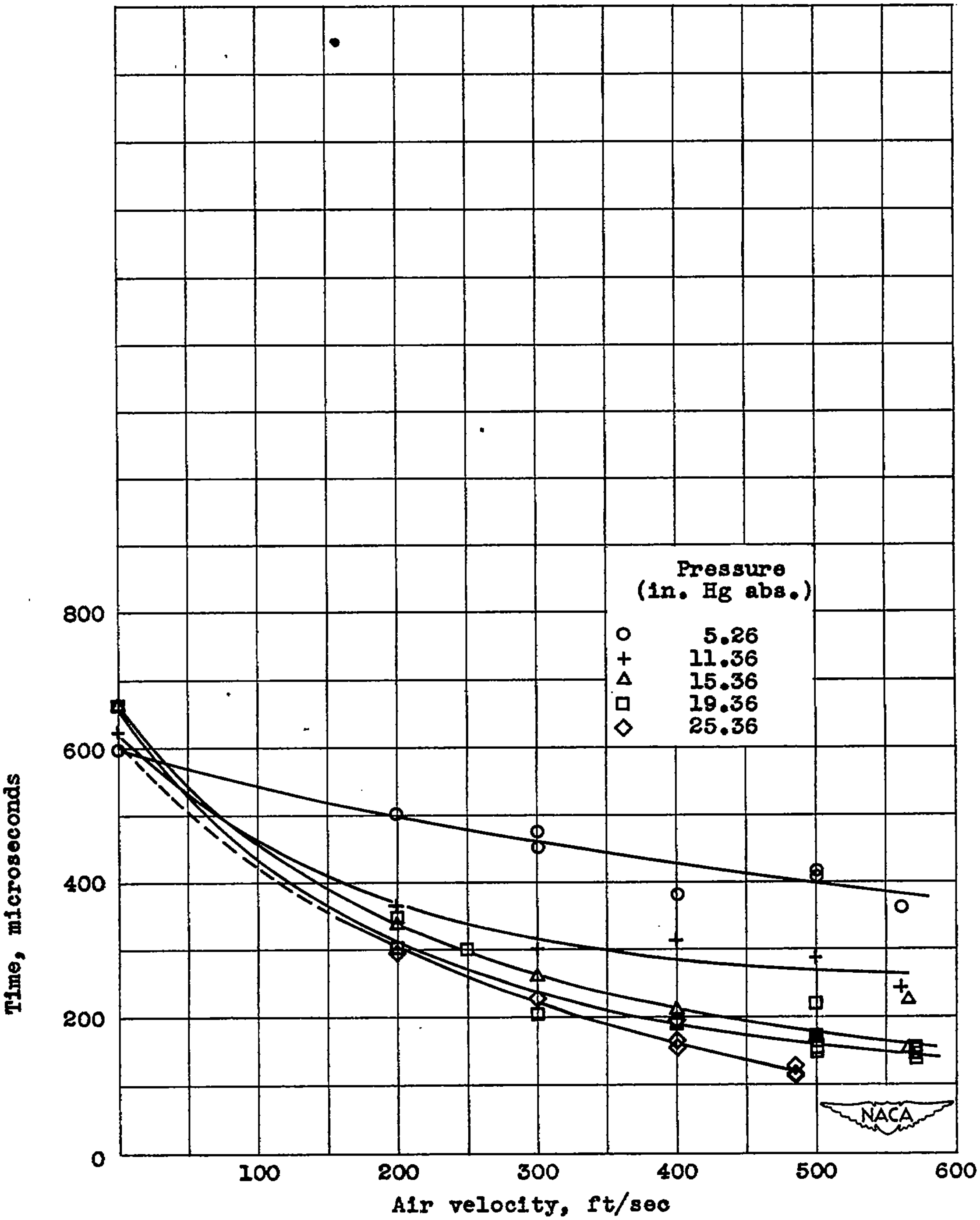
(b) Electrode spacing, 0.250 inch.

Figure 9. - Concluded. Effect of air velocity on energy in discharge at various pressures. Electrode diameter, 3/16 inch; temperature, 80° F.



(a) Electrode spacing, 0.125 inch.

Figure 10. - Effect of air velocity on duration of discharge at various pressures. Electrode diameter, 3/16 inch; temperature, 80° F.



(b) Electrode spacing, 0.250 inch.

Figure 10. - Concluded. Effect of air velocity on duration of discharge at various pressures. Electrode diameter, 3/16 inch; temperature, 80° F.

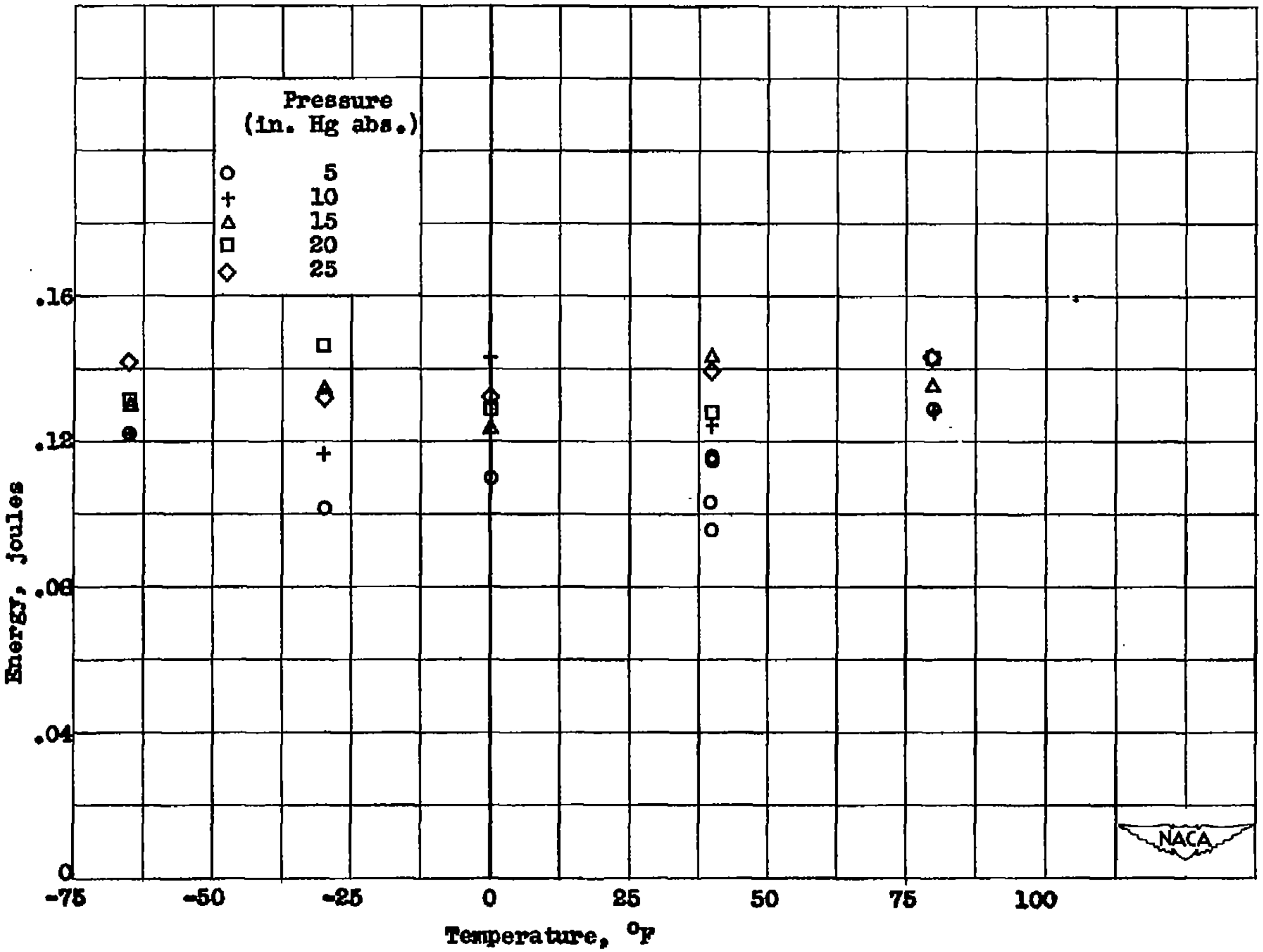


Figure 11. - Effect of temperature on energy in discharge at various pressures. Velocity, 200 feet per second; electrode spacing, 0.250 inch; electrode diameter, 1/16 inch.

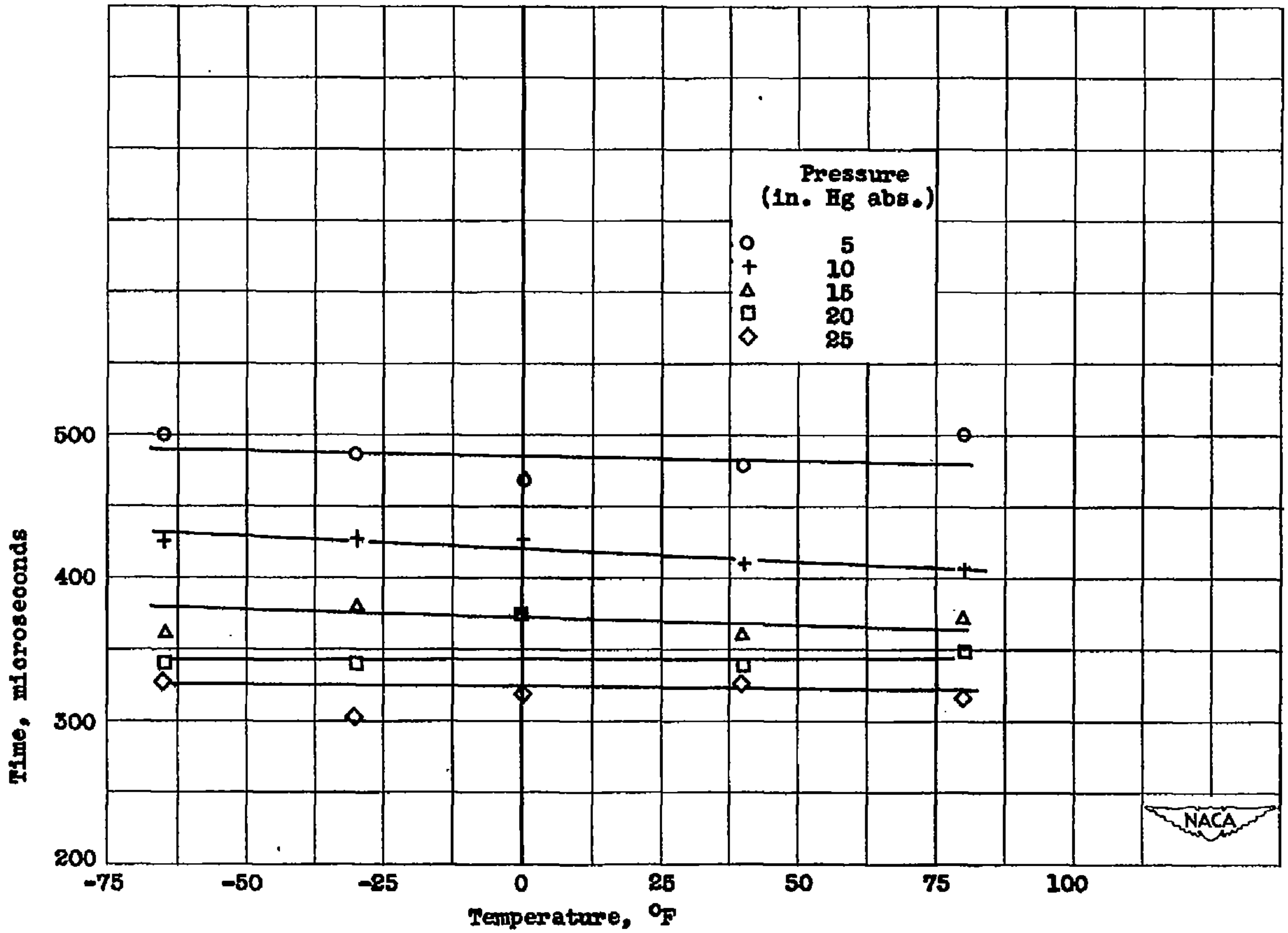
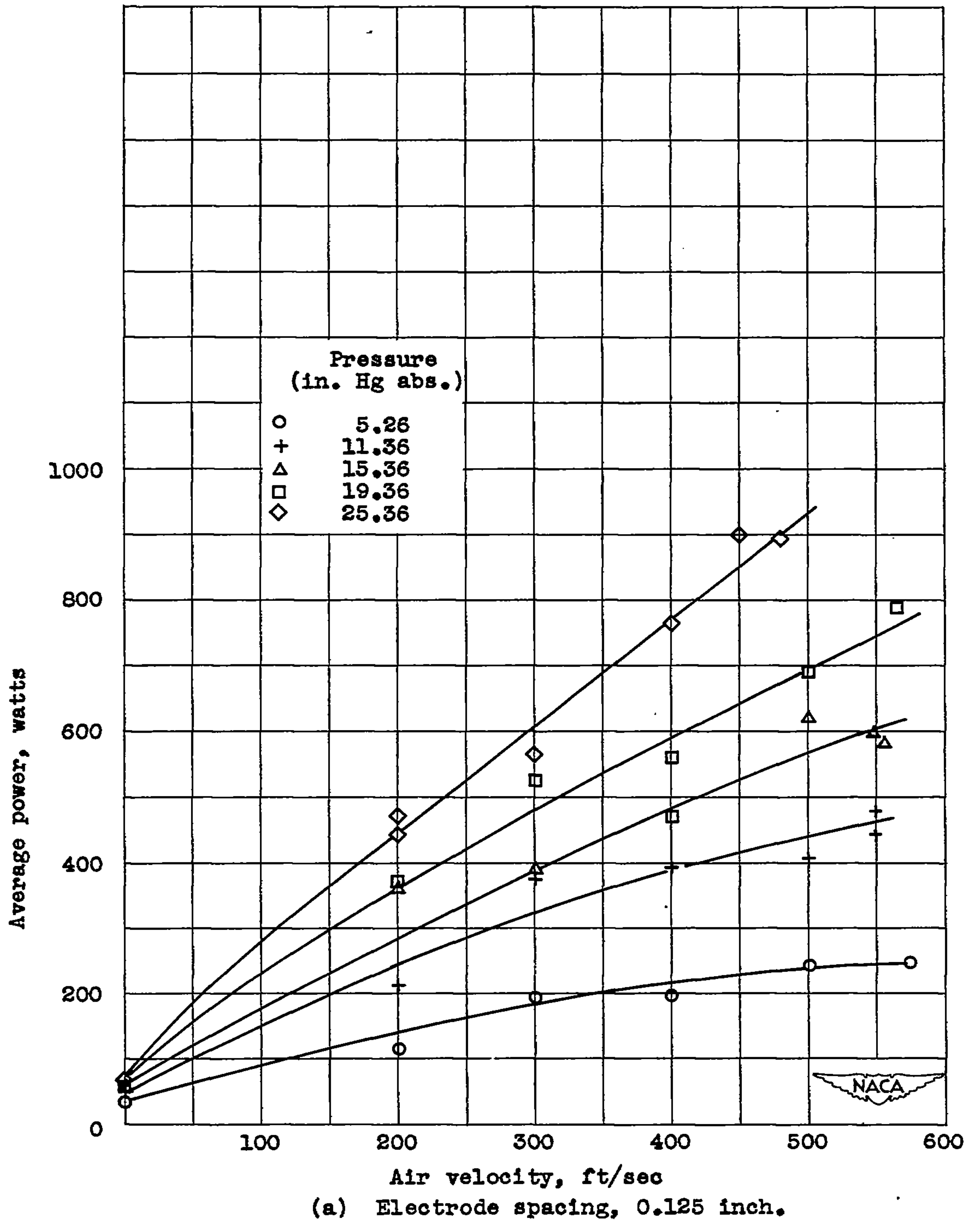
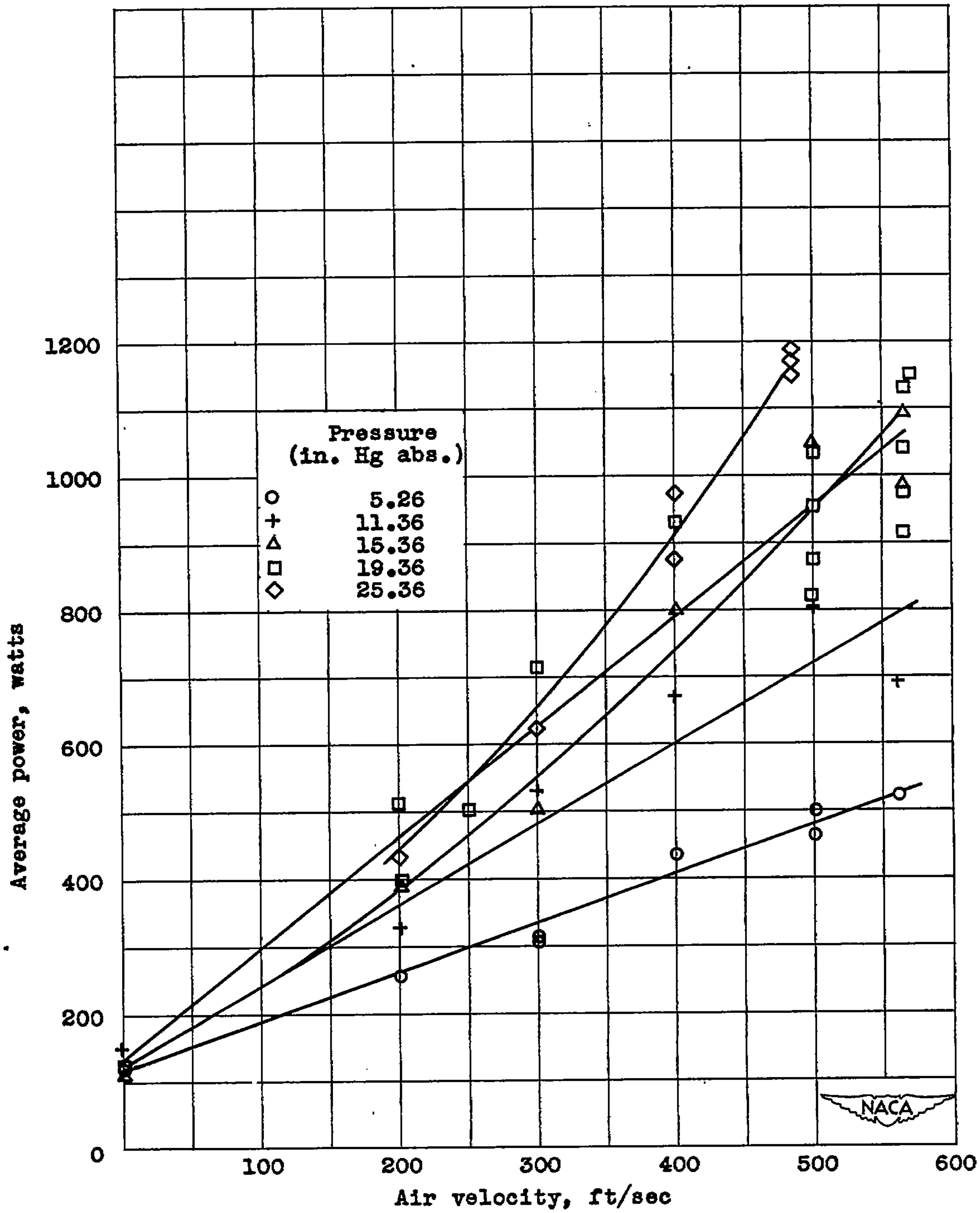


Figure 12. - Effect of temperature on duration of discharge at various pressures. Velocity, 200 feet per second; electrode spacing, 0.250 inch; electrode diameter, 1/16 inch.



(a) Electrode spacing, 0.125 inch.

Figure 13. - Effect of air velocity on average power in discharge at various pressures. Electrode diameter, 3/16 inch; temperature, 80° F.



(b) Electrode spacing, 0.250 inch.

Figure 13. - Concluded. Effect of air velocity on average power in discharge at various pressures. Electrode diameter, 3/16 inch; temperature, 80° F.

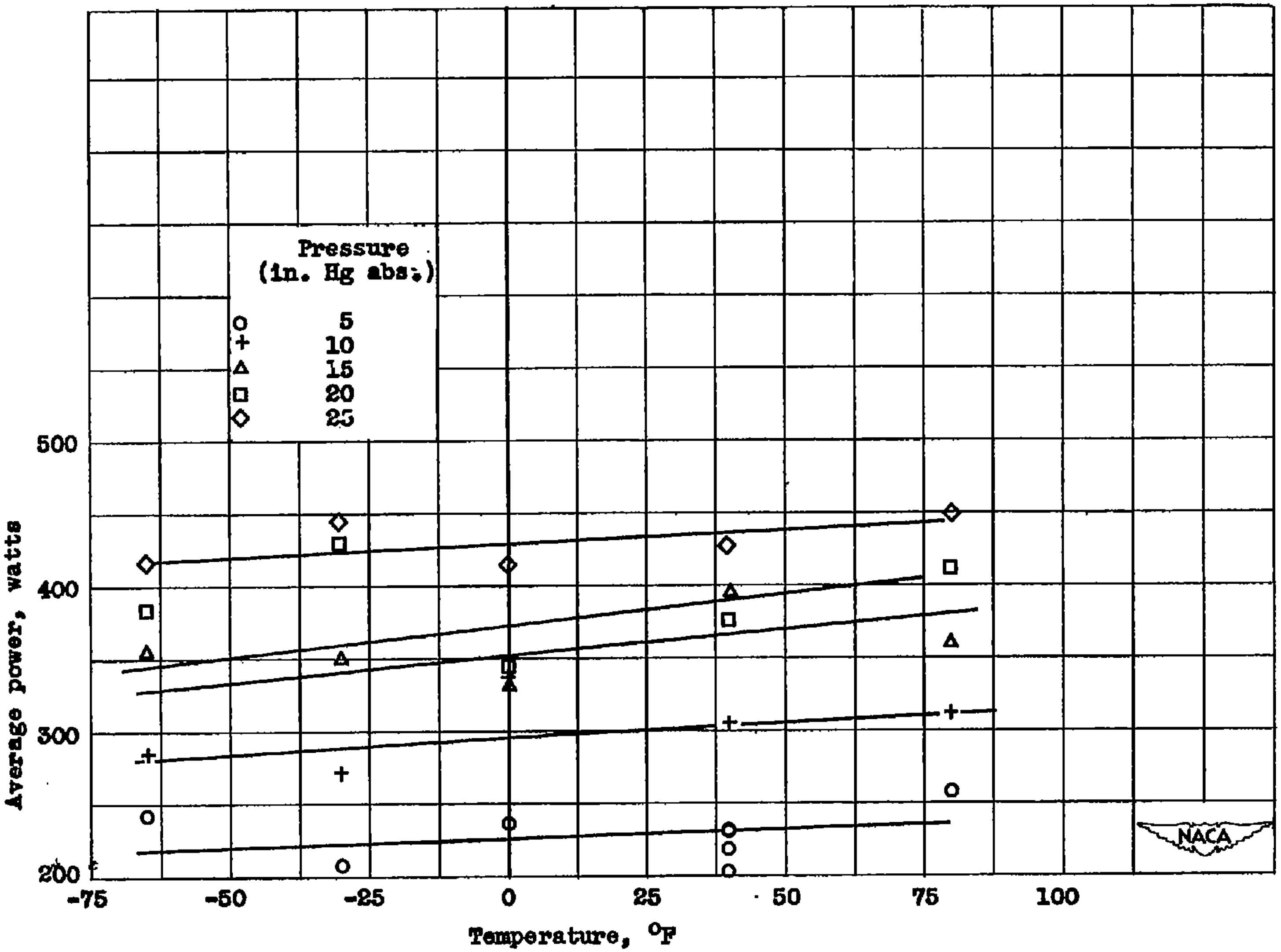


Figure 14. - Effect of temperature on average power in discharge at various pressures. Velocity, 200 feet per second; electrode spacing, 0.250 inch; electrode diameter, 1/16 inch.

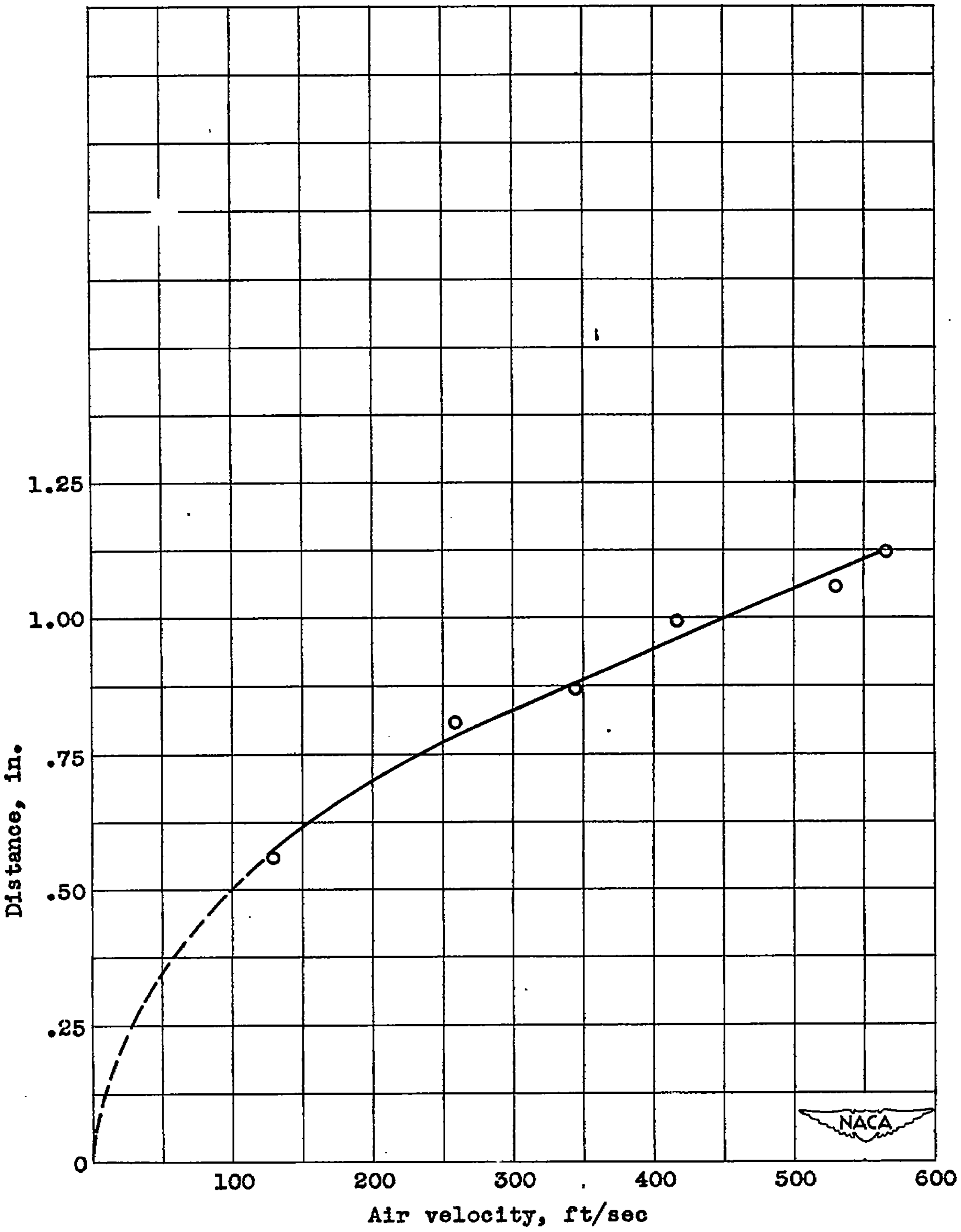


Figure 15. - Effect of air velocity on distance downstream from electrodes that traces of discharge could be seen by eye. Pressure, 11.36 inches mercury absolute; electrode spacing, 0.250 inch; electrode diameter, 3/16 inch; temperature, 80° F.