DEC 23 1946

ACR No. E5G27

Copy 1

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

# WARTIME REPORT

ORIGINALLY ISSUED

November 1945 as
Advance Confidential Report E5G27

## RUBBER CONDUCTORS FOR AIRCRAFT IGNITION CABLES

By Clyde C. Swett, Jr. and Joseph R. Dietrich

Aircraft Engine Research Laboratory
Cleveland, Ohio

NACA



WASHINGTON

NACA ACR No. E5G27

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE CONFIDENTIAL REPORT

# RUBBER CONDUCTORS FOR AIRCRAFT IGNITION CABLES

By Clyde C. Swett, Jr. and Joseph R. Dietrich

## SUMMARY

The possibility of using conducting rubber as the conductor in aircraft ignition cable is considered in this report. Cables using such conductors are expected to eliminate internal corona and gas leakage in the cable, to reduce erosion of spark-plug electrodes, and possibly to reduce radio interference and to attenuate unwanted high-frequency, high-voltage surges. Rubber conductors were investigated and tested for use in aircraft ignition cables. The effects of stretch, temperature, and continuous and impulsive currents on the resistance of several conducting-rubber test strips of the same composition were determined. Two types of experimental conducting-rubber cable were tested. The conductivity requirements for application of conducting rubber to ignition cables have been estimated.

The resistivity of conducting rubber of the composition tested is too high to permit its use in cables of more than about 2 feet in length. The resistivity was radically affected by the method of fabrication used and varied from approximately 10 ohm-centimeters for samples in sheet form to 1600 ohm-centimeters for cable samples.

Typical variations of resistivity with stretch, temperature, and current are presented in the following table:

| Condition producing resistivity change[a] | Range of condition tested | Resistivity increase (percent) |
|---|---|---|
| Stretch followed by return to unstretched length | 0 to 67 percent | 270 |
| Temperature | $0^{\circ}$ F to $140^{\circ}$ F | 42 |
| Current (60 cycles, 30-min duration) | 0 to 0.53 ampere/$cm^2$ | -54 |
| Current (magneto output, 320-hr duration) | 0 to magneto output for one spark plug | -9 |
| Impulsive voltage (1 impulse) | 0 to 450 volts/cm | 0 ± 5 |

[a]The changes are not permanent in all cases.

Tests on two experimental cables showed that a satisfactory method of fabricating conducting-rubber cables has not yet been developed. One cable had a dielectric strength approximately 25 percent above that of a similar standard cable but had a prohibitively high resistance, whereas the other cable had a much lower resistance but a poor dielectric strength.

The development of ignition cable employing a rubber conductor depends on the development of a satisfactory method of fabrication. The existence of a wide field of application for such cables depends upon the development of conducting rubber having a resistivity of less than 1 ohm-centimeter.

## INTRODUCTION

Standard aircraft ignition cable has two important disadvantages that are closely related to the use of stranded metallic wire as a conducting element. The first disadvantage is that air voids, which may be formed during either the manufacture or the installation of the cable, occur quite frequently between the conductor and the surrounding insulation. When the voltage is applied to the cable, corona may occur in the voids because of the high electrostatic field near the surface of the conductor. The corona converts the oxygen of the air to ozone, which is highly destructive to the insulation because of its powerful oxidizing properties. Some standard cable has the second disadvantage of longitudinal air passages, which may exist between strands of the conductor or between the conductor and the insulation and extend throughout a considerable length of the cable. When installed in an ignition system, such a cable may act as a pipe line and conduct moisture, oil vapors, and products of combustion and gaseous discharges, which might otherwise remain localized, to various parts of the ignition system.

These disadvantages could be eliminated in cables by using conducting rubber as the conducting element because the insulation and conductor would be vulcanized together. A cable of such construction would be free from voids (and therefore free from corona inside the cable) and would prevent gases and liquids from traveling within the cable. The similarity of the elastic properties of the conductor and the insulating material would eliminate the possibility of failure of the vulcanized bond by mechanical stress. Because the core could be made of a single conductor of circular cross section, the use of a rubber conductor would result in a lower value for the maximum dielectric stress than exists in standard cables employing small stranded conductors. The use of conducting rubber in high-tension cables as a means of controlling the electrostatic field and as a means of eliminating ionization in air voids has been patented by van Hoffen (U.S. Patent Office No. 2,081,517, May 25, 1937; U.S. Patent Office No. 2,165,738, July 11, 1939) and Zoethout (U.S. Patent Office No. 2,142,625, Jan. 3, 1939). Patent No. 2,081,517 covers the case in which conducting rubber is the sole conductor.

The results reported in reference 1 show that the limitation of the maximum current in an ignition spark by insertion of a resistor in series with the spark plug decreases the rate of erosion of the spark-plug electrodes. The use of conducting rubber for ignition cable should produce this desirable effect by permitting the incorporation of the resistor in the cable itself. Further benefits that might result from the use of a conductor of relatively high resistance are reduction of the difficulty of radio shielding and attenuation of any high-frequency, high-voltage surges.

At request of the NACA, William L. Holt, Chief of the Rubber Section, National Bureau of Standards, fabricated conducting-rubber sheets and cables. These, in addition to another experimental cable, were tested during the period from 1942 to 1944 to determine the suitability of conducting rubber in aircraft-engine ignition cable. The results of the tests are reported herein in two main sections: I - Tests of Conducting-Rubber Samples and II - Tests of Experimental Cables. The effect of diameter and resistivity of the cable conductor on voltage, the determination of optimum conductor diameter for a short length of cable, and the effect of conductor diameter on dielectric strength of the cable are discussed in appendixes A, B, and C, respectively.

## I - TESTS ON CONDUCTING-RUBBER SAMPLES

### Description of Test Samples

Five different sheets of conducting rubber, each about 1/2 square foot in area and approximately 1/32 inch to 1/16 inch thick, were fabricated at the National Bureau of Standards for the tests. Throughout this report, the five sheets are considered as five different samples and are designated samples A-1 to A-5. For test purposes several strips were cut from each sample. Each strip is given the same designation (A-1 to A-5) as the sample from which it was cut. The composition of the samples and a description of the method of processing them, as furnished by the National Bureau of Standards, are given in the following table:

| Ingredient | Parts by weight |
|---|---|
| Rubber | 100 |
| Sulphur | 3 |
| Zinc oxide | 10 |
| Altax (accelerator) | 1 |
| Age Rite powder (antioxidant) | 1 |
| Reogen (plasticizer) | 3 |
| Shawinigan black (acetylene black) | 80 |

The rubber was broken down well and then all of the ingredients except the Reogen and the Shawinigan black were added. These two ingredients were added last and as rapidly as possible with a minimum of milling. The time of vulcanization was about 25 minutes at 287° F.

The following tests were made to determine some of the properties of conducting rubber: low-voltage resistivity tests, stretch tests, temperature tests, high-voltage impulse test, sustained-current tests, and ignition-current tests. The properties of the various sheets were qualitatively the same although there was considerable quantitative variation

### Low-Voltage Resistivity Tests

Low-voltage resistivity measurements were made on the samples by clamping the ends of thin strips approximately $7\frac{1}{2}$ inches long and 1/32 inch square between brass plates and measuring the resistance. Either a Wheatstone bridge or a voltmeter-ammeter method was used, depending on which was the most convenient for the particular test being run. When the voltmeter-ammeter method was used, the current was kept low (less than 1 ma) to avoid heating the sample.

The resistivity of the rubber varied from sample to sample, being in the range of 20 ohm-centimeters for sample A-1 and 9 ohm-centimeters for sample A-2. The resistivites of the other samples were within these limits. Adjacent strips cut from the same sample showed some variation in resistivity. Strips cut at right angles from the same sample showed approximately the same variation.

## Stretch Tests

The resistivity of conducting rubber was greatly affected by stretching. When a strip was stretched and then released, its resistance increased several fold. When the rubber was then allowed to rest, its resistance decreased toward its original value at a rate that decreased with time. In some cases several days were required for the resistance to return within a few percent of its original value. Figure 1 shows the conductance recovery of two strips with time. After approximately 1 minute, the resistance changed linearly with the logarithm of the time over the range tested. The rate of recovery may be accelerated by raising the temperature of the strip.

The effect of successive stretches, each of greater amplitude than the preceding one, is shown in figure 2. The procedure in taking the data was as follows: After its initial resistance was measured, the strip was stretched 1 inch and immediately released. After 40 seconds the resistance was measured and 30 seconds later the strip was stretched 2 inches and released. The cycles of stretching and measuring were continued with the same time schedule, increasing the stretch 1 inch each time up to 5 inches. A separate experiment showed that the second of two successive stretches of equal amplitude produced little additional change in resistance.

Determination of the resistance during stretch required rapid measurement and an oscillographic method was used. The test strip was connected in series with a 140,000-ohm resistor and a 284-volt battery. The vertical deflection plates of the oscillograph were directly connected across the rubber strip. The vertical deflection was thus proportional to the voltage drop across the strip and indicated the resistance of the strip.

A small test engine with the cylinder head removed was used as the stretching machine. One end of the rubber strip was fastened to a support directly above the piston; the other end was so fastened to the piston that the strip was periodically stretched and relaxed as the engine was motored. The 220-volt direct-current line provided sweep voltage for the oscillograph. The horizontal deflection plates were directly connected across the output of a slide-wire rheostat connected to the 220-volt line in potentiometer fashion. The rheostat slide was operated by a crank and a connecting rod coupled to the engine shaft to give a sweep voltage that was proportional to the piston displacement, and hence to the stretch of the rubber strip.

The change in resistance during the stretching and retracting process is illustrated in figure 3. The measurement was made by the oscillographic method described and was completed in approximately 2 seconds. The stretching machine was manually operated during the first two cycles (fig. 3(a)) and was motored thereafter. During the initial stretch the resistance rose along line 1 and continued to rise along line 2 as the stretch was decreased. The maximum at point C was probably caused by a momentary pause in the operation of the machine, during which the resistance of the strip decreased. The rubber became slack at point A (fig. 3(a)) because after its first stretch, the strip had a slight set that was more or less permanent. The rubber strip was allowed to rest again for a short time (fraction of a second) and was stretched again. During the rest period the resistance fell to the value of point B (fig. 3(a)). As the rubber strip was stretched the second time, its resistance decreased along line 3 and as the strip was retracted, the resistance increased along line 4. Subsequent cycles qualitatively followed lines 3 and 4. After the rubber strip had been run through several stretch-retraction cycles by motoring the stretching machine, successive cycles quantitatively repeated each other. One such cycle, measured while the stretching machine was being motored at 200 rpm, is shown in figure 3(b).

## Temperature Tests

Tests of the effects of temperature on resistance were conducted in a wooden box lined with asbestos. The box had two compartments, which were separated by baffles. One compartment held the rubber strip and a thermometer; the other compartment contained a heating coil, or a quantity of dry ice, to heat or cool the sample, as desired.

The effects of temperature on resistance were quite complicated, varied with time, and depended upon the previous history of the sample. The brief survey presented here is incomplete and for the most part, the results are only qualitative.

The resistance change of a new strip that was first cooled and then heated is shown in figure 4. The curve is typical of the results of temperature runs on several samples. The displacement of the heating curve B from the cooling curve A represents a change in the properties of the rubber. If the strip should be cooled from any point on the heating curve B, the resulting cooling curve would be below curve B and subsequent heating and cooling would continue to lower the resistance curve of the strip.

At a temperature of approximately 140° F, the resistance of strip A-2 suddenly began to decrease. A test on another strip showed that the decrease continued with time, even if the temperature was held constant. The shape of the temperature-resistance curve above 140° F therefore has little meaning, inasmuch as it depends on the rate of change of temperature. In that region the plotted points in figure 4 were taken at intervals of 3 to 4 minutes. It is possible that the rate of change of temperature may influence the shape of the temperature-resistance curve even at low temperatures. The effect, however, if present, is small compared with that above 140° F. A similar test on strip A-5 gave the same results with the exception that the decrease occurred at approximately 240° F.

Cooling of strip A-2 to room temperature after the run plotted in figure 4 did not appreciably change its resistance from the high-temperature value. Subsequent reheating of this strip caused its resistance to rise again. No sudden drop in resistance corresponding to that at 140° F (fig. 4) was observed even though the temperature was increased to 220° F. Recooling of the strip to room temperature reduced its resistance to a value lower than any previously observed. After eight or nine such heating-cooling cycles, the strip attained a state in which subsequent cycles repeated each other. Table I gives the maximum and minimum temperatures for these cycles, with the corresponding resistances. The minimum-temperature value for cycle 1 in the table corresponds to the point on the heating curve in figure 4 at room temperature. The heating portion of cycle 1 is given in detail by the portion of curve B (fig. 4) from 82.5° F to 212° F.

The final state of the strip could possibly have been attained by holding the strip at a high temperature for a prolonged time, as well as by running the strip through many heating-cooling cycles. The point was not investigated.

After cycle 12, the final resistance of the strip (14,900 ohms, table I) corresponds to a resistivity of 5.9 ohm-centimeters. When the resistance was measured again 2 weeks after test, it was found to have increased to 18,800 ohms, corresponding to a resistivity of 7.4 ohm centimeters.

At room temperature the temperature coefficient of resistance (percentage increase of resistance per degree of temperature rise) along curve B (fig. 4) was approximately the same for two samples of type A and was not greatly affected by the previous temperature history of the sample. The value of the coefficient at 77° F was between 0.34 and 0.41 percent per °F.

The effect of high temperature on a conducting-rubber strip was determined by placing a strip in an oven and heating it to 334° F. The strip was bent double and fastened with a clip to see if the rubber would flow. No apparent effects from the high temperature, such as sticking or cracking, were observed. The same strip after being cooled was then heated to 410° F. Examination showed cracking and slight sticking.

The effect of low temperature on a strip was determined by placing it in a container packed in dry ice. The temperature was slowly dropped to -72° F. After having been kept at this temperature about 5 minutes, the strip was flexed. It was slightly stiff but it could be bent double without cracking.

## High-Voltage-Impulse Test

The high-voltage-impulse resistance of one of the strips was measured by a Du Mont type 175-A cathode-ray oscillograph. A 0.002-microfarad condenser was charged to 8000 volts and discharged through the rubber strip. The voltage across the strip was applied to the horizontal deflection plates of the oscillograph through a capacity-type voltage divider. The vertical deflection plates were connected across a low resistance of known value in series with the rubber strip. The horizontal deflection was thus proportional to the voltage drop across the rubber strip, whereas the vertical deflection was proportional to the current through the strip. The resistance was calculated from the slope of the resulting trace.

The high-voltage-resistance test showed that the resistance was constant up to the applied voltage of 8000 volts, which corresponded to a gradient of 450 volts per centimeter for the sample tested. The measurement was accurate to within about 5 percent.

## Sustained-Current Tests

As shown in the high-voltage-impulse test, the high current of short duration produced by the condenser discharge had no effect on the resistance. Further tests were conducted to determine the effect of relatively large current of long duration. A 20-milliampere alternating current (60 cycles) was passed through a strip and the resistance was determined by the voltmeter-ammeter method. The dimensions of the strip were $5\frac{5}{8}$ inches long by 3/32 inch wide by 1/16 inch thick.

As shown by figure 5, the resistance suddenly increased and then decreased below the initial value. The heating effect of the current was probably quite important in determining the variation of the resistance. The resistance reached a constant value after the current had persisted for some time. After the current was stopped and the strip had cooled, the resistance dropped slightly.

The effect of passing successively larger currents through a strip of sample A-5 conducting rubber, the current being increased when the resistance approached a constant value, is shown in figure 6. The strip was $5\frac{1}{4}$ inches long by 1/16 inch wide by 1/16 inch thick. Successive increases of current tended to lower the resistance. In another test the resistivity was reduced by a factor of 35 in this manner, although the large current caused the rubber to crack and become brittle, ruining it for any practical use.

A strip, through which a 20-milliampere current had been passed, was stretched one-half inch to see if the stretch properties had been affected. The initial resistance of 6500 ohms had been reduced to 3500 ohms because of the current. Stretch increased the resistance in the same general manner as in figure 3(a). The final value of resistance was 5700 ohms.

The same strip was then subjected to a stretch test with a constant current of 20 milliamperes. The strip was stretched one-half inch at the rate of 4 stretches per minute for about 1 hour while the current was flowing continuously. At this point the resistance had fallen to 4200 ohms; however, when the strip was again stretched without current flowing, the resistance increased. This effect was the opposite of that shown in figure 3(b). When the strip was stretched beyond the 1/2-inch limit at which it had been treated, the resistance again began to decrease with stretch and began to behave in the manner illustrated by figure 3(b), regardless of how much or how little it was stretched.

## Ignition-Current Tests

In order to determine whether rubber conductors would be adversely affected by the current output of an aircraft-engine magneto, a test was made during which the output of a standard magneto was passed through conducting-rubber strips for a long period of time.

The test strips were mounted between brass terminals on a bakelite board. Nine conductors were tested: three single A-1 strips; three single A-2 strips; and three conductors, each made up of two A-2 strips connected in series. The strips were $7\frac{1}{2}$ inches long and approximately 1/32 inch square. One end of each conductor was connected to one of the nine distributor terminals of a Scintilla V-AG9-DF magneto. The opposite ends of the strips were grounded through individual three-point spark gaps set to spark at 10 kilovolts (peak). The gap settings were periodically checked during the run by means of a calibrated brass-sphere gap illuminated by a quartz mercury arc. The rubber strips were protected from oxidation by a coating of Tito Seal No. 2 compound approximately three-sixteenths inch thick. The magneto was driven by an electric motor at a speed to give between 1000 and 1100 discharges per minute through each rubber strip.

The following table gives the initial resistance of the strips used in the test at a temperature of 77° F:

| Strip connected to distributor terminal | Initial resistance (ohms) | Strip | Description |
|---|---|---|---|
| 1 | 27,300 | A-1 | Single strip |
| 2 | 41,700 | --do- | Do. |
| 3 | 37,100 | --do- | Do. |
| 4 | 18,400 | A-2 | Do. |
| 5 | 18,300 | --do- | Do. |
| 6 | 19,600 | --do- | Do. |
| 7 | 35,900 | --do- | Double-length strips (two strips in series) |
| 8 | 34,000 | --do- | Do. |
| 9 | 37,500 | --do- | Do. |

The test was run for 310 hours, the last 187 hours nonstop. The resistance of the strips was checked each time the run was stopped. The resistance was observed to decrease rather rapidly immediately after the magneto current was turned off but it became steady after dropping 4 or 5 percent. The drop is attributed to the cooling of the strips.

Measurements taken after the resistance became steady showed that the resistance had slightly decreased during the run. Percentage decrease is plotted in figure 7 as a function of duration of run for all nine test strips. Curves are drawn through the points only for strips that were connected to distributor terminals 3 and 5 and showed typical variations. The room temperatures at which the resistances were measured varied over a range of 19° F The resistances were corrected to 77° F (the initial temperature) by applying the temperature coefficient previously mentioned.

The two single-length test strips that had the highest resistance (those connected to distributor terminals 2 and 3) showed the greatest percentage change during the run. The results for all A-2 strips are grouped rather closely, regardless of whether they are for single-length or double-length strips. The resistance of the strips increased slightly during the last 187 hours of the run.

The changes in the conductance of the rubber produced by the passage of ignition current through the strips are unimportant compared with those caused by temperature changes and by stretching. It is quite possible that the changes recorded in figure 7 should not be attributed to electrical conduction as such but to heating-cooling cycles caused by changes in room temperature and by electrical heating of the strip. In order to test this possibility, a new test strip was heated from 100° F (room temperature) to 120° F and cooled back to 100° F. The resistance was found to be about 5 percent lower than the initial value. On the following day the strip was run through the same cycle, with the result that its resistance fell another 5 percent.

## Adaptability of Conducting Rubber to Cable Applications

The tests of the properties of conducting rubber have shown that in most respects the material is suitable for use in ignition cables. Rubber conductors of small cross section are capable of transmitting magneto impulses for long periods of time without adverse effects. The ability of the rubber to withstand low temperatures is adequate for cable applications and its performance at high temperatures is promising. Some improvement, however, is desirable inasmuch as it is generally assumed that the temperature in the spark-plug-terminal well may reach 375° F to 400° F (reference 2). The low tensile strength and the low resistance to deformation of the rubber give rise to the problem of providing strength for conducting-rubber cables, but a solution is probably available in the use of braids or other strengthening coatings for the cables. The large variations in the resistivity of the rubber resulting from stretch and temperature changes are striking. These variations are probably unimportant if the cable can be so designed that the variations do not result in a prohibitively high resistance. The attainment of such a design can result, however, only from the development of conducting rubber of considerably lower resistivity than the rubber tested. The conclusion may be drawn from the tests of the properties of conducting rubber that its high resistivity is at present the biggest obstacle to its use as a cable conductor.

## II - TESTS ON EXPERIMENTAL CABLES

### Description of Cables

Inasmuch as the tests on conducting-rubber samples indicated that conducting rubber might be usable for cable conductors, the fabrication of experimental cables having such conductors was attempted. The cables were made to the standard 7-millimeter size but the diameters of the conducting cores were made large in order to minimize resistance. The disadvantages of the larger conductor diameters were accepted in order to provide a cable of reasonably low resistance for experimental purposes.

The fabrication of the cables presented considerable practical difficulty and the two attempts that were made did not result in a successful cable. The first experimental cable (type B) was fabricated by a manufacturer of ignition cables by adaptations of processes used in the manufacture of standard cable. Although the conducting rubber used for the cable had a composition similar to that of the type A strips, the resistance of the fabricated cable was prohibitively high. The mechanical properties of the cable were very good, although the conducting rubber and the insulating rubber were apparently cemented rather than bonded together. The adhesion between the layers appeared to be uniform but it was weak and microscopic voids were present. The joint was, however, gas-tight under a pressure of 50 pounds per square inch.

Because the fabrication process used for the type B cable resulted in extremely high conductor resistance, an attempt was made to fabricate short cable samples by a method that involved a minimum of working of the conductor material. At the request of the NACA, four cable samples were fabricated at the National Bureau of Standards, each of which was constructed by vulcanizing two semiannular strips of insulating rubber to a moulded core of conducting rubber. The construction resulted in two vulcanized, longitudinal seams in the insulating layer. The vulcanization was not perfect and the cable consequently had very poor dielectric strength. The vulcanization of the conducting rubber to the insulating rubber was also imperfect with the result that large voids were present. In the spots where vulcanizing did occur, the bond between the conductor and the insulation was very strong. The resistance of the second type of cable was reasonably low although it was about 30 percent higher than the resistance of the conducting-rubber cores before insulation was applied.

The construction of the cables and their resistances and capacitances are shown in figure 8. The methods of measuring resistance and capacitance will be described in later sections. The cables are designated throughout this report types B and C, as shown in figure 8. Four 46-centimeter lengths of the type C cable were constructed. They are designated cables C-1, C-2, C-3, and C-4.

Although neither type of sample cable was satisfactory for practical use, they were given the resistance, capacitance, dielectric-strength, output-voltage, and engine tests reported in the following sections.

## Resistance Tests

The resistances of the two experimental cables given in figure 8 were measured with a Wheatstone bridge.

Handling. - The handling consisted of straightening the samples that had been bent for packing. The resistance of the type C cables increased less than 10 percent with handling, as shown in the following table:

| Cable | Length (cm) | Conductor diameter (cm) | Resistance (ohms) | | Resistivity before handling (ohm-cm) |
|---|---|---|---|---|---|
| | | | Before handling | After handling | |
| C-1 | 45.8 | 0.310 | 20,500 | 22,200 | 33.7 |
| C-2 | 45.4 | .301 | 22,700 | 24,400 | 35.6 |
| C-3 | 45.9 | .315 | 15,000 | 16,300 | 25.5 |
| C-4 | 45.8 | .324 | 16,500 | 17,400 | 29.6 |

Stretch. - The stretch test consisted of stretching a 7-inch length of type C cable approximately 1 inch by a 6-pound weight and measuring the resistance. The resistance behaved with stretching in a manner similar to the action of the strips as previously described. After a few hours the resistance value tended to approach the initial resistance. The values obtained are listed in the following table:

| Time (min) | Condition of cable | Resistance (ohms) |
|---|---|---|
| 0 | Initial | 15,300 |
| 1 | Stretched | 15,900 |
| 2 | Resting stretched | 15,000 |
| 5 | ---do------------- | 14,600 |
| 10 | ---do------------- | 14,300 |
| 13 | ---do------------- | 14,200 |
| 13 | Retracted | 30,700 |
| 15 | Resting retracted | 27,000 |
| 23 | ---do------------- | 24,100 |
| 38 | ---do------------- | 22,700 |
| 46 | ---do------------- | 21,900 |

<u>Bending</u>. - For the bending test a type C sample was wound around a 1-inch mandrel and resistance measurements were made. The resistance of the sample increased when the sample was wound onto the mandrel but did not increase further when unwound, as it did after retraction in the stretch test. After a few hours the resistance values tended to approach the initial resistance. The following table lists the results:

| Time (min) | Condition of cable | Resistance (ohms) |
|---|---|---|
| 0 | Initial | 14,000 |
| 1 | Wrapped on mandrel | 22,700 |
| 2 | Unwrapped | 21,300 |
| 3 | Resting unwrapped | 20,500 |
| 6 | ---do------------- | 19,700 |
| 9 | ---do------------- | 19,200 |
| 20 | ---do------------- | 18,800 |
| 50 | ---do------------- | 18,500 |
| 115 | ---do------------- | 17,900 |

<u>Current</u>. - A high-voltage transformer was used to pass a 60-cycle current of 50 milliamperes through a length of type B cable for a short time (approximately 5 sec). The resistance immediately droppped from 1.4 megohms to 0.04 megohm, a reduction to one thirty-eighth of the initial value. It seems improbable that such a large decrease in resistance can be attributed to the heating effect of the current alone. The combination of heating and high voltage possibly caused carbonization of the

rubber, which resulted in a decrease of resistance. The reduction was not of a temporary nature because 4 days later the resistance was still 0.04 megohm.

From the results described in part I, it would be expected that such high-current treatment would be destructive to the rubber. It is destructive to the insulation also because it has been found that passing the current through a cable for too long a time causes an explosion through the insulation. Evidently, because of heat, gas is formed in pockets with sufficient pressure to rupture the insulation.

Temperature. - A length of the type B cable was subjected to a temperature of 158° F for 2 hours and the resistance was measured at the end of this period. The resistance had increased from 1.2 to 2.2 megohms. When the cable was cooled, the resistance decreased, taking 3 days to reach its initial value. The resistance kept decreasing for a few days longer and finally leveled off at about 65 percent of the initial resistance. In general, the results were comparable with those of the conducting-rubber strips reported in part I.

## Capacitance Tests

The capacitances of the cables are given in figure 8. The measurements were made by an impedance bridge, with the cables installed in detachable lead harnesses. An external oscillator (1000 and 10,000 cps) was used to excite the bridge and an oscillograph was used as the detector.

A check was made to determine what effect the distributed resistance had on the measurement. Open-circuit and short-circuit measurements were made on the type B cable and calculations were made to determine the capacitance. The capacitance was only about 3 percent higher than the open-circuit value. Similar measurements on the type C cable showed that the resistivity was low enough that the capacitance was measurably the same as the open-circuit capacitance.

The capacitances of the cables as measured in the harnesses were 54 micromicrofarads (μμf) for the type B cable, 46 for the type C cable, and 30 for an equal length of standard cable. These values correspond to 46, 39, and 26 micromicrofarads, respectively, per foot length of harness.

## Dielectric-Strength Tests

The dielectric strength of type B cable was determined by applying a 60-cycle voltage between the conductor and a metal tube 7.7 millimeters in diameter with belled ends that enclosed a 13.4-inch length of the cable. Voltage was applied at the approximate rate of 1 kilovolt per second. The cable broke down at 71 kilovolts (peak).

The same test was made using two different types of standard cable. The first type of cable, which had a lacquered coating, broke down at 46 kilovolts; the second type of cable, which had the same kind of insulation as the type B cable, broke down at 57 kilovolts. Comparison of the value of 57 kilovolts to that of the type B cable shows that the type B had about a 25-percent greater dielectric strength than the standard cable, although the resistance of the type B cable may have affected the result of the test.

A similar test on the type C cable determined the breakdown voltage to be 6 kilovolts, breakdown occurring through the seam. This low-voltage breakdown was expected from the appearance of the cable. A short section of the cable, which was selected by visual inspection for good construction, was placed in a snugly fitting metal tube $1\frac{1}{2}$ inches long that had belled ends and was tested in the same manner. The cable broke down at 19.8 kilovolts, near or on the seam.

## Output-Voltage Tests

Type C cable in a conventional shielding harness was placed in a circuit as shown in figure 9 in order to simulate roughly an engine installation. Shunt resistance was placed across the firing gap to simulate fouling conditions and a shunt capacitance of 185 micromicrofarads was placed between the magneto and the test sample to simulate the remainder of the harness. Gaps irradiated with ultraviolet light were used to measure voltages. A similar test was run using standard ignition cable. The precision of the measurements was ±5 percent. The results are presented in the following table:

| Standard cable | | | Conducting-rubber cable type C | | |
|---|---|---|---|---|---|
| Shunt resistance, $R_s$ (ohms) | Voltage applied to cable, $E_1$ (kv) | Voltage output of cable, $E_2$ (kv) | Shunt resistance, $R_s$ (ohms) | Voltage applied to cable, $E_1$ (kv) | Voltage output of cable, $E_2$ (kv) |
| Voltage $E_1$ without test cable 18.7 kv | | | Voltage $E_1$ without test cable 19.0 kv | | |
| 100,000 | 3.5 | 3.3 | 100,000 | 4.2 | 3.0 |
| 200,000 | 6.1 | 5.8 | 200,000 | 6.7 | 5.5 |
| 700,000 | 11.4 | 11.1 | 920,000 | 12.0 | 11.3 |
| Infinite | 17.7 | 17.7 | Infinite | 17.1 | 16.8 |

As shown in the preceding table, the results of the two tests are almost the same; the spark obtained with the conducting-rubber cable was much weaker in appearance, however, than that obtained with the standard cable. Such a result would be expected inasmuch as one of the functions of the conducting-rubber cable is to reduce erosion of spark-plug electrodes by limiting spark current.

## Engine Tests

Engine tests on a CFR engine were made using type C cable and a standard cable in conventional shielding harnesses as the ignition cable, with a switch arrangement whereby either cable could be used as the ignition cable without stopping the engine. The length of the cables was 17.9 inches in 14-inch harnesses and the capacitances were 46 micromicrofarads for the type C cable and 30 micromicrofarads for the standard cable. The resistance of the type C cable was 22,700 ohms. After the readings were taken for one cable, it was switched out of the ignition circuit, the other cable was switched in, and the readings were repeated. The indicated mean effective pressures were measured for various fuel-air ratios at three conditions of manifold pressure and speed. (See table II.)

The leanest and richest fuel-air ratios listed in each part of table II represent the limits of smooth engine running with the two types of cable. The use of the type C cable apparently decreased to some extent the range of fuel-air ratios over which the engine would operate and caused a slight decrease in engine power near either end of the operating range. The tests indicate that the cable resistance (22,700 ohms) was as high as could be tolerated. The maximum permissible resistance may not, however, be independent of the cable length.

## DISCUSSION

It is evident from the foregoing tests and observations that the most serious obstacle to the development of a practical conducting-rubber cable is the difficulty of achieving sufficient conductivity in the rubber conductor. The tests on the type B experimental cable indicated that, once this problem has been solved, the insulation properties of conducting-rubber cable will be very desirable. The difficulty of the conductivity problem is increased by the fact that cable-fabrication processes may decrease the conductivity of the rubber.

Excessively high cable resistance is undesirable because it reduces the voltage available to fire the spark plug and because it may impair the igniting effectiveness of the spark. Although no extensive test data covering the effect of cable resistance on the reduction of the igniting quality of the spark are available, the engine tests of the type C cable indicated a noticeable, though not serious, effect at a cable resistance of approximately 20,000 ohms. The effect of cable resistance on the voltage delivered to the spark plug is discussed in detail in appendix A, where it is shown that the voltage loss due to a cable resistance of 20,000 ohms is relatively small (about 6 percent). It seems reasonable, in the absence of more extensive data, to assume that 20,000 ohms marks the upper limit of acceptable cable resistance. If conducting-rubber cable is to be made with a conductor diameter no larger than that of conventional cable and if the total resistance for an entire lead (say 7 ft) is to be no greater than 20,000 ohms, the resistivity of the conducting rubber can be no greater than 0.8 ohm-centimeter. Such a cable would have the widest possible field of application. An increase in the conductor diameter by a factor of 1.41 would permit the use of rubber of twice the 0.8-ohm-centimeter value of resistivity but would result in an estimated increase of 20 percent in the cable capacitance with approximately 3-percent reduction in open-circuit voltage at the spark plug.

Conducting rubber of considerably higher resistivity than 0.8 ohm-centimeter can be used in detachable flexible leads, which are of relatively short length. As shown in appendix B, such short leads, inasmuch as they constitute only a fraction of the total cable system, permit the use of conductors of greater diameter and of greater resistance per unit length. If the conductor diameter is increased to 0.3 centimeter, leads up to 18 inches long can be constructed of rubber of 30-ohm-centimeter resistivity (experimental cable, type C). As shown in appendix C, the chief disadvantage of large conductor diameter is the resulting increase in the tendency of the cable toward the formation of external corona. If this disadvantage is tolerated, detachable leads incorporating rubber of 10-ohm-centimeter resistivity will provide the large safety factors on the resistance that are needed to allow for the possibility of an increase in the resistivity of the rubber because of deformation or temperature change. The only obstacle to the production of such a lead is the lack of a method of fabrication that can produce a cable of good dielectric properties without increasing the resistivity of the rubber above that obtainable in sheet form.

## SUMMARY OF RESULTS

From tests conducted to investigate the possibility of using rubber conductors in aircraft ignition cables, the following results were obtained:

1. Different samples of conducting rubber of the same composition, which had been processed by various methods, exhibited electrical resistivities of various magnitudes. The resistivity was 9 to 20 ohm-centimeters for samples in sheet form and 30 to 1600 ohm-centimeters for samples constituting the cores of ignition cables.

2. Handling, stretching-retracting, and bending-straightening of conducting rubber increased its resistance; when the rubber was allowed to rest, however, the resistance decreased toward the initial value at a rate that decreased with time. Stretching-relaxing caused the resistance to increase by an amount roughly proportional to the amplitude of stretch, the increase amounting to several times the initial resistance for large stretches.

3. The resistivity of the rubber increased with temperature up to a maximum point at which a change occurred and the resistance decreased. This maximum occurred at $140^{\circ}$ F and $240^{\circ}$ F on the two strips tested. The resistivity at any given temperature depended on the previous temperature history of the sample; successive heating-cooling cycles tended to lower the resistivity.

4. Conducting rubber withstood high temperatures up to about $335^{\circ}$ F, beyond which the rubber cracked and slight sticking occurred.

5. Conducting rubber withstood the low temperature of $-72^{\circ}$ F and exhibited only slight stiffening when flexed at that temperature.

6. For impulse voltages the resistance of conducting rubber was independent of applied voltage, at least up to the gradient of 450 volts per centimeter.

7. The resistivity of the rubber increased suddenly and then decreased to approximately 50 percent of its initial value when a large continuous current of sufficient magnitude was passed through it. Successively larger currents caused similar action, resulting in lower and lower resistance.

8. Strips of the rubber withstood 310 hours of operation under magneto voltage without significant change in resistance or noticeable deterioration.

9. The first of two conducting-rubber cables that have been fabricated had a dielectric strength approximately 25 percent above that of a standard cable, although it had a prohibitively high resistance. The second cable had much lower resistance but poor dielectric strength.

10. The use of a 17.9-inch length of shielded conducting-rubber cable having a resistance of 22,700 ohms and a capacitance of 46 micromicrofarads as the ignition cable on a CFR engine resulted in a slight reduction of output for very lean and very rich mixtures and some decrease in the range of fuel-air ratios over which the engine would operate smoothly.

11. Because of its high resistivity, rubber of the type tested is applicable only to short lengths (about 2 ft) of cable (detachable loads) with conductors of large diameter.

## CONCLUSIONS

1 The development of satisfactory ignition cable employing a rubber conductor depends upon the development of a satisfactory method of fabrication.

2. The existence of a wide field of application for conducting-rubber ignition cable depends upon the development of conducting rubber having a resistivity of less than 1 ohm-centimeter.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

# APPENDIX A

## EFFECT OF DIAMETER AND RESISTIVITY OF CABLE CONDUCTOR ON VOLTAGE

Effect of cable resistance on output voltage. - The effect of a given ignition cable on the voltage applied to the spark plug is determined by two factors: the load imposed on the magneto by the cable itself and the transmission characteristics of the cable.

For conventional cable of negligible resistance, the only important effect of the cable is the capacitance load that it imposes on the magneto. The load imposed on the magneto when it is used in the conventional ignition system is represented diagrammatically in figure 10(a). The capacitance C of the cable is determined by the construction of the cable and its accompanying shield. In conventional installations, the maximum permissible value for C is set at about 250 micromicrofarads. The shunt resistance $R_s$ is determined by the condition of the spark plug. For clean spark plugs it is quite high but for badly fouled spark plugs it may reach short-circuit values. In practice a good ignition system is expected to fire spark plugs shunted by resistances as low as about 200,000 ohms.

If the ignition cable has appreciable resistance, its transmission properties must be considered. For this case the magneto load may be represented by figure 10(b). Inasmuch as the output frequency of the magneto is of the order of a few kilocycles, the distributed nature of capacitance C and conductor resistance $R_c$ can be neglected for the purposes of this discussion.

It is apparent that $R_c$ and $R_s$ constitute a voltage divider that determines the maximum obtainable spark-plug voltage to be the magneto voltage times the factor $R_s/(R_s + R_c)$. One requirement of good cable design is therefore that $R_c$ be kept small with respect to 200,000 ohms.

If the resistivity of the material for the cable core is fixed, the resistance of a given length of cable can be decreased only by increasing the conductor diameter. Such a change results in an increase of cable capacitance if the outer diameter of the cable is held constant. Quantitative considerations of the relative effects of cable capacitance and resistance make possible a quantitative evaluation of the diameter of the cable core for maximum output voltage.

Effect of capacitance and resistance loads on magneto output voltage. - A capacitance load affects a magneto by reducing the output voltage. Figure 11 shows how the output voltage of a service-type magneto varies with capacitance load.

The magneto voltage is also reduced, in a similar manner, by resistance load. (See fig. 12.) In an ignition system, the resistance load is determined by the condition of the spark plug and the cable resistance.

Effect of conductor resistance on voltage at a fouled spark plug. - When a resistance is placed in series with a fouled spark plug (fig. 10(b)), the actual resistance load on the magneto is $R_c + R_s$. If the conductor resistance $R_c$ is increased for any constant spark-plug resistance $R_s$, the magneto output voltage tends to rise; however, the voltage applied to the spark plug is $R_s/(R_s + R_c)$ times this voltage, so the spark-plug voltage is actually reduced. Figure 13 shows the percentage decrease in spark-plug voltage with increasing conductor resistance, assuming $R_s$ to be 200,000 ohms. This curve was obtained by taking the corresponding magneto voltage $E_m$ for load $R_c + R_s$ from figure 12, multiplying it by the factor $R_s/(R_s + R_c)$, and computing the percentage decrease in voltage $\frac{E_o - E_r}{E_o} \times 100$.

APPENDIX B

DETERMINATION OF OPTIMUM CONDUCTOR DIAMETER

Relation of capacitance and resistance to conductor diameter. - The capacitance of ignition cable can be determined from reference 3 by means of the following equation; the notation has been changed slightly from that of the reference:

$$C = \frac{3\pi K}{\frac{\log_e \frac{r_2}{r_1}}{k_1} + \frac{\log_e \frac{r_3}{r_2}}{k_2} + \ldots + \frac{\log_e \frac{r_{x+1}}{r_x}}{k_x} + \ldots + \frac{\log_e \frac{a}{r_n}}{k_n}} \qquad (1)$$

where

| | |
|---|---|
| $C$ | capacitance, farads/cm length of cable |
| $K$ | constant, $8.84 \times 10^{-14}$ |
| $r_1, r_2, r_x, r_n$ | inside radii of successive layers of insulation, cm |
| $k_1, k_2, k_x, k_n$ | dielectric constants of successive layers of insulation |
| $a$ | inside radius of outer cylinder or harness, cm |

The resistance of tho conductor is found by the equation:

$$R = \frac{\rho l}{A} \qquad (2)$$

where

| | |
|---|---|
| $R$ | resistance, ohms |
| $\rho$ | resistivity of conductor, ohm-cm |
| $l$ | length of conductor, cm |
| $A$ | area of cross section of conductor, sq cm |

Figure 14 is a plot of the capacitance and resistance per foot length of cable as a function of the conductor diameter. Values used were:

$r_3 = 0.355$ cm $\qquad k_3 = 1.0$

$a = 0.397$ cm $\qquad \rho = 10$ ohm-cm

$k_1 = 3.5 \qquad l = 30.5$ cm

$k_2 = 5.6$

It was assumed for ease in calculating that, as $r_1$ was increased, the remaining solid insulation would be equally divided between $k_1$ and $k_2$. Therefore, $r_2 = \frac{r_3 + r_1}{2}$.

Choice of conductor diameter. - It is apparent from the relations between capacitance, resistance, and conductor diameter that, for a given length of cable employing a conductor of given resistivity, an optimum conductor diameter exists that will make available the maximum voltage for firing a partly fouled spark plug. Other considerations will, of course, restrict the range of usable diameters. In general, the optimum diameter increases and the output voltage decreases with increasing resistivity of the core material. A practical conducting-rubber cable must deliver an output voltage approximating that of a good metallic cable. Little capacitance increase due to an increase in conductor diameter is consequently permissible if the conducting-rubber cable is to be used to replace the conventional cable in its entirety. If the high-resistance cable, however, constitutes only a small fraction of the complete cable assembly, such as a detachable lead, an increase in the diameter of the high-resistance conductor has a relatively small effect on the total capacitance load on the magneto and is therefore permissible.

In order to determine the optimum diameter for a short length of cable employing rubber of 10-ohm-centimeter resistance, a simulated cable with adjustable constants was prepared. This arrangement was deemed more practical than making equivalent circuits, which would have required laborious calculations and many condensers, inductors, and resistors. The only electrical difference between the actual cable and the simulated cable was the inductance, the effect of which is negligible at magneto frequency.

The simulated cable consisted of a glass tube of 0.22-inch inside diameter placed within a second glass tube of 0.30-inch inside diameter. Insulating oil was placed between the tubes to provide a dielectric constant that would lead to a reasonable length of resistor for the desired capacity. The inner tube was used to hold the conductor, which was either copper-sulfate solution or mercury, depending on the resistance desired. The concentration of the copper-sulfate solution was varied to provide various values of resistance. A layer of tin foil was placed around the outer tube to provide the desired capacitance. The capacitance could be adjusted by removing or adding tin foil. The length of the conductor was always adjusted to correspond to the length of the tin foil.

The simulated cable was placed in the circuit as shown in figure 15 and the output voltages were measured by illuminated sphere gaps for various capacitances and resistances, both with and without the shunting resistance of 200,000 ohms.

The capacitance with no shunting resistor in the circuit caused only a slight reduction in the peak voltage owing to magneto loading. This drop was within the limits of precision of the measurements, which was about ±5 percent. The lack of precision was a result of slight variations in the output of the magneto and variations, owing to time lag, in the breakdown voltage of the spark gap. With the shunt resistor in the circuit, the cable acted as a divider and reduced the voltage accordingly. The results of the tests are plotted in figure 16.

The 200,000-ohm leakage curve (fig. 16) was used to plot figure 17, which shows spark-plug voltage as a function of conductor diameter for various resistivities. Figure 17 was plotted by first calculating the resistance that any given conductor diameter and resistivity would produce for a 14-inch length of cable and then determining the corresponding voltage for that resistance.

Figure 17 shows that the optimum diameter occurs past 0.4 centimeter; for all practical purposes, however, any increase in diameter beyond 0.1 centimeter has small effect on increasing the voltage for resistivities of 10 ohm-centimeters or less. This fact leads to the conclusion that other considerations - tendency toward spark-plug fouling and erosion, engine operation, radio interference, and dielectric strength - will determine the diameter for short lengths of cable having a resistivity of 10 ohm-centimeters or less.

## APPENDIX C

### EFFECT OF CONDUCTOR DIAMETER ON DIELECTRIC STRENGTH OF CABLE

If conductors of large size are used in conducting-rubber cable, the effect of the change in conductor diameter on the dielectric strength of the cable must be considered. In the following discussion, it is assumed that the conventional 7-millimeter diameter is maintained for the cable as a whole and that any increase in conductor radius results in a corresponding decrease in the thickness of the layers of insulating material.

Breakdown of solid insulation. - Conventional 5-millimeter ignition cable with an insulation thickness of approximately 2 millimeters has been used extensively and experience has shown that its dielectric strength is adequate. An increase in the conductor diameter up to 3 millimeters for 7-millimeter cable should therefore be quite safe, especially inasmuch as the maximum dielectric stress in a 7-millimeter cable with a 3-millimeter conductor would be much lower than the maximum stress in a conventional 5-millimeter cable. Actually, the maximum stress in a 7-millimeter cable is decreased by an increase of conductor diameter up to a diameter of at least 3 millimeters.

The stress or voltage gradient at any point in a cable surrounded by a coaxial shield for any applied voltage can be computed by means of the following equation (with slightly changed notation) from reference 3:

$$g_x = \frac{e}{x k_x \left( \frac{\log_e \frac{r_2}{r_1}}{k_1} + \frac{\log_e \frac{r_3}{r_2}}{k_2} + \ldots + \frac{\log_e \frac{r_{x+1}}{r_x}}{k_x} + \ldots + \frac{\log_e \frac{a}{r_n}}{k_n} \right)} \tag{3}$$

where

$g_x$ voltage gradient at any point x, kv/cm

$e$ applied voltage, kv

$x$ distance from center of conductor, cm

$k_x$ dielectric constant of insulation in which $x$ falls

$r_1, r_2, r_3, r_x, r_n$ inside radii of successive layers of insulation, cm

$k_1$, $k_2$, $k_3$, $k_x$, $k_n$ dielectric constants of successive layers of insulation

a inside radius of outer cylinder, cm

Equation (3) can be applied to an ignition cable in the following manner: It is assumed that the ignition cable is constructed as in figure 18, the conductor being surrounded by two solid insulations, a layer of air, and the outer cylinder or harness. The conductor is considered as one large wire and all the insulation layers are considered concentric in order to give a uniform radial-field distribution that can be easily calculated. In the actual case the field is distorted and the stresses are increased. The uniform-field method, however, gives an answer that approximates the correct one and is sufficiently accurate for most purposes.

Typical values for the cable would be $k_1 = 3.5$, $k_2 = 5.6$, $k_3 = 1.0$, $r_3 = 0.355$ centimeter, and $a = 0.397$ centimeter. Values are not given for $r_1$ and $r_2$, because these values will be varied. Whenever $r_1$ is varied, it will be assumed that the remaining solid insulation is equally divided between $k_1$ and $k_2$, thus $r_2 = \frac{r_3 + r_1}{2}$. The maximum gradient occurs at the surface of the conductor or where $x = r_1$.

When the proper values are substituted in equation (3), the gradient at the surface of the conductor is a function of increasing radius, as in curve 1 of figure 18 for constant applied voltage. The gradient decreases over the range of practical conductor diameters. This curve is based on the assumption that the applied voltage is not too high to cause breakdown of the air layer between the cable and the harness. If this air layer is broken down, the gradient is higher and the minimum point occurs at a smaller conductor diameter as in curve 2 (fig. 18); however, the gradient is still less than the gradient that occurs with the standard conductor diameter up to 0.4-centimeter diameter.

Breakdown of air voids. - The breakdown of air voids (corona) is a more important consideration than the breakdown of the solid insulation, inasmuch as the cables are operated at voltages far below the instantaneous breakdown voltage of the solid insulation but still at voltages high enough to cause corona. It is, however, a subject about which little information is available because of the difficulties involved in obtaining data on the breakdown of extremely small air layers.

In a conventional-cable installation, corona may occur in voids around the conductor (internal corona) and in the air space between the cable and the shield harness (external corona). The use of a rubber conductor is expected to eliminate internal corona through the elimination of voids. External corona would not be eliminated and would, in fact, occur at lower cable voltages if the conductor diameter were increased.

The electrical breakdown of an air space is determined by the dimensions of the space, the air density, and the electrostatic field that exists in the space. The electrostatic field in turn is determined by the cable voltage, the construction of the cable, and the location and dimensions of the air space. If the dimensions of the space are such that the field within the space is essentially uniform, the magnitude of the gradient required to cause breakdown can be determined from available experimental data. Data from references 4 and 5 were reduced to atmospheric pressure by the application of Paschen's law and plotted in figure 19 to show the variation of breakdown gradient at atmospheric density with length of the air space in the direction of the field (electrode spacing).

The data of figure 19 should be applicable to external-corona breakdown, inasmuch as the air space between the cable and the surrounding shield is sufficiently thin (0.042 cm) in relation to its radius of curvature to justify the assumption of a uniform field. The value of breakdown gradient for a spacing of 0.042 centimeter was read from figure 19 and was used with equation (3) for computation of the cable voltage causing external corona for various conductor diameters. The cable shown diagrammatically in figure 18 was assumed for the computations. The results are plotted as a dashed line in figure 20. The decrease in corona voltage with increasing conductor diameter is quite rapid. The curve applies, of course, only at sea-level density but the trend would be the same at higher altitudes. In a practical installation, the cable would not lie coaxially in the shield harness and all air-gap spacings from 0 to 0.084 centimeter would exist. Computation showed, however, that over the range of conductor diameters from 0.05 to 0.3 centimeter the cable voltage causing corona was in the neighborhood of a minimum for an air space of 0.042-centimeter thickness.

In order to show the relation between internal and external corona for cables in which air voids exist around the conductor, the voltage required for internal corona is plotted as a solid line in figure 20. The method of computation was similar to that for external corona. The void around the conductor was arbitrarily selected as an annulus of a constant thickness of 0.005 centimeter; otherwise the assumed cable was the same as that assumed for the external-corona calculations. The voltages would, of course, be quite different if a void of a different size were assumed. Computations of internal-corona voltages are subject to large uncertainties because of the lack of experimental data on the applicability of Paschen's law at very small electrode spacings.

Figure 20 shows that increasing the conductor diameter increases external corona but reduces internal corona; therefore, if conducting-rubber cable must employ a larger conductor diameter than standard cable, it should exhibit worse external-corona effects than a standard cable. As far as internal corona is concerned, any air voids that did exist in the conducting-rubber cable would be less subject to corona than the same size air voids in the standard cable.

It should also be pointed out that a magneto voltage slightly higher than that applied to a standard cable will be applied to the conducting-rubber cable in the case of a badly fouled spark plug because of the divider action of the cable and spark-plug resistances. Worse corona effects should therefore occur toward the magneto end of the cable terminated with a fouled spark plug.

The possibility exists of applying a thin layer of conducting rubber to the outside of the cable, thereby eliminating external corona. This arrangement would increase the cable capacitance, although the increase could be partly counteracted by the elimination of the neoprene sheath of the cable, which makes a large contribution to the cable capacity. The merits of this possibility have not yet been completely evaluated.

## REFERENCES

1. Bairsto, G. E.: Some Factors Controlling the Development of Electrical Ignition of Aero Engines. R.A.S. Jour., vol XLIV, no. 350, Feb. 1940, pp. 119-175.

2. Wermine, H. H.: High-Voltage-Ignition-Cable Design for Aircraft. Elec. Eng., vol. 62, no. 11, Nov. 1943, pp. 716-719.

3. Peek, F. W., Jr.: Dielectric Phenomena in High-Voltage Engineering. McGraw-Hill Book Co., Inc., 3d ed., 1929, p. 34.

4. Loeb, Leonard B.: Fundamental Processes of Electrical Discharge in Gases.. John Wiley & Sons, Inc., 1939, p. 411.

5. Thomson, J. J., and Thomson G. P.: Conduction of Electricity through Gases. Vol. II. Univ. Press (Cambridge), 3d ed., 1933, pp. 488-489.

TABLE I - EFFECT OF SUCCESSIVE HEATING-COOLING CYCLES ON RESISTANCE OF CONDUCTING-RUBBER STRIP A-2

| Cycle | Minimum (initial) temperature (°F) | Initial resistance (ohms) | Maximum temperature (°F) | Resistance at maximum temperature (ohms) | Final temperature (°F) | Final resistance (ohms) | Duration of cycle (hr) | Time before start of succeeding cycle (hr) |
|---|---|---|---|---|---|---|---|---|
| 1 | 82.5 | 27,900 | 212 | 20,400 | 91.5 | 20,000 | 1.8 | 0 |
| 2 | 91.5 | 20,000 | 212 | 31,700 | 90 | 18,900 | .7 | 0 |
| 3 | 90 | 18,900 | 215 | 33,300 | 90 | 18,400 | .9 | 0 |
| 4 | 90 | 18,400 | 212 | ----------- | 90 | 17,500 | 1.2 | 0 |
| 5 | 90 | 17,500 | 218 | 31,700 | 90.5 | 16,900 | 1.2 | 0 |
| 6 | 90.5 | 16,900 | 210 | 27,500 | 92 | 16,200 | [a]2.0 | 0 |
| 7 | 92 | 16,200 | 215 | 20,600 | 97 | 16,200 | | 16.5 |
| 8 | 87 | 16,200 | 220 | 23,200 | 95 | 14,700 | 5.0 | 0 |
| 9 | 95 | 14,700 | 220 | 26,400 | 101 | 14,900 | [a]2.5 | 0 |
| 10 | 101 | 14,900 | 220 | 24,500 | 136 | 15,900 | | 15.7 |
| 11 | 87 | 14,700 | 217 | 19,100 | 90 | 14,700 | -------- | 0 |
| 12 | 90 | 14,700 | 190 | ----------- | 101 | 14,900 | -------- | ------------- |

[a]Total of two cycles.

National Advisory Committee
for Aeronautics

TABLE II. - CFR ENGINE TEST SHOWING THE EFFECT OF FUEL-AIR RATIO ON INDICATED MEAN EFFECTIVE PRESSURE AND INPUT VOLTAGES USING CONDUCTING-RUBBER-CABLE, TYPE C, AND STANDARD-CABLE SAMPLES

[Cable length, 17.9 in.; harness length, 14 in.; capacitance of type C cable, 46 μμf; capacitance of standard-cable sample, 30 μμf; resistance of type C cable, 22,700 ohms; precision of voltage measurements, ±5 percent]

| Standard cable | | | Conducting-rubber cable type C | | |
|---|---|---|---|---|---|
| Fuel-air ratio | Indicated mean effective pressure (lb/sq in.) | Input voltage to cable (kv) | Fuel-air ratio | Indicated mean effective pressure (lb/sq in.) | Input voltage to cable (kv) |
| Engine speed, 900 rpm; manifold pressure, 20 in. Hg absolute; spark advance, 35° B.T.C. | | | | | |
| 0.065 | 72 | 4.3 | -------- | -------------- | -------- |
| .075 | 78 | 5.4 | 0.075 | 74 | 6.0 |
| .084 | 83 | 3.5 | .083 | 78 | 5.4 |
| .108 | 76 | 3.0 | .108 | 71 | 3.4 |
| .119 | 70 | 2.8 | -------- | -------------- | -------- |
| Engine speed, 2400 rpm; manifold pressure, 30 in. Hg absolute; spark advance, 45° B.T.C. | | | | | |
| 0.054 | 82 | 3.4 | -------- | -------------- | -------- |
| .059 | 107 | 3.8 | 0.059 | 102 | 4.0 |
| .083 | 124 | 4.4 | .083 | 124 | 3.8 |
| .136 | 94 | 2.0 | .133 | 81 | 1.5 |
| .142 | 76 | 1.8 | -------- | -------------- | -------- |
| Engine speed, 3000 rpm; manifold pressure, 40 in. Hg absolute; spark advance, 45° B.T.C. | | | | | |
| 0.054 | 114 | 4.2 | -------- | -------------- | -------- |
| .055 | 124 | 4.4 | 0.056 | 115 | 4.8 |
| .084 | 170 | 4.4 | .084 | 169 | 3.6 |
| .140 | 125 | 2.4 | .137 | 119 | 2.3 |
| .141 | 114 | 2.4 | -------- | -------------- | -------- |

National Advisory Committee
for Aeronautics

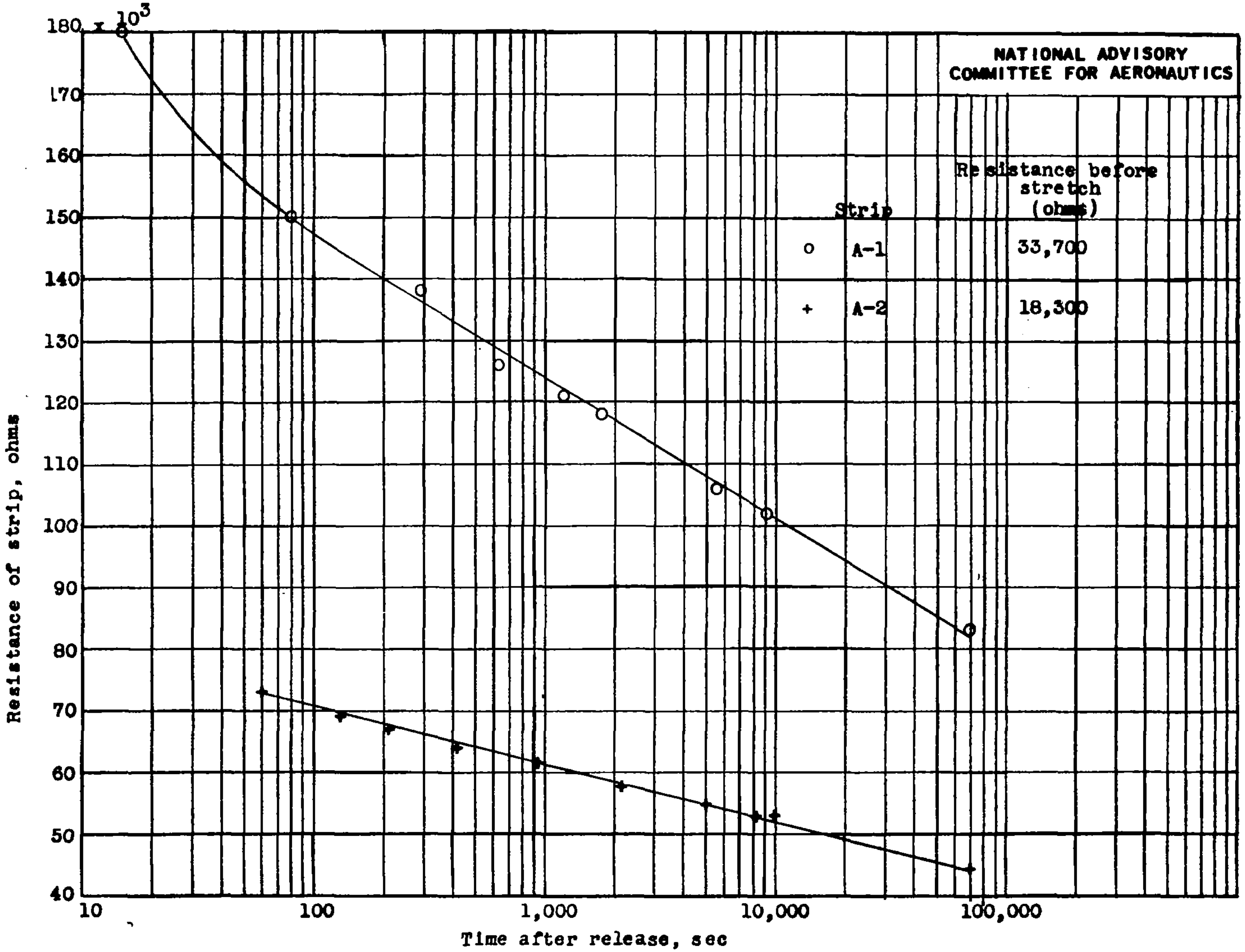



Figure 1. - Recovery of conductance of conducting rubber after stretch and release plotted as function of time after release. Length of strips, $7\frac{1}{2}$ inches.

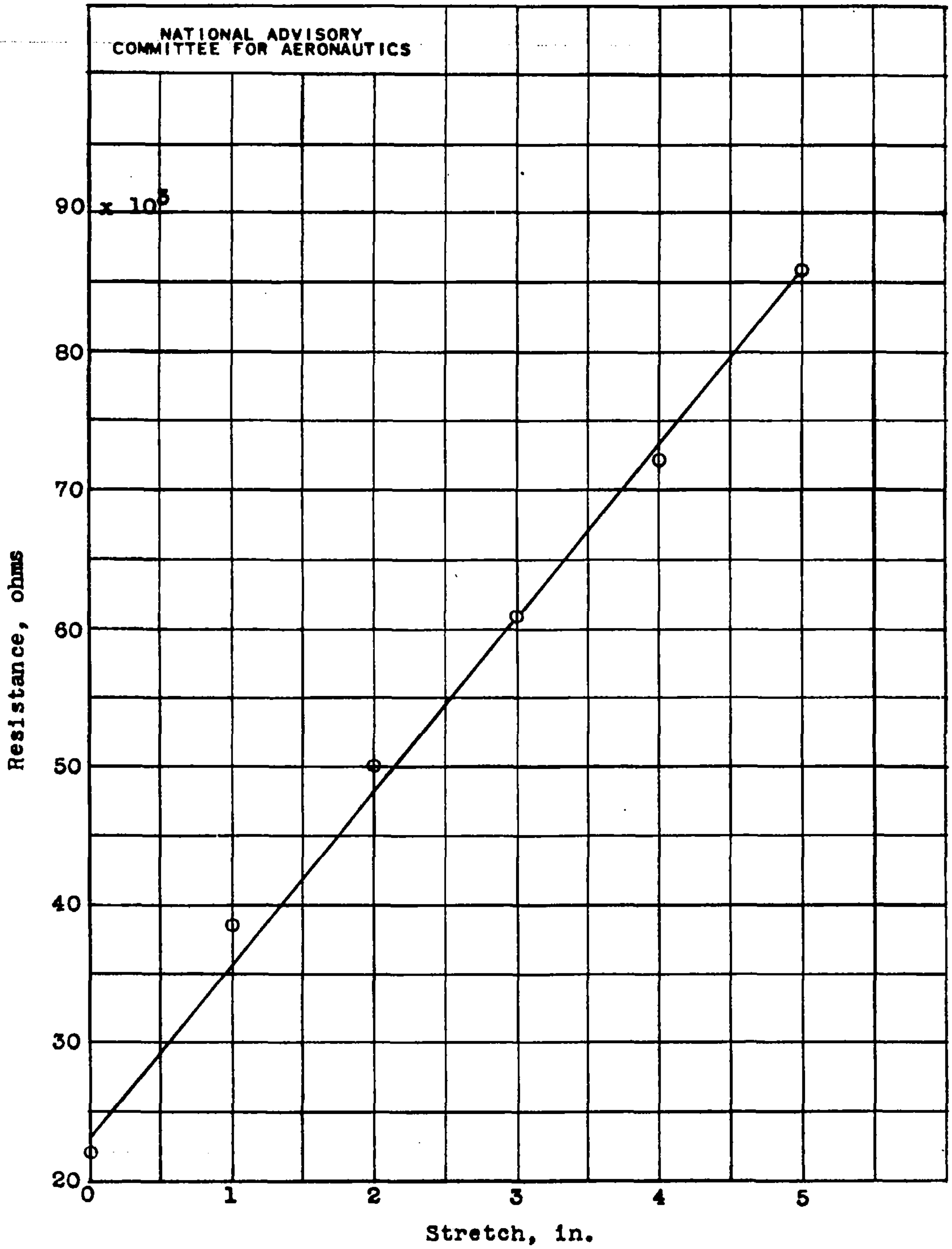



Figure 2. - Effect of stretch and release on resistance of conducting rubber 40 seconds after release. Rest after each measurement, 30 seconds; sample, A-2; length, $7\frac{1}{2}$ inches.

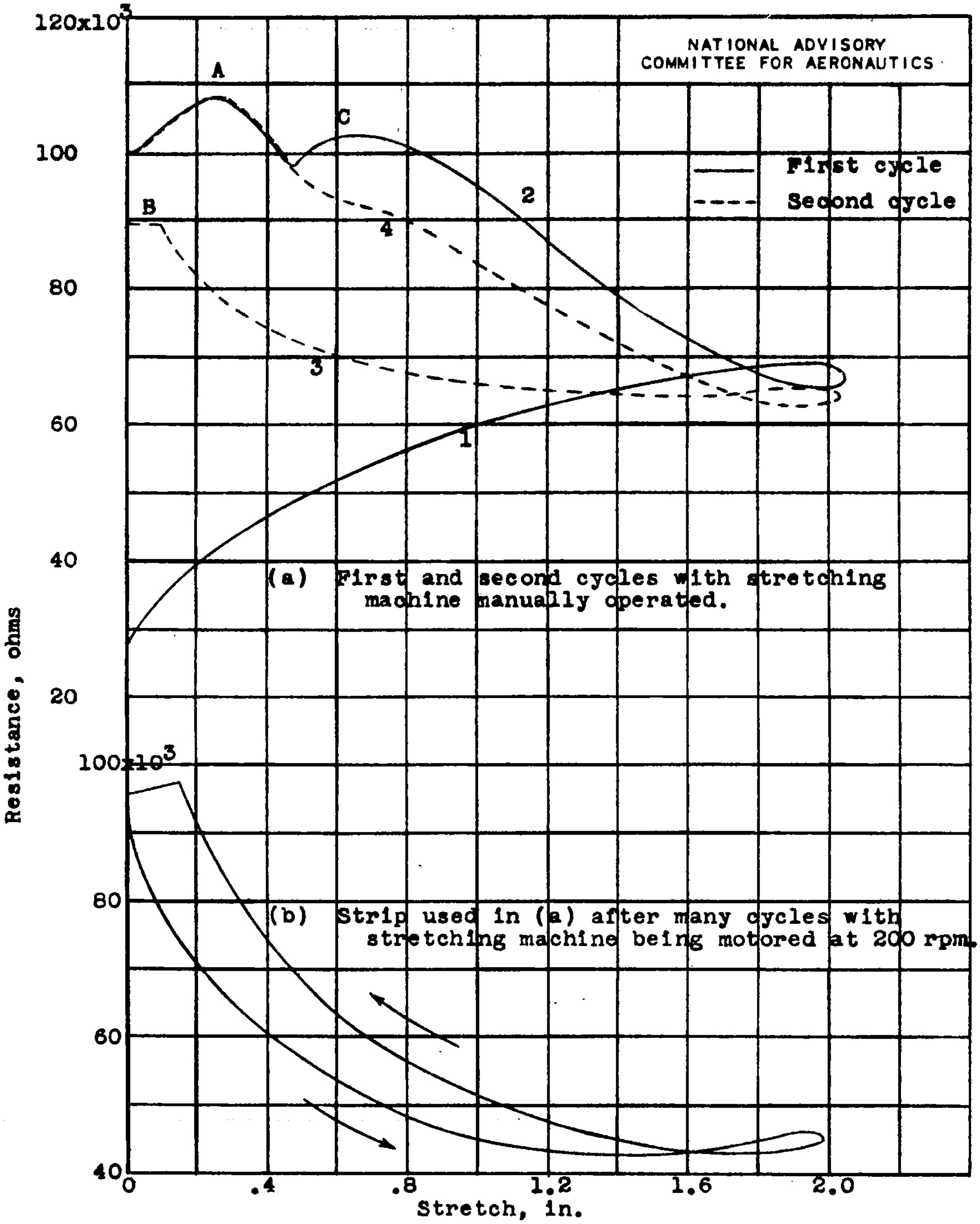



Figure 3. - Resistance of conducting-rubber strip A-2 during successive stretch and retraction cycles.

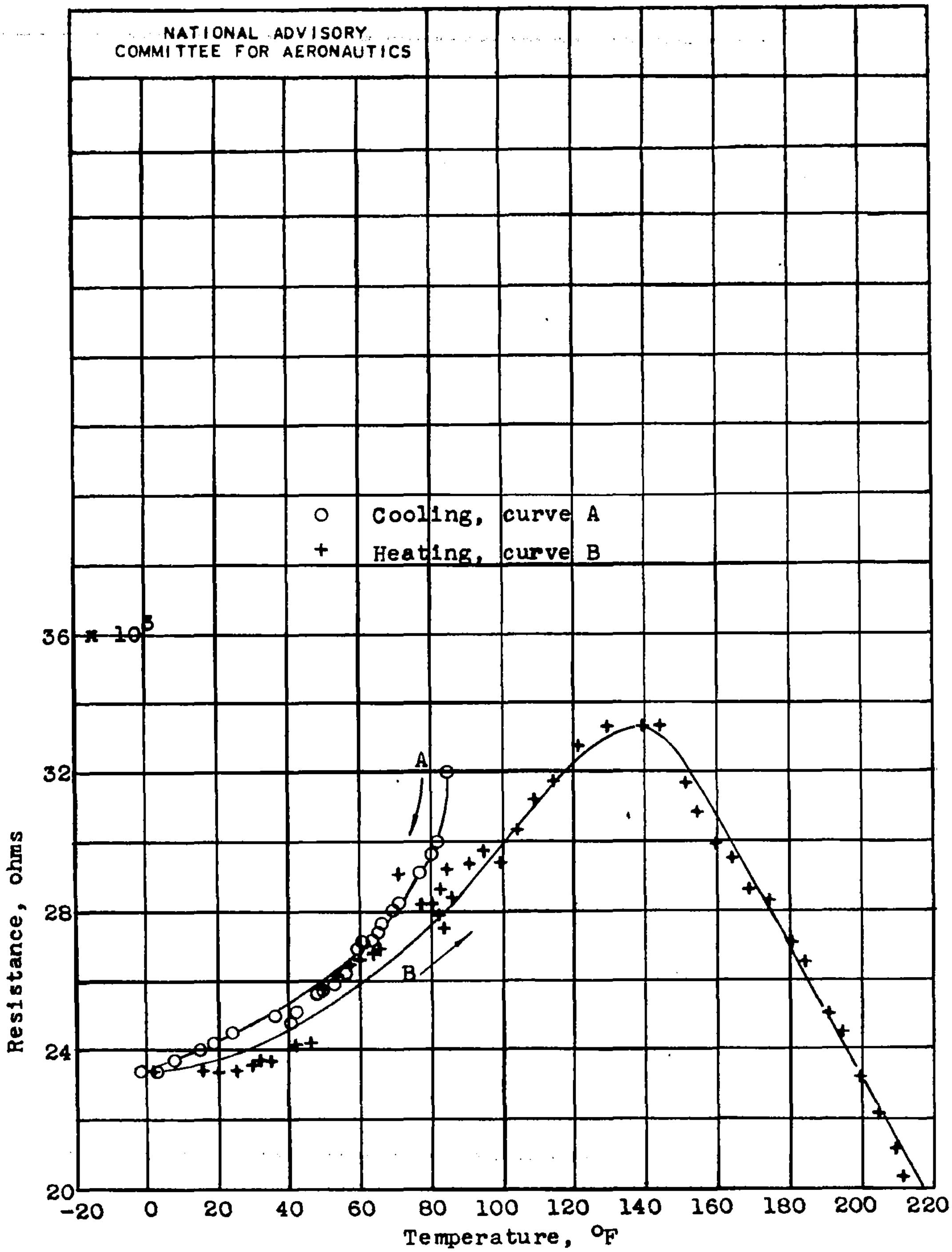



Figure 4. - Variation of resistance of conducting rubber with temperature. Strip A-2; length, $7\frac{1}{2}$ inches.

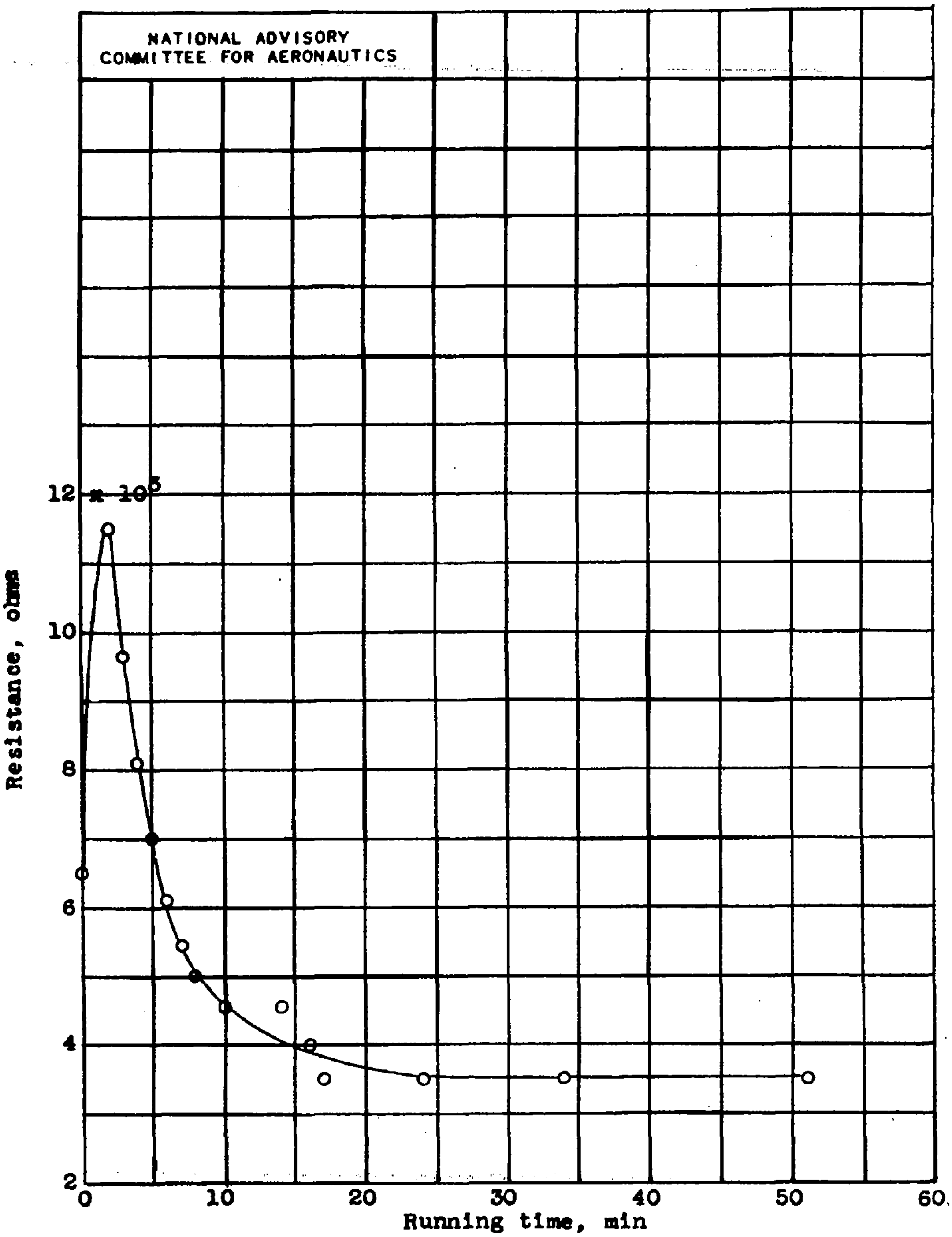



Figure 5. - Change of resistance of conducting-rubber strip A-5 with time of flow of current. Alternating current, 20 milliamperes, 60 cycles; dimensions of strip: length, $5\frac{5}{8}$ inches; width, 3/32 inch; thickness, 1/16 inch.

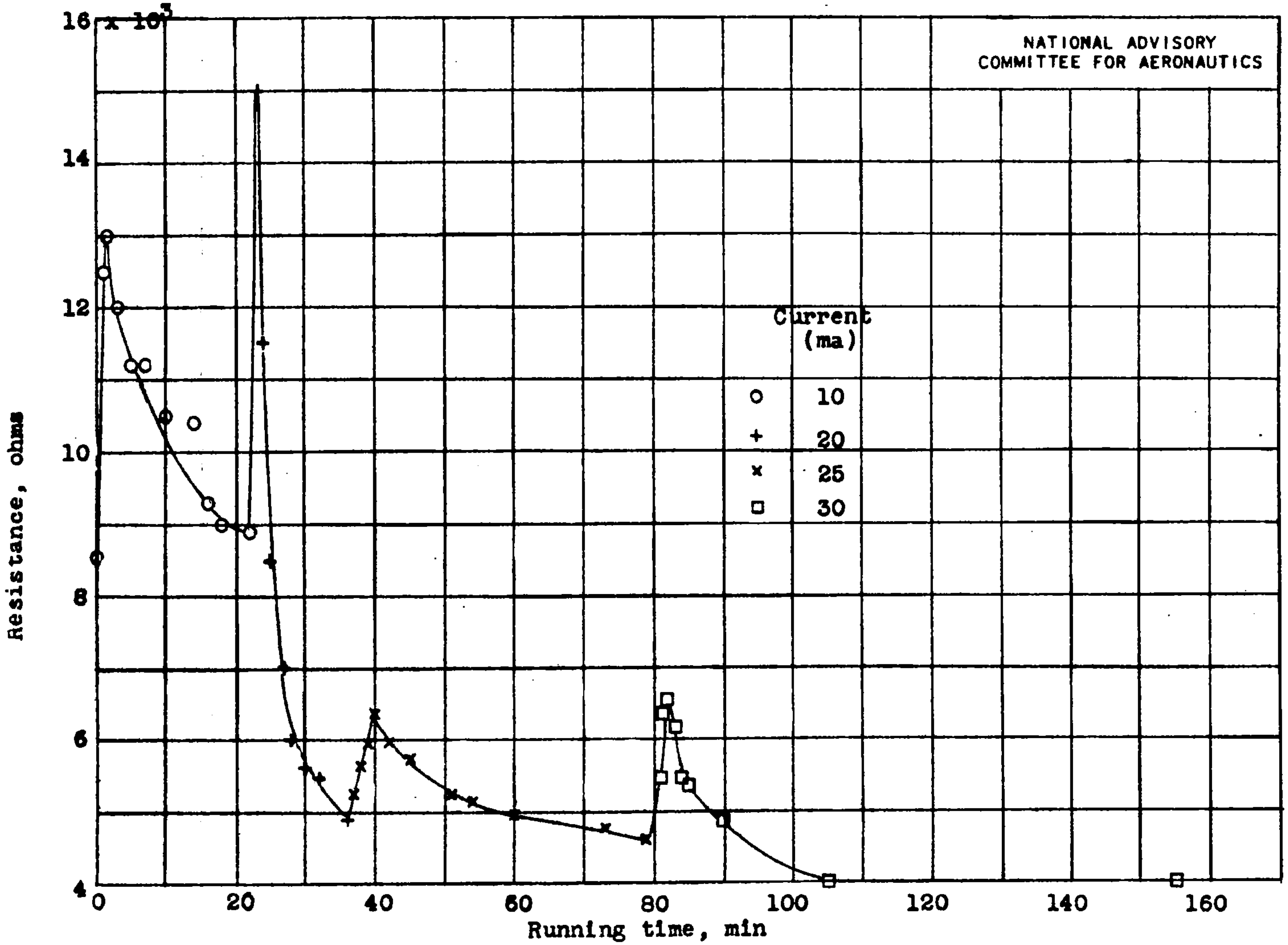



Figure 6. - Effect of successive increases in current on resistance of conducting-rubber strip A-5. Dimensions of strip: length, $5\frac{1}{4}$ inches; width, 1/16 inch; thickness, 1/16 inch.

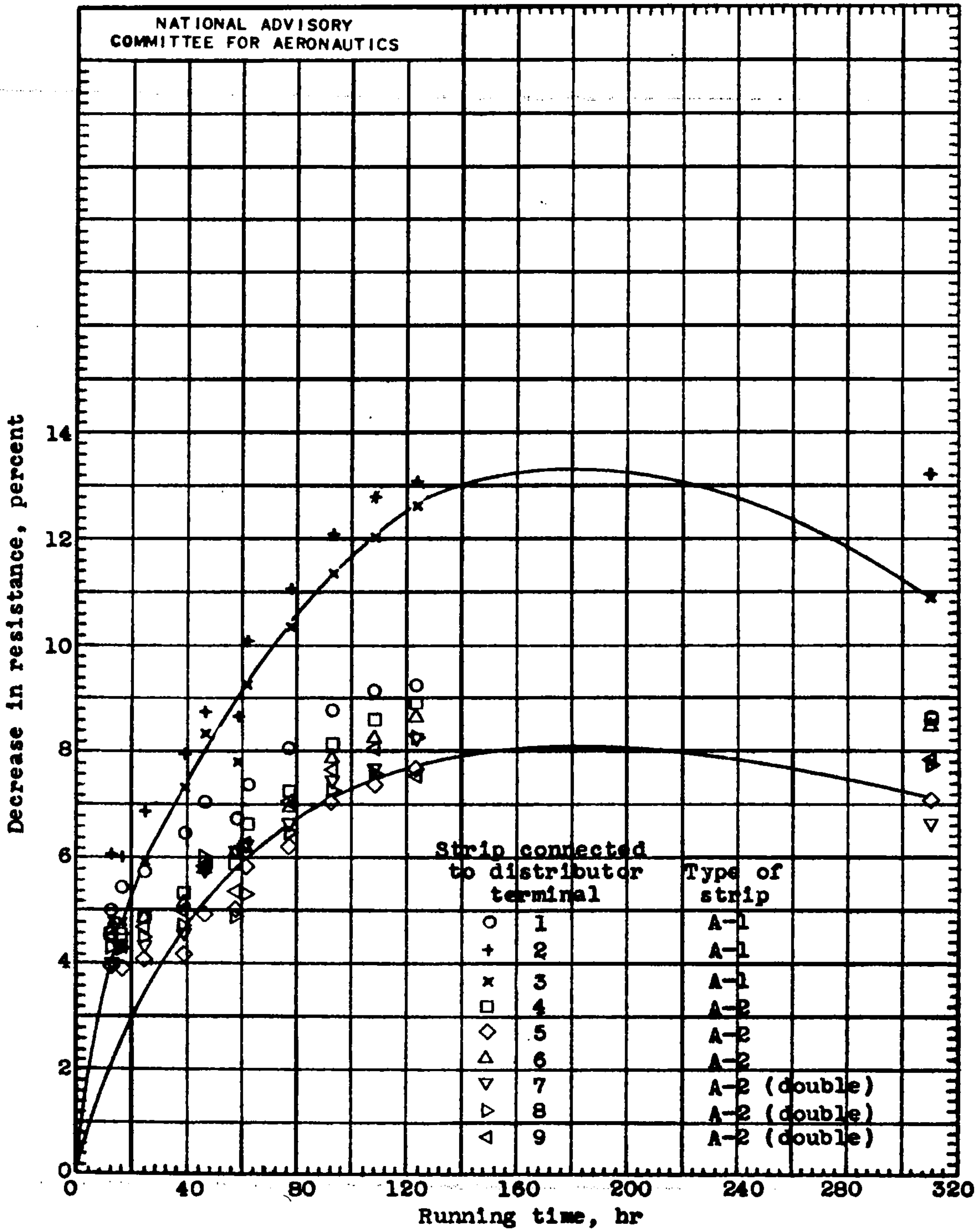



Figure 7. - Decrease in resistance of conducting-rubber strips during test of effect of ignition current. Curves drawn for only strips connected to distributor terminals 3 and 5. Length of strips, $7\frac{1}{2}$ inches.

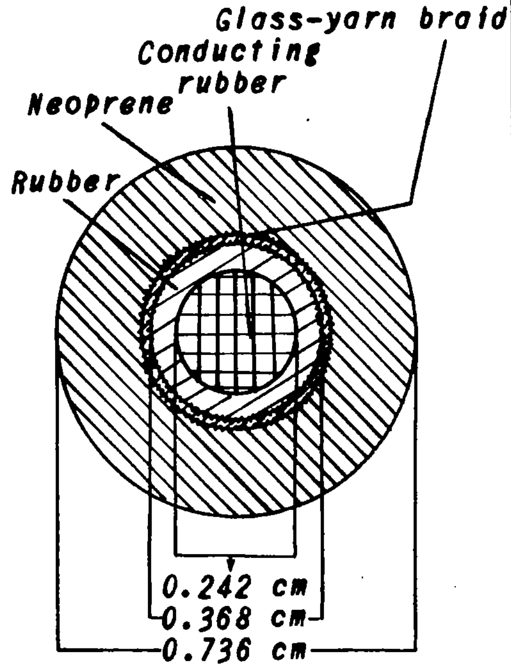
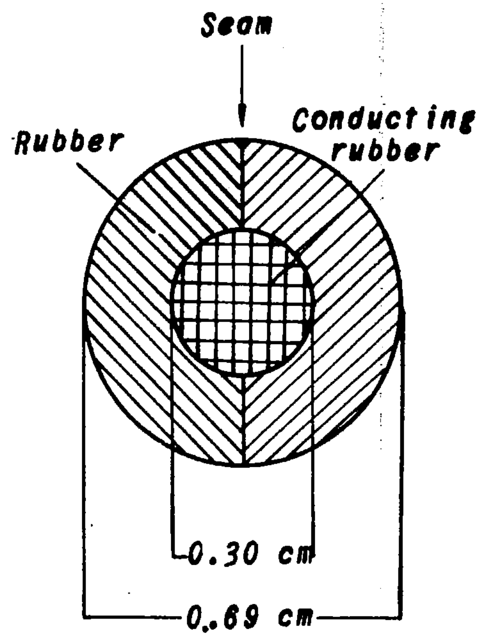
| Cable → | Type B | Type C |
|---|---|---|
| Construction |  |  |
| Resistance, ohm/ft | $1.04 \times 10^6$ | $1.25 \times 10^4$ |
| Capacitance, μμf/ft | 46 | 39 |

Figure 8. - Conducting-rubber cables used in tests.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

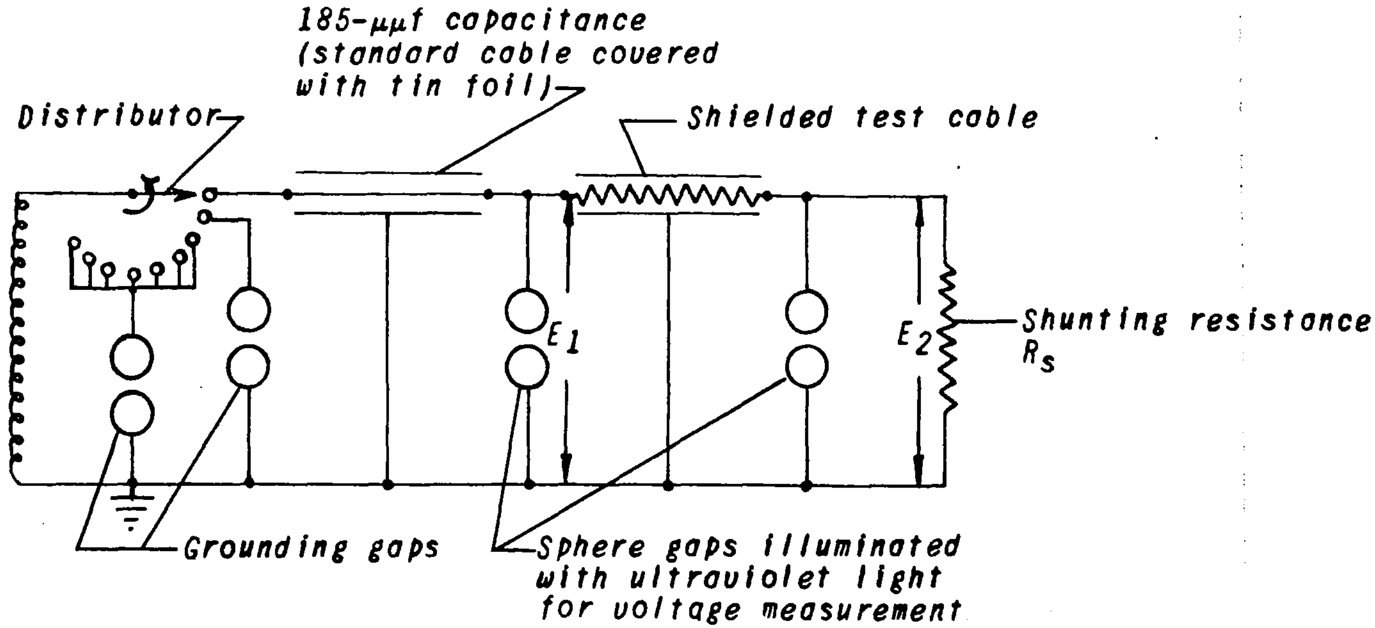
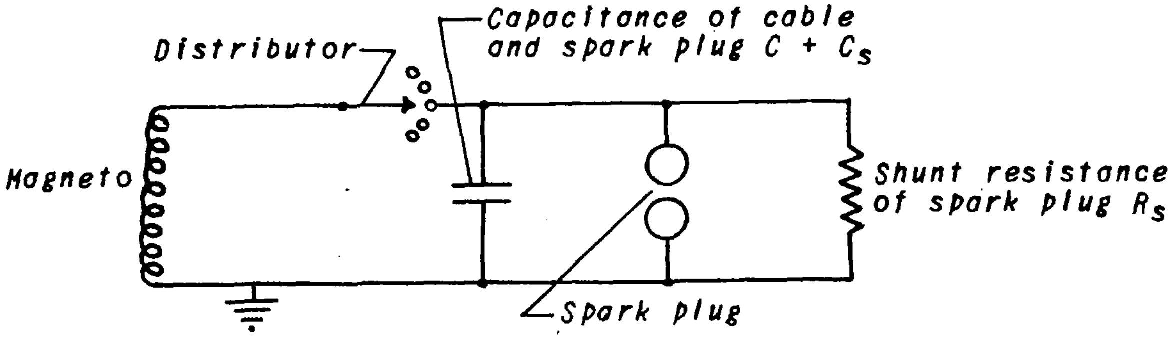
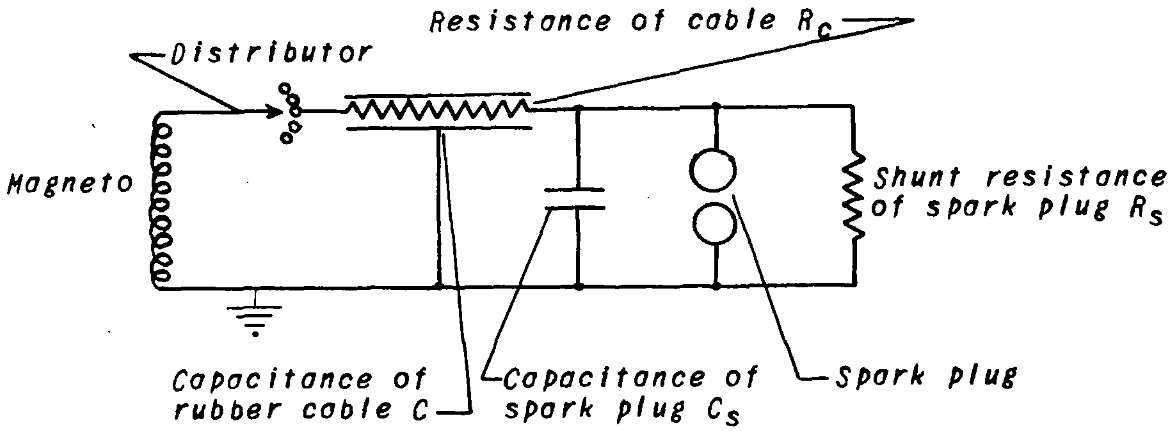



Figure 9. - Circuit diagram of simulated engine installation used to obtain output voltage of short length of conducting-rubber cable.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS




(a) Conventional ignition system.




(b) Ignition system having resistance cable.

Figure 10. - Diagrammatic representations of ignition systems without and with resistance cable.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

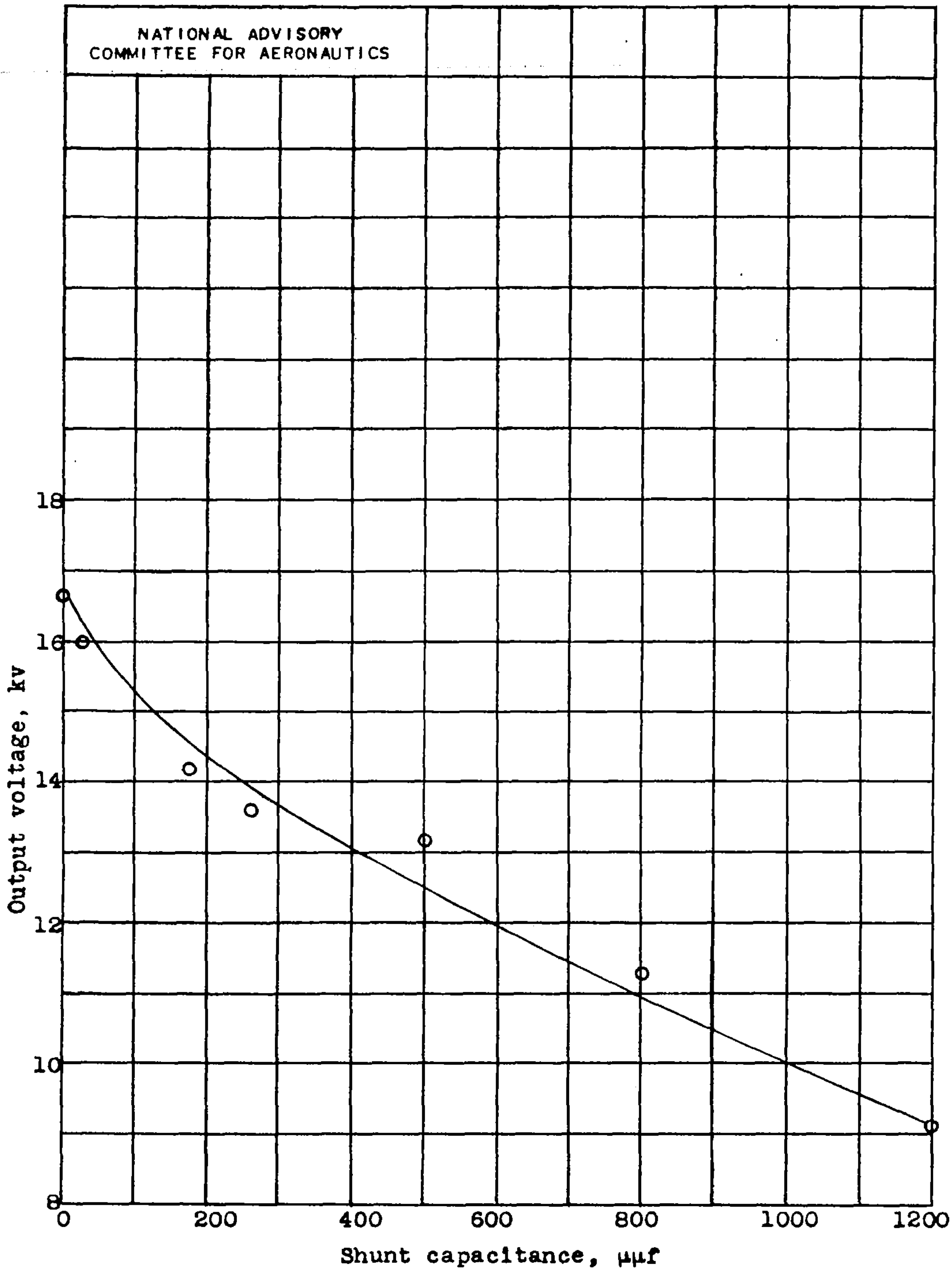



Figure 11. - Effect of shunt capacitance on output voltage of conventional magneto for 9-cylinder aircraft engine. No resistance load; magneto speed, 2000 rpm.

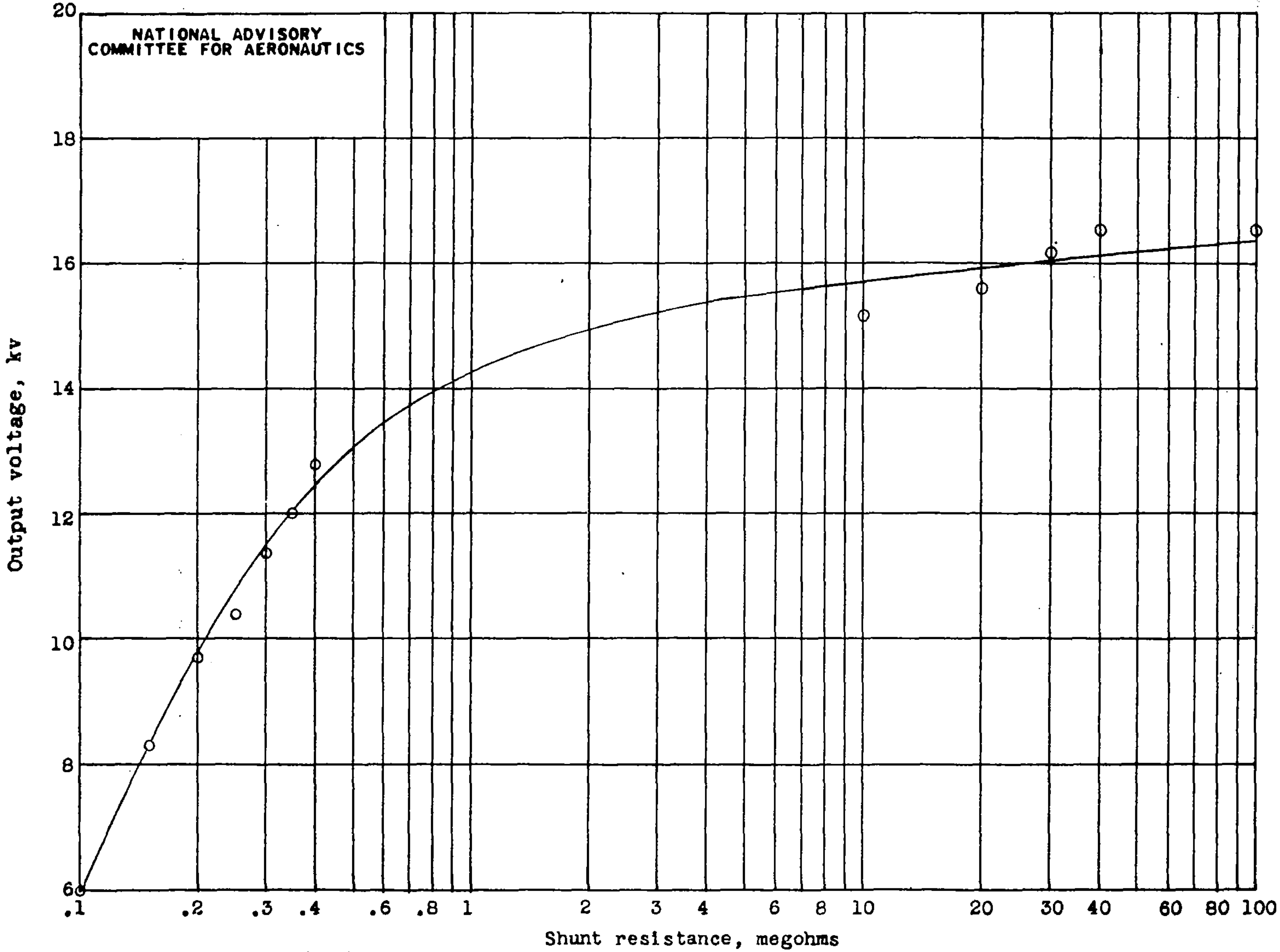
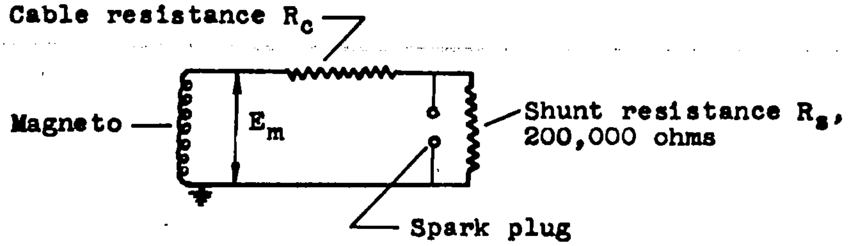



Figure 12. - Effect of shunt resistance on output voltage of conventional magneto for 9-cylinder aircraft engine. No capacitance load; magneto speed, 2000 rpm.




$E_0$ voltage across spark plug with $R_c = 0$

$E_r$ voltage across spark plug for any $R_c$,

$$E_r = \frac{R_s}{R_c + R_s} E_m$$

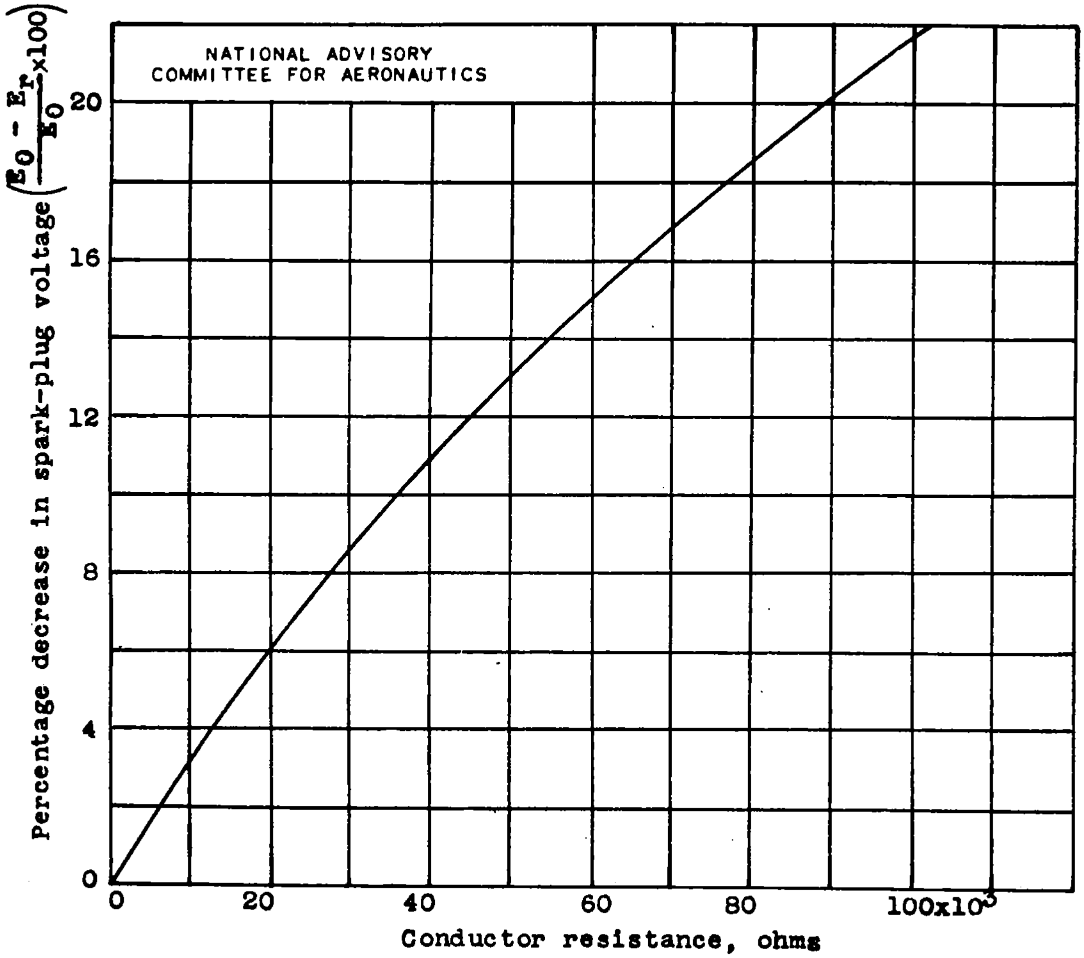



Figure 13. - Percentage decrease in voltage at fouled spark plug with increasing conductor resistance. (Data derived from fig.12.)

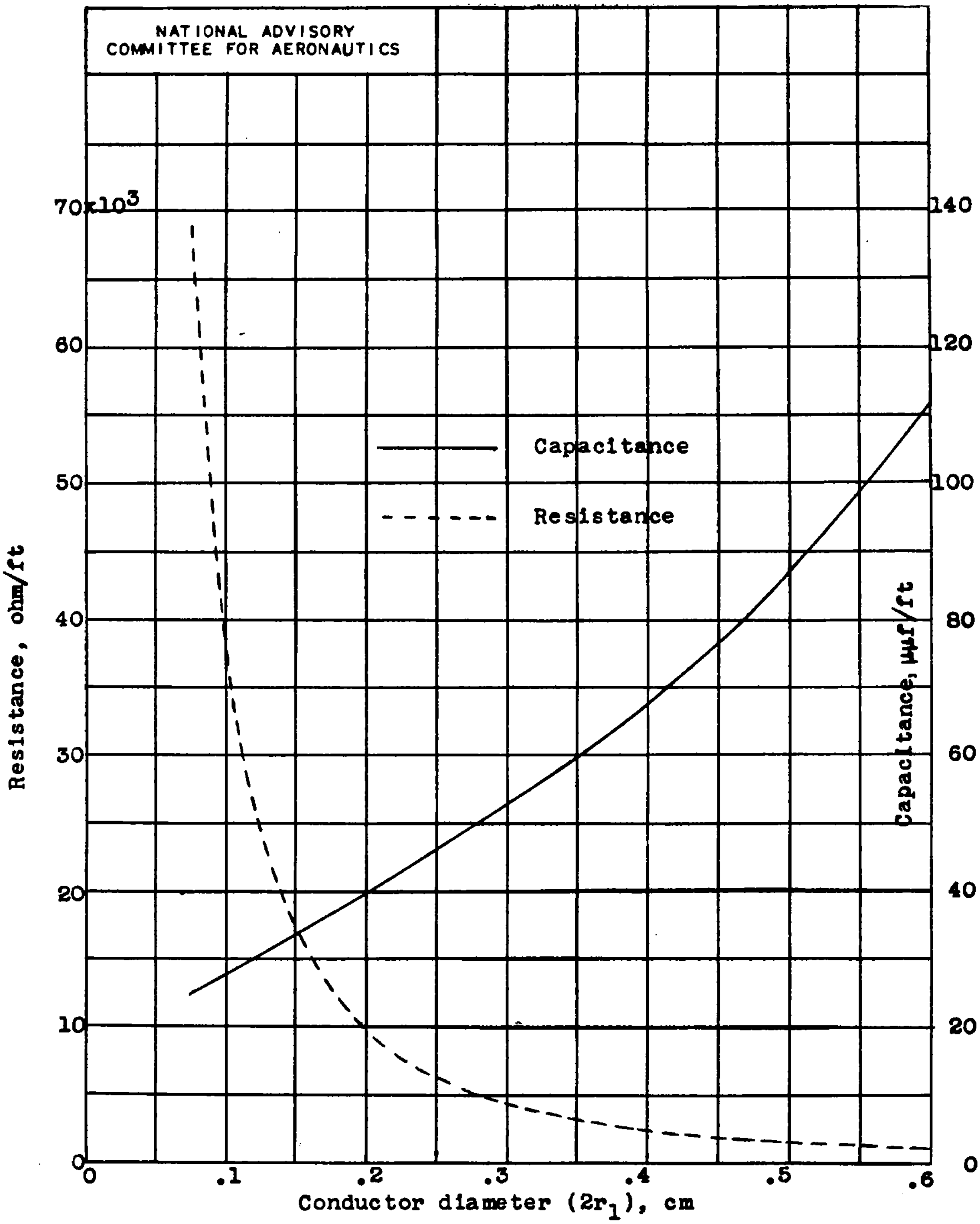



Figure 14. - Capacitance and resistance of 7-millimeter conducting-rubber cable for various conductor diameters. Resistivity, 10 ohm-centimeters.

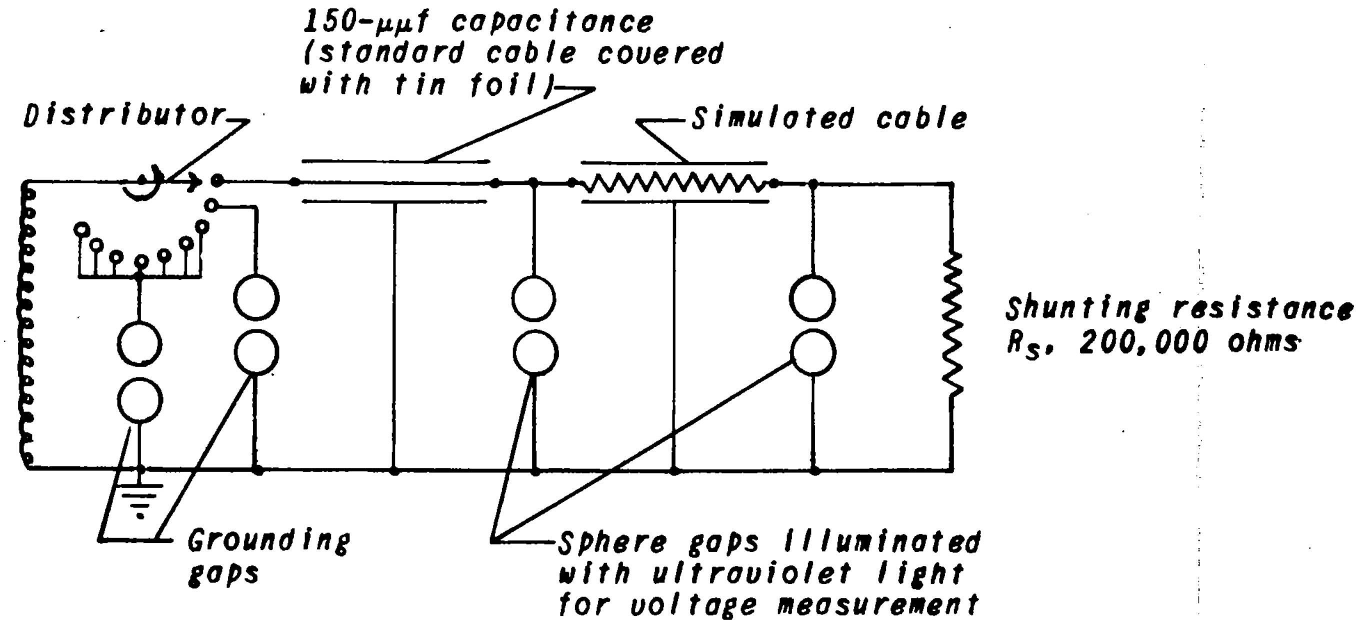



Figure 15. - Circuit diagram of test setup used to determine the optimum conductor diameter for 14-inch length of conducting-rubber cable.

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

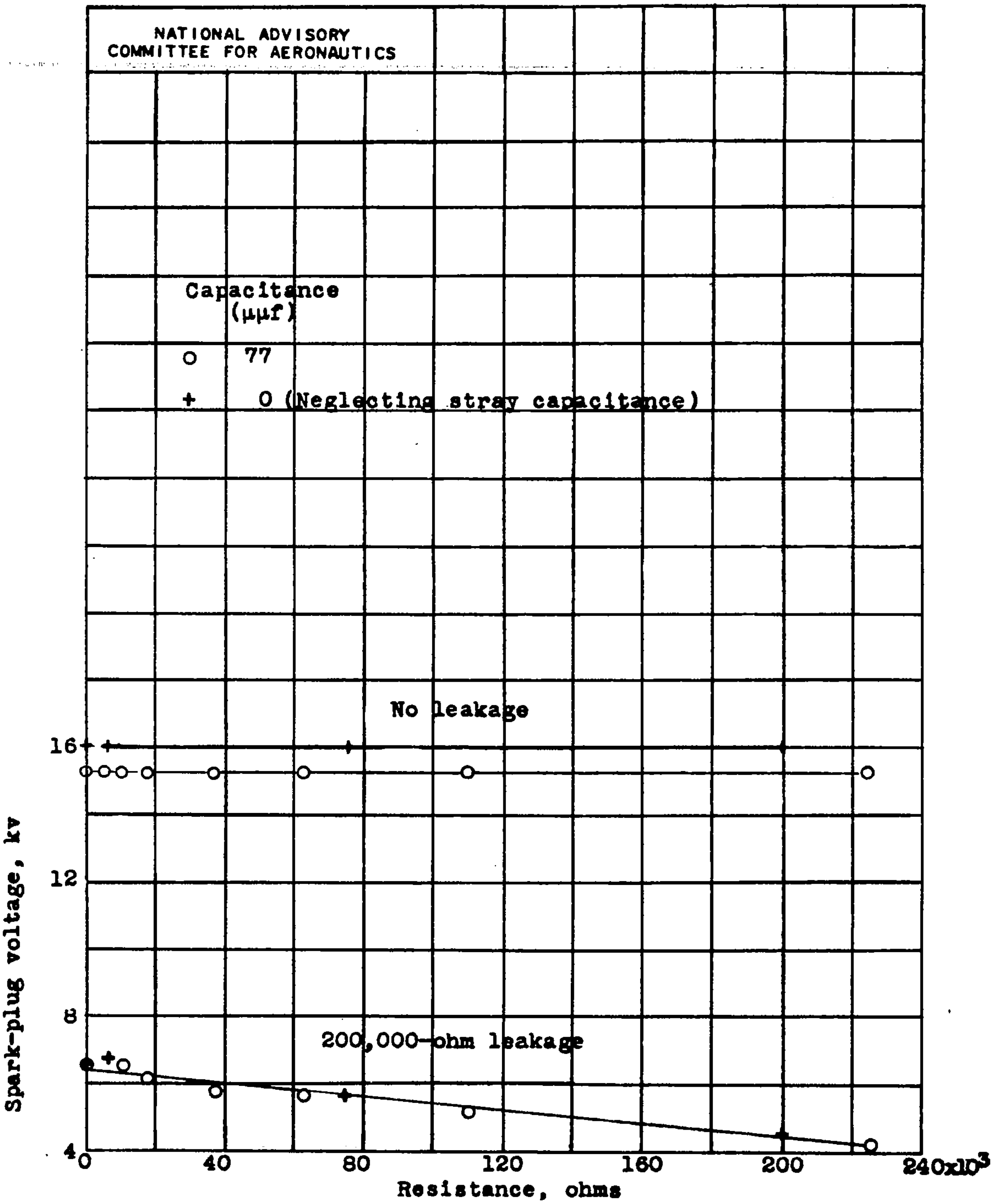



Figure 16. - Effect of various values of resistance and capacitance of simulated cable on the spark-plug voltage.

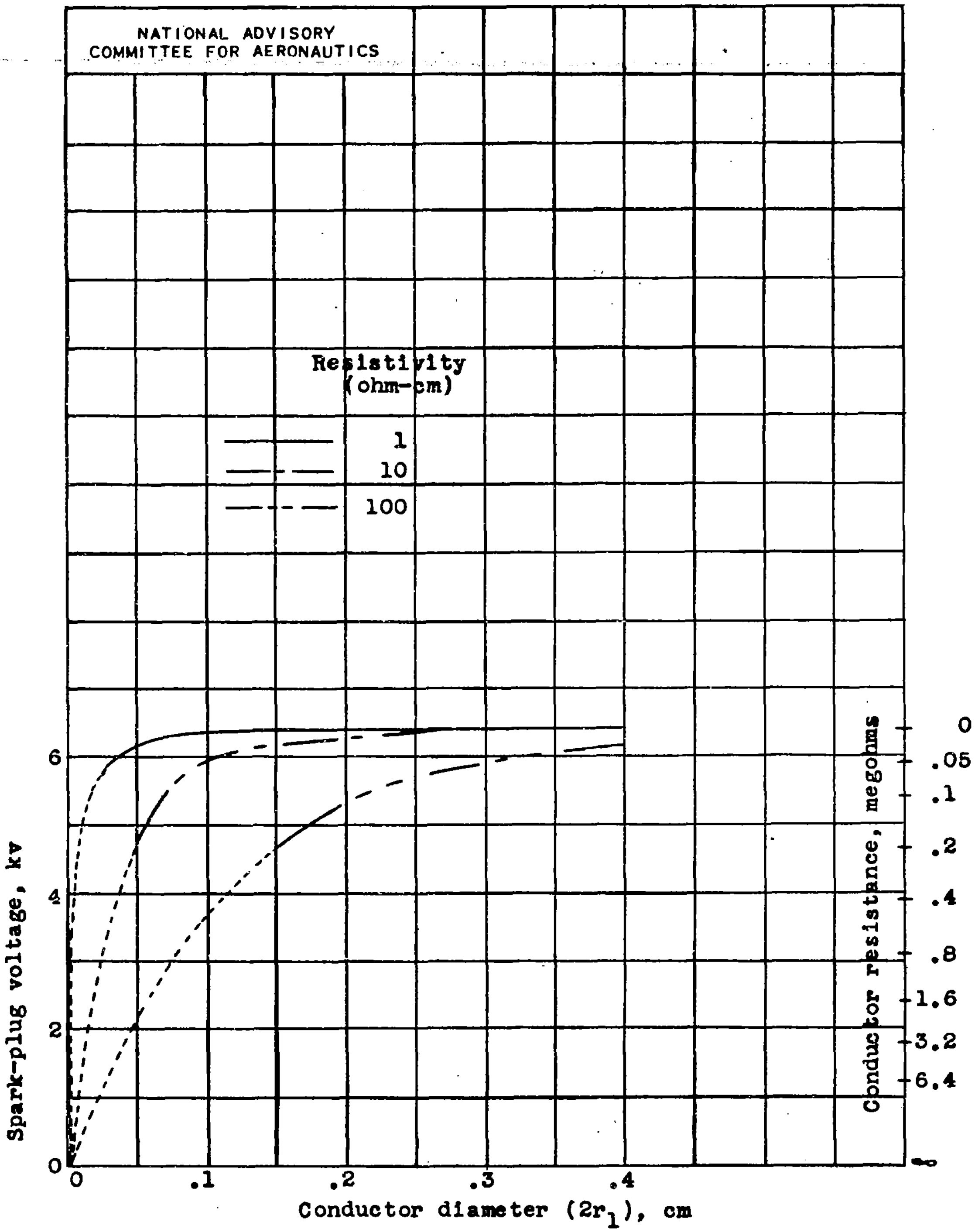



Figure 17. - Effect of conductor diameter on spark-plug voltage for various resistivities of conductor. (Determined from 200,000-ohm leakage curve of fig. 16.)

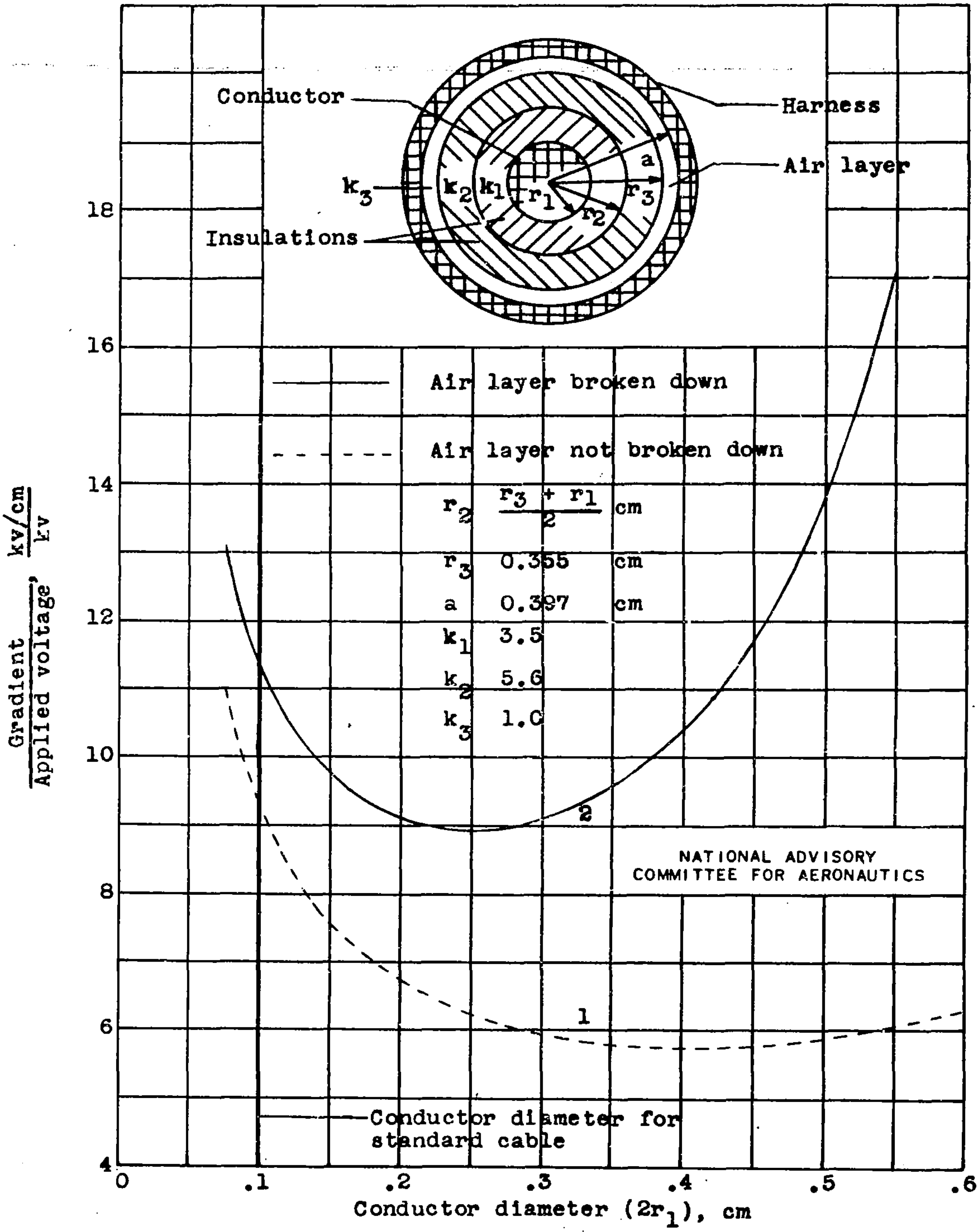



Figure 18. - Gradient at surface of conductor of 7-millimeter ignition cable plotted as a function of conductor diameter.

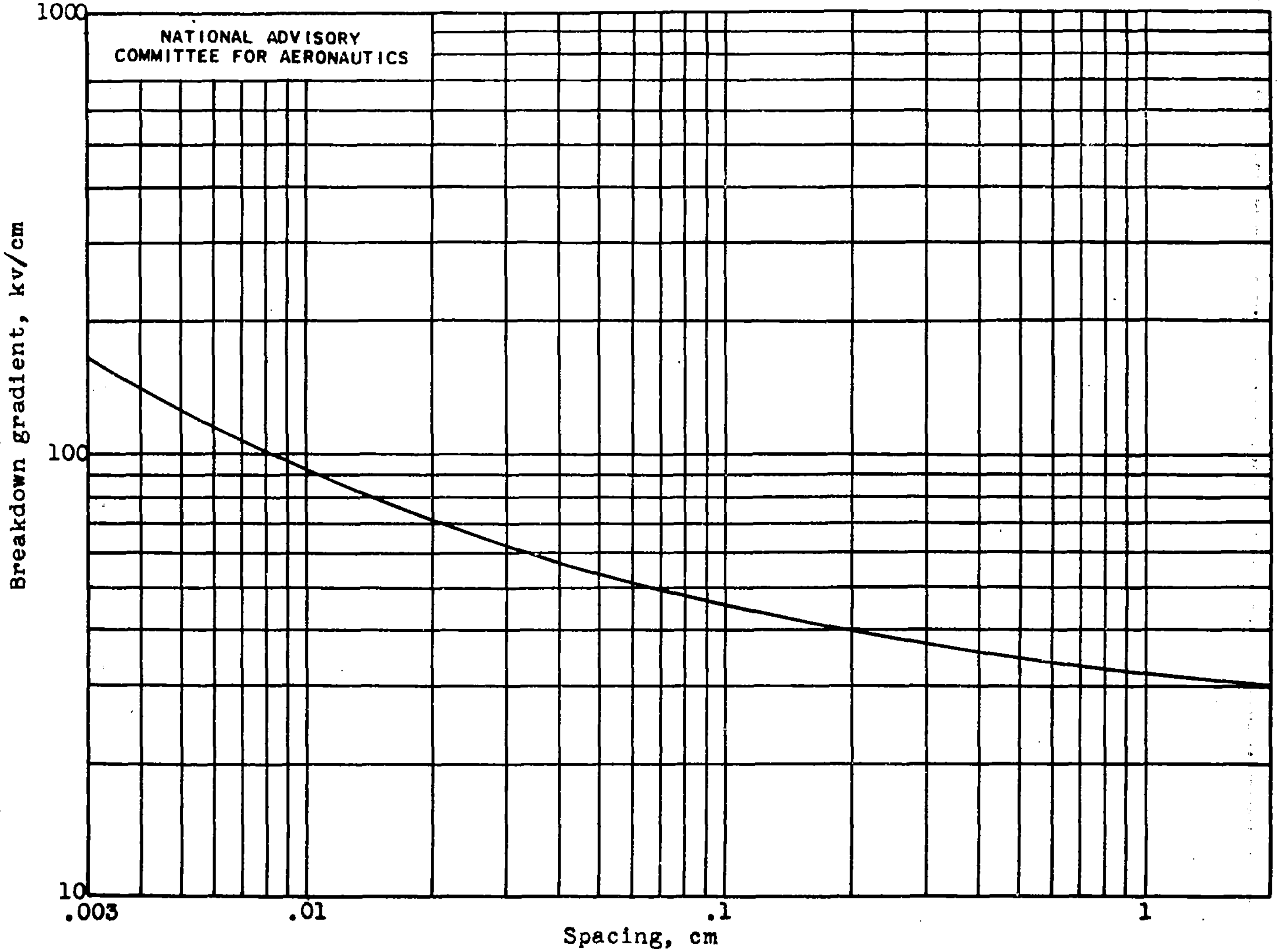



Figure 19. - Effect of electrode spacing on breakdown gradient of air in uniform field as determined by Paschen's law. Absolute pressure, 760 millimeters mercury. (Data derived from references 4 and 5.)