High voltage flashover of insulating barriers

by Paul Uhlrich

A THESIS Submitted to the Graduate Committee in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

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Many investigation of high-voltage flashover in air have been recorded in the literature. Studies of various standard configuration such as rod gaps, needle gape, sphere gape, needle point to plane, sphere to plane, etc. are numerous. Studies of corona discharge, insulation creep age properties, and the potential breakdown of gases have been made under various conditions of pressure, temperature, and humidity. This paper is offered as an extension of these data to include the study of air breakdown over insulating barriers.

This paper presents information concerning the use of insulating barriers between adjacent live terminals or between a live terminal and ground. Curves are included showing the effect of various barriers upon d-c flashover voltages for altitudes up to 80,000 feet. Similar curves show the effect of 60-cycle a-c flashover voltages for altitudes up to 100,000 feet. High altitude conditions were simulated in the laboratory by use of a vacuum chamber. All tests were performed using the same insulating material (black laminated micarta) for the test blocks. This report is intended to determine the comparative effectiveness of various barriers; no attempt is made here to study the properties of insulating materials.

The necessity for adequate spacing between terminals of electrical equipment is fundamental. Sparkover between terminals or to ground normally causes the arcing part to fail with resulting circuit malfunction. Protection against sparkover is especially important in the design of aircraft electrical units because circuit failure in flight may be costly. The use of insulating barriers between points at different potential provides protection against sparking with small sacrifice of space and weight.

HIGH VOLTAGE FLASHOVER OF INSULATING BARRIERS

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A THESIS

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Dean, Graduate Division

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Paul E. Uhlrich

ABSTRACT

Many investigations of high-voltage flashover in air have been recorded in the literature. Studies of various standard configurations such as rod gaps, needle gaps, sphere gaps, needle point to plane, sphere to plane, etc. are numerous. Studies of corona discharge, insulation creepage properties, and the potential breakdown of gases have been made under various conditions of pressure, temperature, and humidity. This paper is offered as an extension of these data to include the study of air breakdown over insulating barriers.

This paper presents information concerning the use of insulating barriers between adjacent live terminals or between a live terminal and ground. Curves are included showing the effect of various barriers upon d-c flashover voltages for altitudes up to 80,000 feet. Similar curves show the effect of 60-cycle a-c flashover voltages for altitudes up to 100,000 feet. High altitude conditions were simulated in the laboratory by use of a vacuum chamber. All tests were performed using the same insulating material (black laminated micarta) for the test blocks. This report is intended to determine the comparative effectiveness of various barriers; no attempt is made here to study the properties of insulating materials.

The necessity for adequate spacing between terminals of electrical equipment is fundamental. Sparkover between terminals or to ground normally causes the arcing part to fail with resulting circuit malfunction. Protection against sparkover is especially important in the design of aircraft electrical units because circuit failure in flight may be costly. The use of insulating barriers between points at different potential provides protection against sparking with small sacrifice of space and weight.

INTRODUCTION

The major portion of this paper deals with the breakdown of dry air. The effect of humidity upon air breakdown has been reported in previous literature.[1,2] Some tests were made with saturated air (with and without moisture condensation on the test block) and the results seem to verify the conclusions of these writers. A qualitative study of the influence of ozone upon air breakdown is included.

For convenience, breakdown voltages are plotted here as a function of altitude. All curves are based on the United States standard atmosphere as established by the National Advisory Committee for Aeronautics.[3,4]

As seen in Figure 1, the temperature of the standard atmosphere decreases linearly with altitude from sea level to 35,000 feet and is isothermal at -67^{o}F. from 35,000 feet to 105,000 feet. Since the data used here were taken at room temperature, correction is required in order to correlate these data with standard temperature conditions. At each

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1. Berberich, L.J., Moses, G.L., Stiles, A.M., Veinott, C.G. EFFECT OF ALTITUDE ON ELECTRIC BREAKDOWN AND FLASHOVER OF AIRCRAFT INSULATION. AIEE Transactions, Volume 63, 1944, pages 345-53.

2. Delerno, M.J. POTENTIAL BREAKDOWN OF SMALL GAPS UNDER SIMULATED HIGH-ALTITUDE CONDITIONS. AIEE Transactions, Volume 63, 1944, pages 109-12.

3. National Advisory Committee for Aeronautics, Technical Report No. 538, 1935. ALTITUDE-PRESSURE TABLES BASED ON THE UNITED STATES STANDARD ATMOSPHERE.

4. NACA Technical Report No. 837 and Supersonic Aerodynamics Handbook. STANDARD ALTITUDE TABLE.

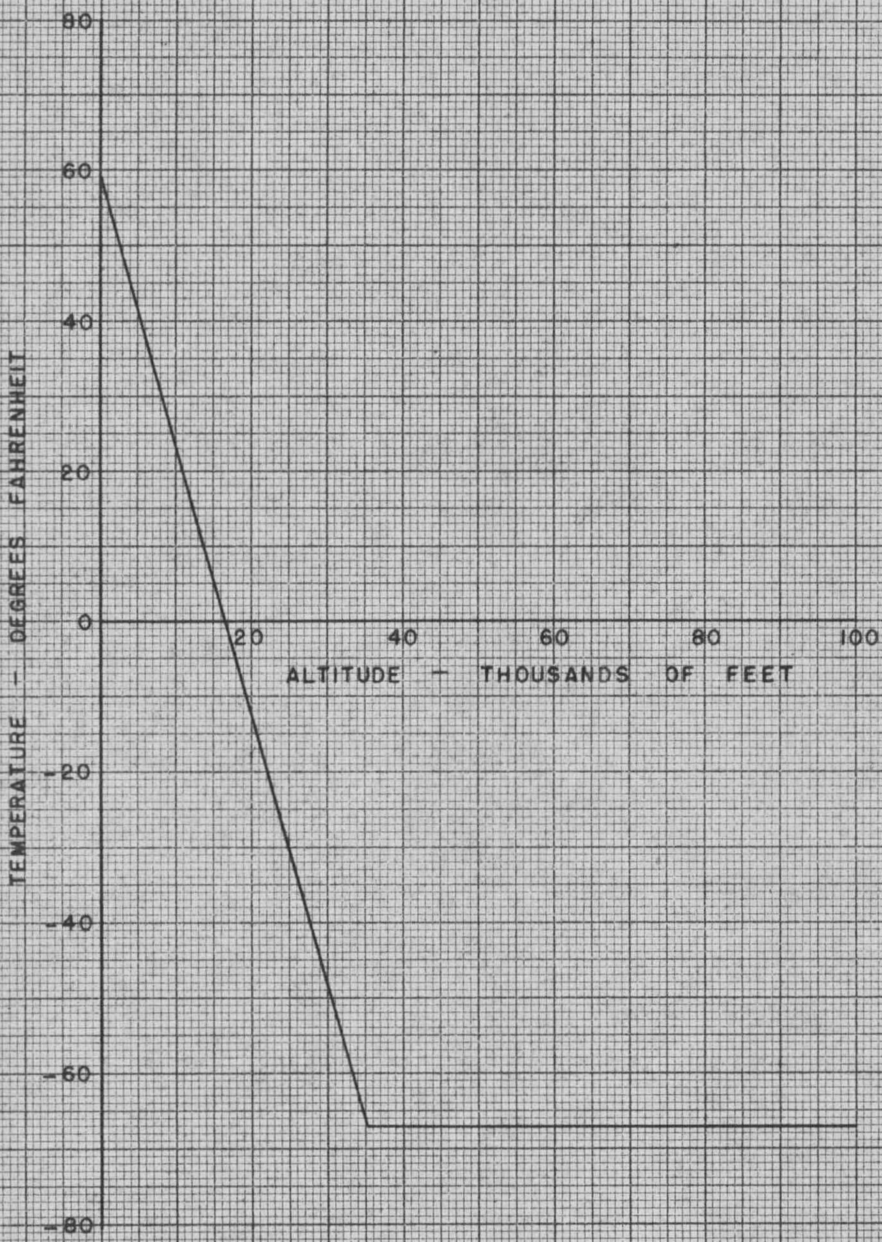

FIG. I

ALTITUDE VS. TEMPERATURE CURVE

BASED ON

UNITED STATES STANDARD ATMOSPHERE

data point, the density of the air in the evacuation chamber was calculated from temperature and pressure readings according to the formula:

$$\text{Density of Dry Air} = \frac{0.205}{1 + 0.00367\ t}\ \frac{P}{76}$$

Density in pounds per cubic feet

P in inches of mercury

t in degrees centigrade

The air density was converted to the corresponding altitude by use of the NACA density-altitude relationship (Figure 2) which is calculated from the standard atmosphere tables.[1,2] Therefore, at each set of readings, the density of the air in the evacuation chamber is equivalent to the density of the air at the specified altitude under standard atmospheric conditions. See Appendix I for a sample reduction of laboratory data to the standard atmosphere.

This method of temperature correction is based on the assumption that the potential breakdown of air at a given pressure is dependent upon air temperature only insofar as the temperature influences the air density. The validity of this assumption may be proved from Paschen's law which is fundamental for all work related to gaseous breakdown. Paschen's Law states that the sparking potential of a gas is a function

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1. National Advisory Committee for Aeronautics, Technical Report No. 538, 1935. ALTITUDE-PRESSURE TABLES BASED ON THE UNITED STATES STANDARD ATMOSPHERE.

2. NACA Technical Report No. 837 and Supersonic Aerodynamics Handbook. STANDARD ALTITUDE TABLE.

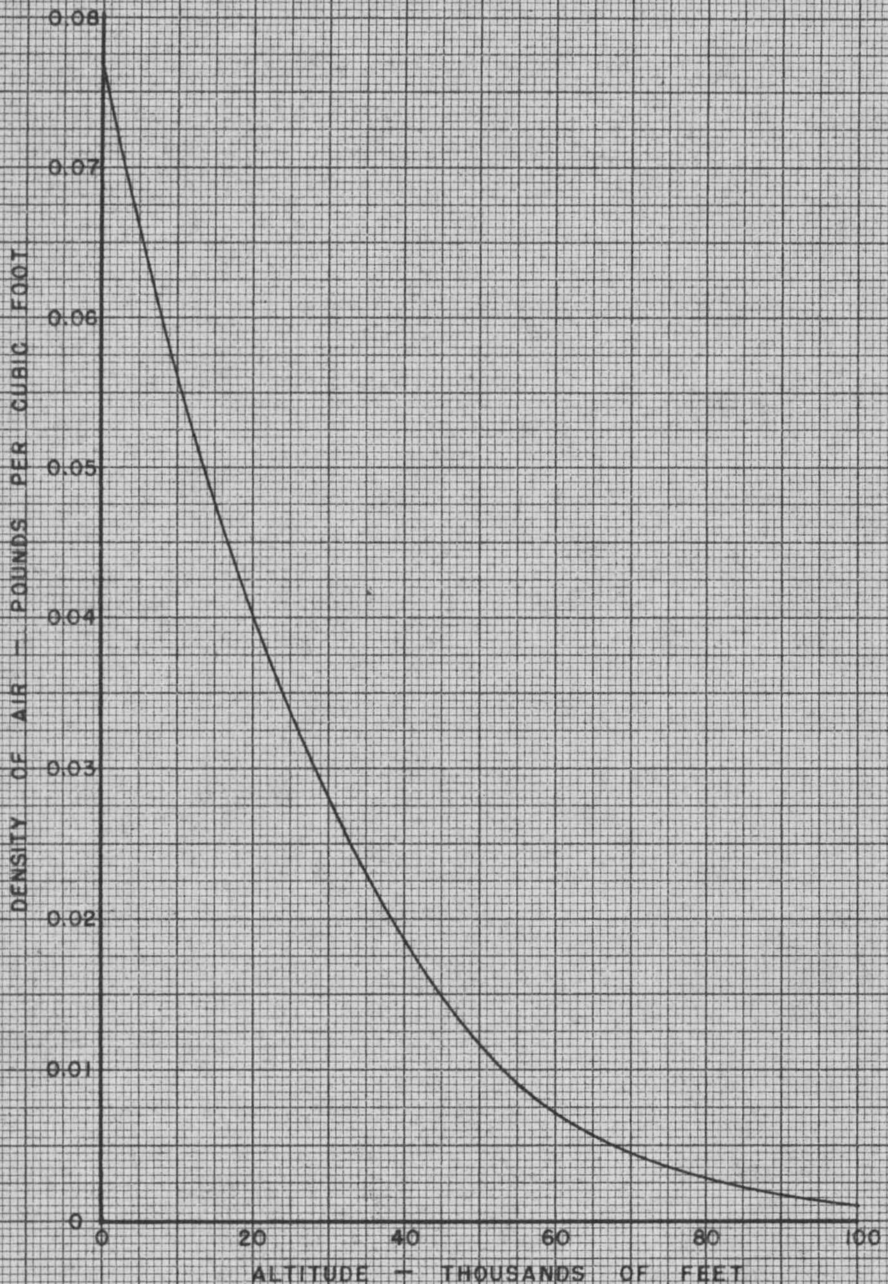

FIG. 2
DENSITY OF DRY AIR VS. ALTITUDE
BASED ON
UNITED STATES STANDARD ATMOSPHERE

only of the product of the sparking distance and the pressure of the gas (constant temperature) or, in other words, the mass of the gas between the electrodes.[1] That is, for constant temperature,

$$\text{Breakdown voltage} = K_1 \text{ (pressure x electrode spacing)}$$

where the constant K_1 is dependent upon the units chosen. The actual mass of the gas between terminals is proportional to the density of the gas which is a function of temperature as well as pressure. A more convenient statement of Paschen's Law would involve sparking distance and density of the gas as independent variables rather than sparking distance and gas pressure:

$$\text{Breakdown voltage} = K_2 \text{ (density x electrode spacing)}$$

Therefore, for a given electrode-barrier configuration, the sparking potential of a gas is a function only of the density of the gas.

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1. Knowlton, A.E. STANDARD HANDBOOK FOR ELECTRICAL ENGINEERS. Seventh Edition, 1941, Section 4-654, page 405.

TEST EQUIPMENT

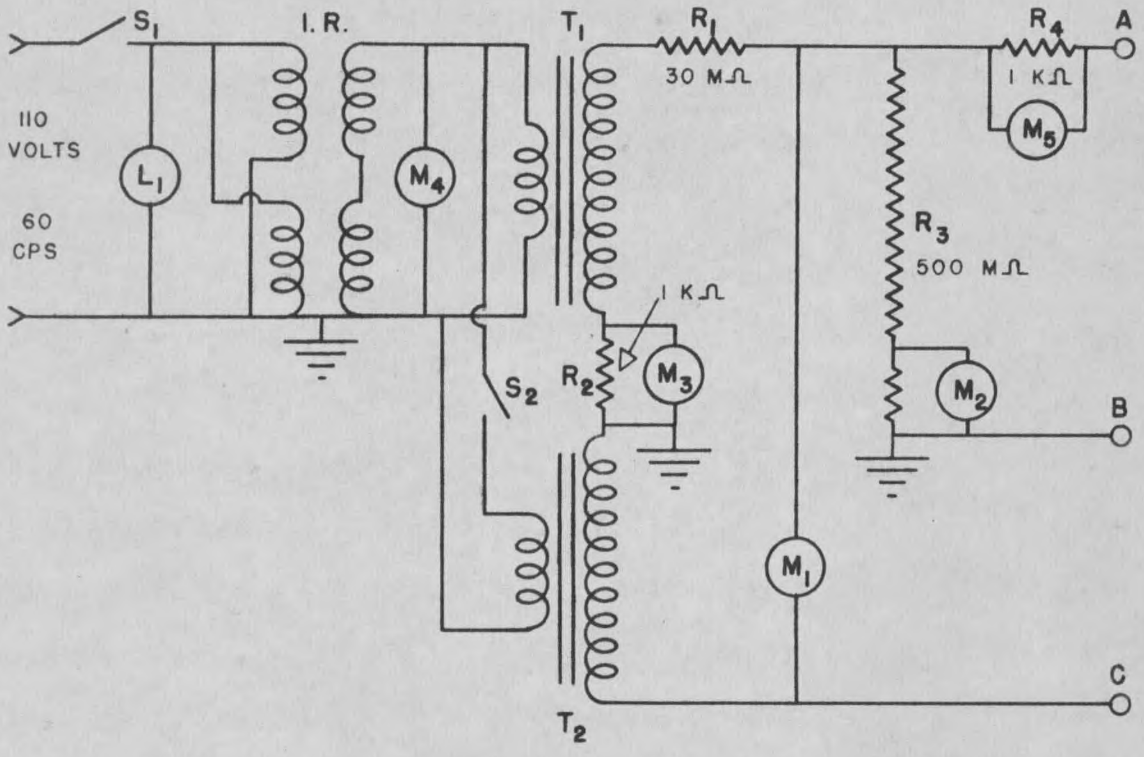
The vacuum equipment used in these tests consisted of a bell jar, rotary vacuum pump, mercury manometer, drying train, and thermometer. The bell-jar base was made of one-inch black laminated micarta with six terminal studs sealed into the base. See Photograph 122030. High-voltage tests showed the leakage current between studs to be negligible. The bell jar was sealed to the micarta base with a vacuum wax.

The air introduced into the bell jar was dried by passing it slowly through a two-stage silica gel drying train. This method of drying the air was quite effective. To prove this, the entire evacuation chamber, highly evacuated, was placed inside a cold chamber. The chamber was cooled to -75°F and allowed to soak for several hours. When dried air at room temperature (70°F) was released into the chamber, no visible condensation resulted in the bell jar. Thus, the indicated relative humidity was less than one percent.

A standard U-tube mercury manometer was used for most of the d-c tests. One tube of the manometer was exposed to the atmosphere and required correction for barometric pressure. An accuracy of plus or minus 2,000 feet is expected for the U-tube manometer for altitudes up to 80,000 feet. A Wallace and Tiernan reservoir-type manometer (type FA 135) became available for the a-c tests. See Photograph 122029. With this instrument, altitudes may be determined to an accuracy of plus-or-minus 1,000 feet up to 100,000 feet. It was set up as a mercury barometer with one outlet sealed. Consequently, this manometer system was independent of the barometric pressure.

A Takk Corporation model 56 high-voltage insulation tester was used to determine d-c breakdown voltages. See Photograph 122028. The tester will supply up to 15 kilovolts d-c and is provided with a 1.5 and a 15 kilovolt scale. Corrected voltmeter readings are considered to be within plus-or-minus 3 percent of full-scale value. An ammeter with 100 and 500 microampere ranges is included to indicate the current supplied by the instrument. The output of the tester was connected to the test terminals without series resistance. The high regulation of the instrument prevented destruction of the test blocks except for a condition of prolonged arcing. The Takk tester has two limitations for this type of work. First, it is unable to supply top-scale voltages in cases where 300 to 500 microamperes of corona current flow before arcing occurs. Second, the d-c voltage waveform supplied when using the 1.5-kilovolt scale has a strong a-c component. The peak of the waveform was found to be 13 percent higher than the voltmeter indication in the upper half of this low scale. Since it is the peak voltage which determines the point of breakdown, all readings obtained on the 1.5-kilovolt scale are corrected with a multiplying factor of 1.13. The readings obtained from this scale may be distinguished from high-scale readings because only low-scale readings are recorded with two decimal places.

The circuit of Figure 3 was used for the a-c breakdown tests. See also Photograph 122029. Two 115/11500-volt potential transformers were used with the high-voltage windings in series. A continuously-



I. R.	INDUCTION REGULATOR	S_1 & S_2	TOGGLE SWITCH
L_1	INDICATOR LAMP	T_1 & T_2	POTENTIAL TRANSFORMER

M_1 CREST VOLTMETER, 0 – 30 KV. PEAK

M_2 VACUUM TUBE VOLTMETER, 0 – 5 KV. PEAK (WHEN USED WITH R_3)

M_3 VACUUM TUBE VOLTMETER, 0-0.3-1.0 MA. (USED WITH R_2 AS SHUNT)

M_4 VOLTMETER, 0 - 150 VOLTS RMS

M_5 VACUUM TUBE VOLTMETER, 0-0.3-1.0 MA. (USED WITH R_4 AS SHUNT)

TERMINALS A AND C USED WITH METER M_1 (S_2 CLOSED)

TERMINALS A AND B USED WITH METER M_2 (S_2 OPEN)

SEE PHOTOGRAPH 122029 AND APPENDIX II FOR DETAILS.

FIG. 3

CIRCUIT DIAGRAM FOR A-C TEST EQUIPMENT

variable range of voltage up to 30 kilovolts was obtained by using an induction regulator in the primary circuit of the transformers. A 30-megohm series resistance (R_1) was used to prevent destructive arcing at the test terminals after breakdown. This required a very low-current measuring device in order that the drop across the current limiting resistance be a minimum.

A General Electric Type A3 Crest voltmeter (M_1) was used to measure the alternating voltage applied to the terminals. See Photograph 46859-B for panel view of this meter. The maximum voltage which may be measured by this instrument is 30 kilovolts and its nominal input impedance at 60 cycles is about 250 megohms. Local calibration of the meter was not possible, but an accuracy of plus-or-minus 3 percent of full-scale value is claimed by the manufacturer. The meter is battery-operated which permitted the "ground" terminal (and case of the meter) to have a high potential with respect to actual ground potential. The meter was insulated from ground and isolated physically to avoid human contact while in use.

Readings below 5 kilovolts on this meter were not considered to be sufficiently accurate for these tests, so a second metering circuit was prepared to obtain more accurate readings in this range. The test circuit was arranged so that one or both of the transformers might be used. Transformer T_2 could be removed from the circuit by opening switch S_2 and grounding one terminal of the test block. With one test terminal grounded, a potential divider circuit (R_3) and vacuum tube voltmeter (M_2)

could be calibrated to measure voltage. The divider circuit consisted of 52 10-megohm resistors in series and effected a 1000 to 1 step-down ratio. After calibration this arrangement was known to be accurate within plus-or-minus 3 percent of its full-scale value. The vacuum tube voltmeter leads and divider resistances were shielded. The current supplied by the transformers was determined from the reading of voltmeter M_3 across R_2. The current flow to the test block was measured by voltmeter M_5 across R_4. Appendix II contains a list of the equipment used.

The test blocks were made of one-inch black laminated micarta with from two to four insulating barriers milled into each block. See Photographs 122031, 122032, and 122033. With this method, the barriers are an integral part of the block. Each barrier was designed so that the breakdown path around the end of the barrier was longer than the breakdown path over the top of the barrier. Therefore, all arcing occurred over the top of the barrier. A list of the test blocks used is given in Appendix III.

The brass electrodes were chosen as a compromise of the various configurations used in aircraft electrical equipment. All terminals were cut from one-eighth-inch brass stock plates. The ground terminals were one-fourth inch wide and four inches long. The high voltage terminals were one-fourth inch wide and one inch long. On most of the test blocks, flat-head screws and round-head screws were used at opposite ends of each barrier. All terminals were cleaned with fine-grain emery paper before they were mounted on the test block. The terminals and barriers were washed with lacquer thinner before they were used in a test.

TEST PROCEDURE

The following procedure was used in preparing the vacuum chamber and test block for each test. The chamber was evacuated for several minutes until the absolute pressure was about 3mm. of mercury. Then dry air was slowly released into the chamber for a time, shut off for re-evacuation, and released into the chamber a second time. After a third evacuation of the chamber, a valve in the pump line was closed and the vacuum pump turned off. Readings were taken first at low pressure (high altitude simulated) and repeated in steps for higher pressures (lower altitudes) by letting in additional dry air at intervals. This procedure reduced any error due to leakage of the vacuum system by firmly seating the bell jar before data is taken. It also assured the presence of some fresh air, not yet ionized by breakdown, at each data point.

The method used for saturating the air in the chamber was more difficult to control. The drying train was replaced by a bottle of warm water. With minimum pressure in the chamber, air was released slowly through the water into the chamber. The incoming moist air was warmer than the bell jar so that some condensation would occur on the inside surface of the jar. The system was then allowed to reach equilibrium at room temperature. The resulting humidity was considered to be near saturation provided that some condensed moisture was still visible in the bell jar. By proper control of this operation, moisture could be condensed on the barrier and terminals under test or the test block could be left visibly dry with saturated air in the bell jar. No experimental determination of the relative humidity of the air was attempted here. It is readily conceded that the procedure used for the saturated air tests could be refined considerably, but the results desired here were qualitative in nature and intended only as corroboration of similar work already published.

In all tests, the breakdown voltage was considered to be the minimum potential required for a visible arc to jump repeatedly from terminal to terminal. However, corona-starting voltages were recorded in many cases in addition to the voltage required for complete air breakdown. Breakdown sometimes occurred at voltages 5 to 10 percent lower than the value recorded, but these were considered to be false points. These points may be accounted for in part by an analysis of the Takk tester circuits. The direct voltage is obtained from a 0.02 microfarad condenser which acquires additional charge each half-cycle from the secondary winding of a high-voltage transformer. Rectifying action of two type 60.8 cold-cathode tubes prevents discharge of the condenser back through the transformer winding. If the tester voltage is held at a certain value, the output d-c voltage will be steady because the condenser will be charged to the peak value of the a-c wave supplied by the transformer. While the output voltage is being increased to obtain a point of data, the output waveform will include some a-c ripple. The peaks of the a-c component cause breakdown, while the d-c meter indicates an average voltage. To obtain a reading, it was necessary to increase the voltage to the point of arcing, note the approximate breakdown voltage, and then approach the point more slowly to obtain a more accurate reading. For this reason, the breakdown voltage was chosen as the lowest voltage which would cause repeated arcing at the test block with no change in the voltage adjustment. Each point was determined several times to verify the final breakdown point.

The rate of increase of voltage was not accurately controlled in this work. The d-c voltage was controlled by manual adjustment. The rate of increase of voltage for final adjustment was no more than 100 volts per second. The a-c voltage was controlled by manual adjustment of the induction regulator. As an estimate, the rate of increase of a-c voltage was 300 to 500 volts per second. The relative importance of this factor was investigated for the a-c equipment by "soaking" the test configuration at a voltage slightly under the value required for breakdown. Results indicate that the effect of the time of voltage application is too small to be significant in these tests. In addition, it is considered here that voltages high enough to cause breakdown in aircraft systems will most likely be transients or peaks of relatively short duration.

Howell[1] has shown that the surface condition of the electrodes is an important factor in the study of air breakdown. Roughened electrodes lower the breakdown voltage considerably in comparison to highly-polished smooth electrodes. The breakdown voltages obtained with smooth

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1. Howell, A.H. BREAKDOWN STUDIES OF COMPRESSED GASES. AIEE Transactions, Volume 58, 1939, May Section, pages 193-206.

polished electrodes are too high for application to practical electrodes. In addition, Howell points out that more consistent results can be obtained after the electrodes are conditioned. The conditioning process consists of repeated arcing between electrodes to burn off small points or ridges which may influence the point of breakdown. As mentioned previously, the electrodes used in this investigation were cleaned with fine-grain emergy paper and washed in lacquer thinner to remove any surface film. The electrodes used here were not highly polished and screws were used in the electrodes to obtain a more practical electrode configuration. Each configuration was arced several times before actual test in an attempt to condition the electrodes. It is believed that the results obtained here will be directly applicable to many practical electrode-barrier configurations.

Before barrier studies were begun, preliminary tests were made using test block B-1 shown in Photograph 122032. These tests afforded the author a period of familiarization with the test equipment and procedure while attempting to correlate this data with corresponding values recorded in the literature. Test Block B-1 was assembled to compare with the electrode configuration used by Berberich, Moses, Stiles, and Veinott.[1] The comparison of the two sets of data is shown in Figure 4. The breakdown values obtained here were slightly lower than those reproduced from the literature, but since the curves were on the safe side and reasonably

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1. Berberich, L.J., Moses, G.L., Stiles, A.M., Veinott, C.G. EFFECT OF ALTITUDE ON ELECTRIC BREAKDOWN AND FLASHOVER OF AIRCRAFT INSULATION. AIEE Transactions, Volume 63, 1944, pages 345-53.

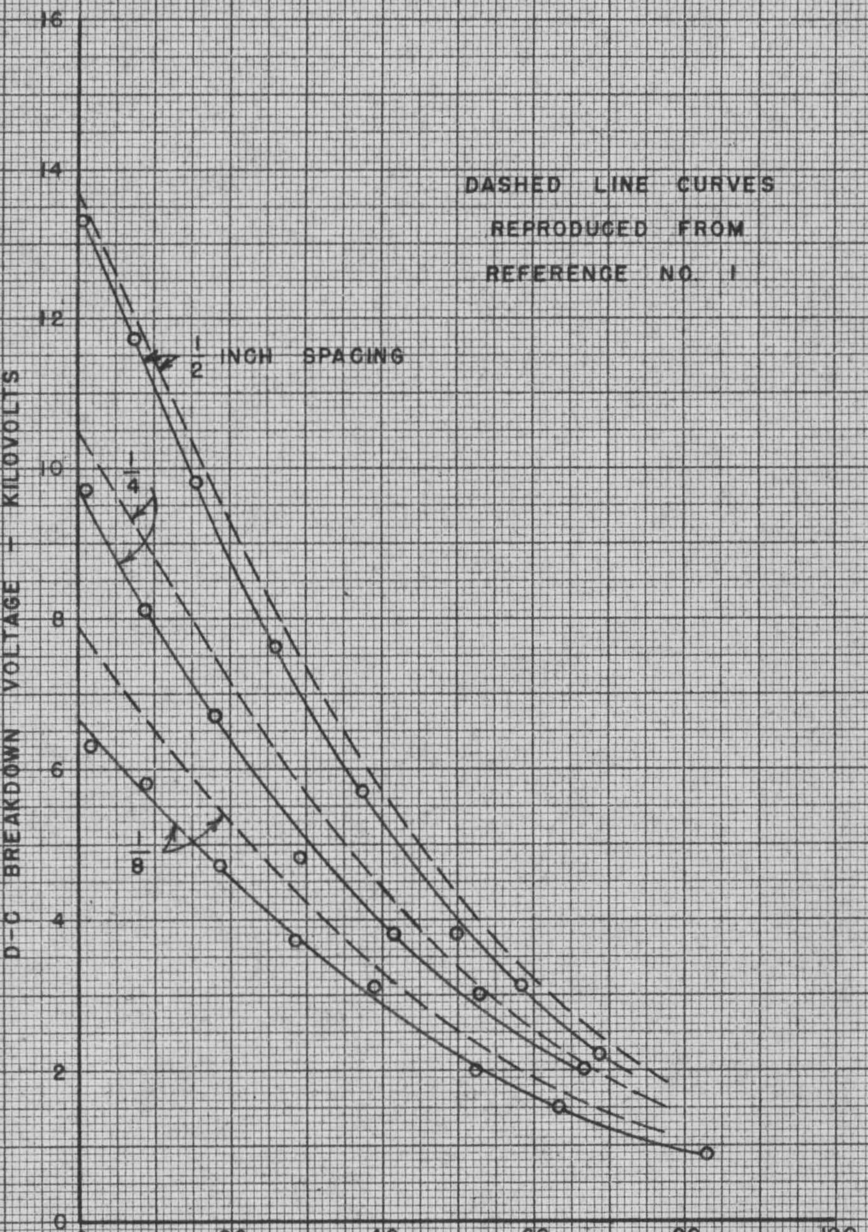

FIG. 4
D-C BREAKDOWN VOLTAGE VS. ALTITUDE
FOR SQUARE ELECTRODES

consistent, the study of barriers was initiated without further preliminary work.

PRELIMINARY DISCUSSION

In the discussion which follows, the terms "creepage distance" and "clearance distance" will be used according to the following definitions. Creepage distance is the shortest distance from electrode to electrode measured along the surface of the insulating material. Clearance distance is the shortest path in air from electrode to electrode.[1] See Table I for diagrams.

Many factors are known to influence the breakdown of gases under dielectric stress. In addition to the electrode spacing and the gas density, the breakdown voltage is dependent upon the gas itself; the electrode metal; the surface condition and the configuration of the electrodes and barrier (if any); the frequency, waveshape, and rate of increase of the voltage used. It is likely that the material of the insulating barrier will also have some effect upon the breakdown of the gas surrounding the barrier. All of these factors are controlled by the choice of test equipment, test procedure, and the design of the test blocks.

The test blocks were designed such that four conditions of electrode and barrier configuration might be studied on a comparative basis:

(1) A series of barriers having the same thickness but different height. Electrodes were mounted flush against the barriers.

(2) A series of barriers having the same calculated creepage distance but different thickness and height. Electrodes were

1. AMERICAN STANDARD DEFINITIONS OF ELECTRICAL TERMS, AIEE. Section 20.10.415-420, page 85.

mounted flush against the barrier.

(3) A series of barriers having the same thickness and height. Electrodes were mounted at various positions parallel to the barrier.

(4) A study of the effect of different electrode shapes (the use of round-head and flat-head machine screws) using a given barrier.

BARRIERS OF SIMILAR THICKNESS

All barriers of the first series were 1/16 inch thick with height varying from 1/8 inch to 3/4 inch by increments of 1/16 inch. The brass terminals were mounted tight against the barrier in each case. Four of the test blocks of this series are shown in Photograph 122031. Figure 6 shows the d-c breakdown voltage vs. altitude curves obtained from these barriers. In order to compare creepage distance over barriers with plane-surface creepage distance, d-c breakdown tests were made using block B-7 shown in Photograph 122032. This block is equipped with a movable ground electrode so that the surface creepage distance could be adjusted as desired. The d-c breakdown voltage vs. altitude curves from this data are shown in Figure 5. These plane-surface breakdown curves compare favorably with the corresponding d-c curves seen above for the first series of barriers (Figure 6). The maximum difference between corresponding curves is apparent at 3/16 inch creepage distance. The d-c breakdown voltages for the 3/16 inch barrier are from 5 to 25 percent lower than the corresponding d-c breakdown voltages for 3/16 inch plane-surface creepage. For longer creepage distances, comparative breakdown voltages over the barriers are slightly higher at low altitudes and somewhat lower at high altitudes than those for plane surface creepage. It is well to note here that creepage distance and clearance distance are identical for these configurations. Thus a creepage (or clearance) distance measured over a barrier (with electrodes close to the barrier) will require nearly the same direct voltage for breakdown as a similar plane-

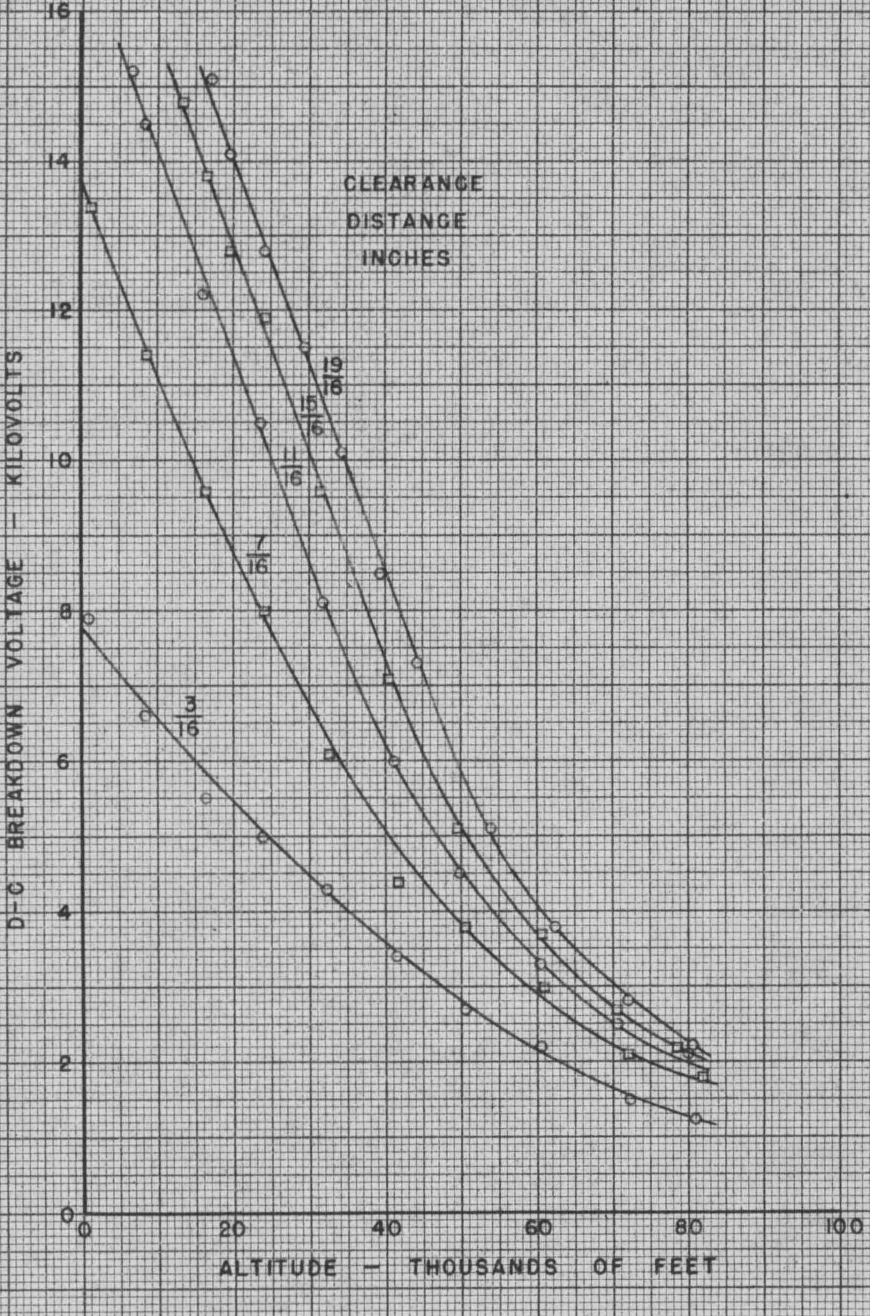

FIG. 5
D-C BREAKDOWN VOLTAGE VS. ALTITUDE
FOR PLANE-SURFACE CLEARANCE

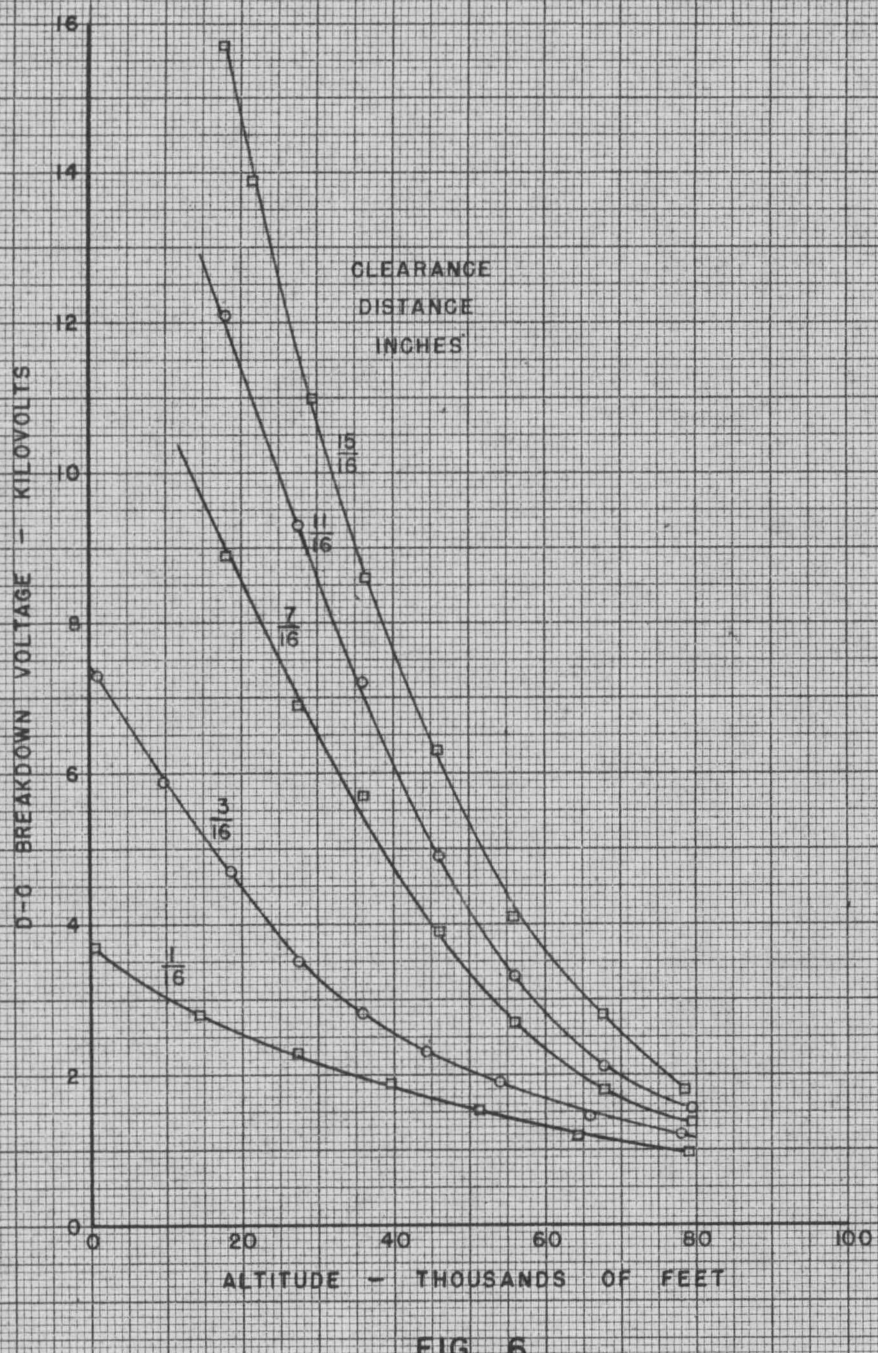

FIG. 6
D-C BREAKDOWN VOLTAGE VS. ALTITUDE
FOR BARRIERS $\frac{1}{16}$ INCH THICK

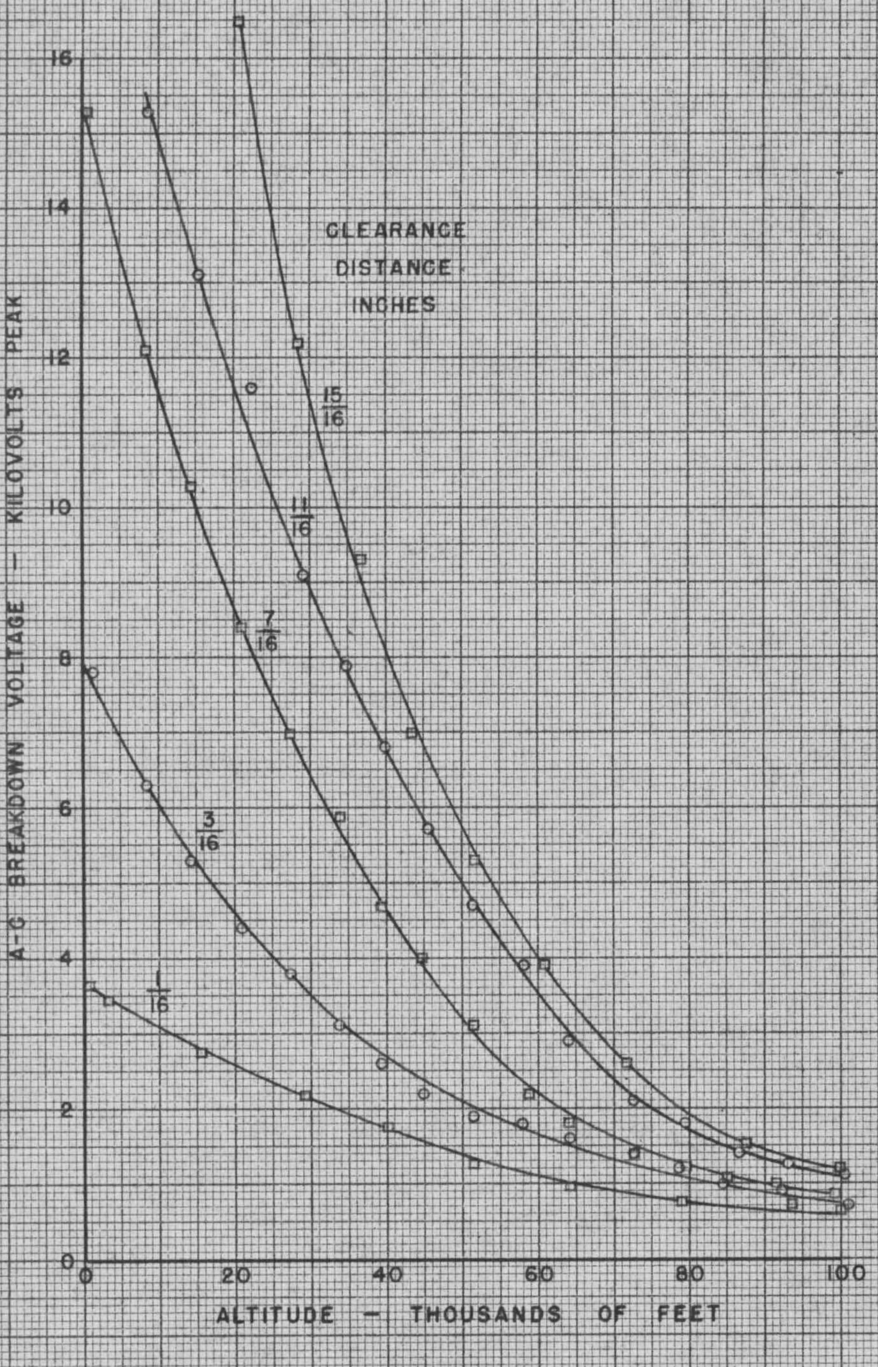

FIG. 7
A-C BREAKDOWN VOLTAGE VS. ALTITUDE
FOR BARRIERS 1/16 INCH THICK

surface creepage (or clearance) distance. For example, terminals (1/8 inch high), which must be separated 7/16 inch to meet breakdown requirements, will be adequately insulated by a 1/16 inch barrier which is 5/16 inch high.

Comparison of the d-c and a-c breakdown voltage vs. altitude curves in Figure 6 and 7 shows that the 60-cycle a-c peak voltage required to cause arcing over a given barrier is nearly the same as the d-c voltage necessary for sparkover under the same conditions. Therefore, it is concluded that d-c and a-c breakdown voltages are similar for the corresponding clearance distances used in this first series of barrier configurations.

The breakdown voltage vs. clearance distance curves shown in Figure 8, 9, and 10 were plotted from the breakdown voltage vs. altitude curves in Figures 5, 6, and 7 respectively. The breakdown voltage vs. clearance distance curves present the same data as the original curves, but lend themselves more readily to detailed analysis of the relative advantages of increasing clearance distance to meet breakdown voltage requirements. Examination of these curves reveals that as altitude increases, the slope of the curves decreases. This means, for example, that a given increase in the clearance distance in an attempt to meet voltage requirements is much less effective at higher altitudes. This phenomenon may be demonstrated most effectively with the curve in Figure 11. In this curve, the slopes of the respective curves in Figure 10 are plotted against altitude. This curve shows the increase of breakdown

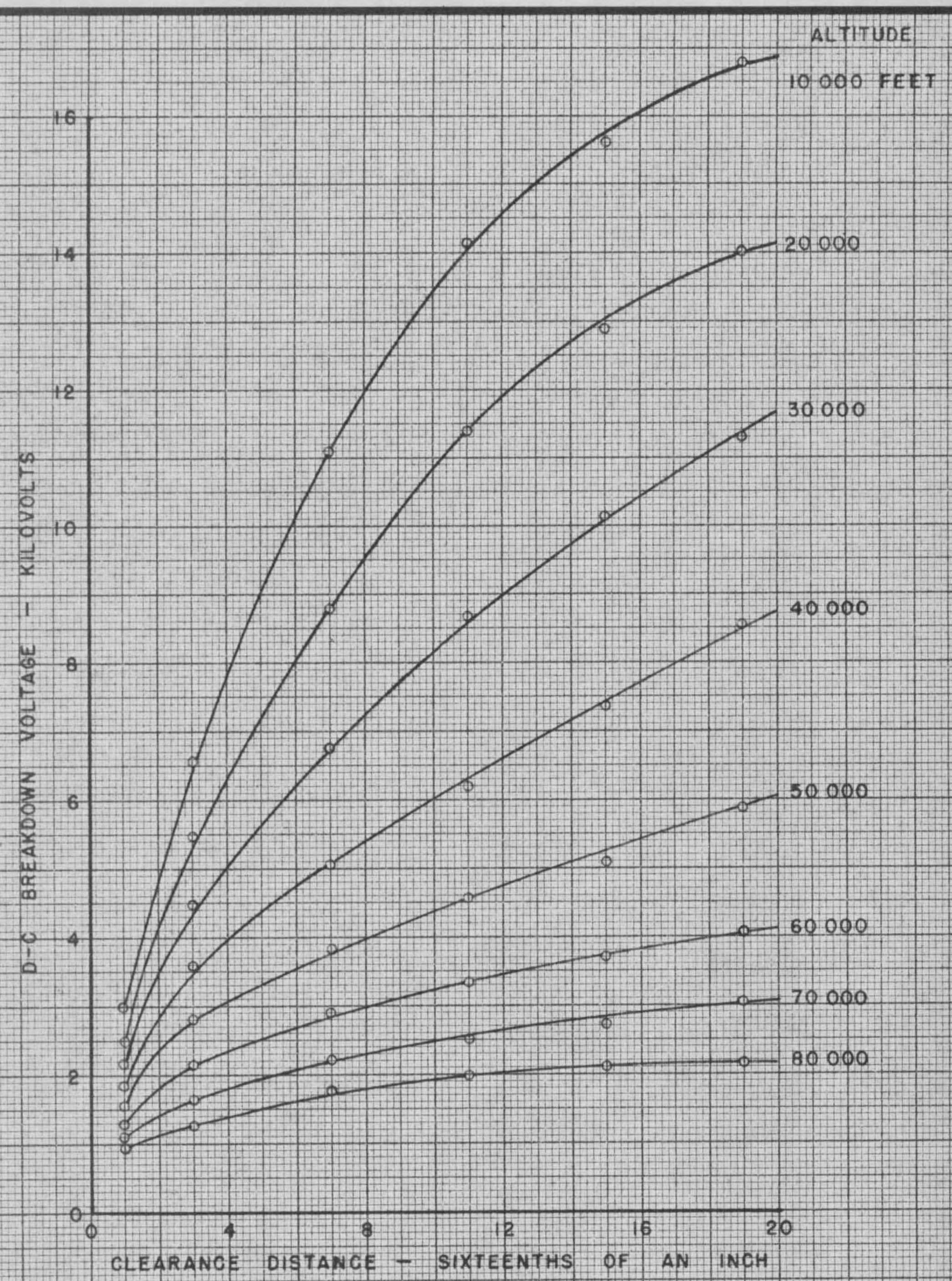

FIG. 8

D-C BREAKDOWN VOLTAGE VS. CLEARANCE

FOR PLANE-SURFACE CLEARANCE

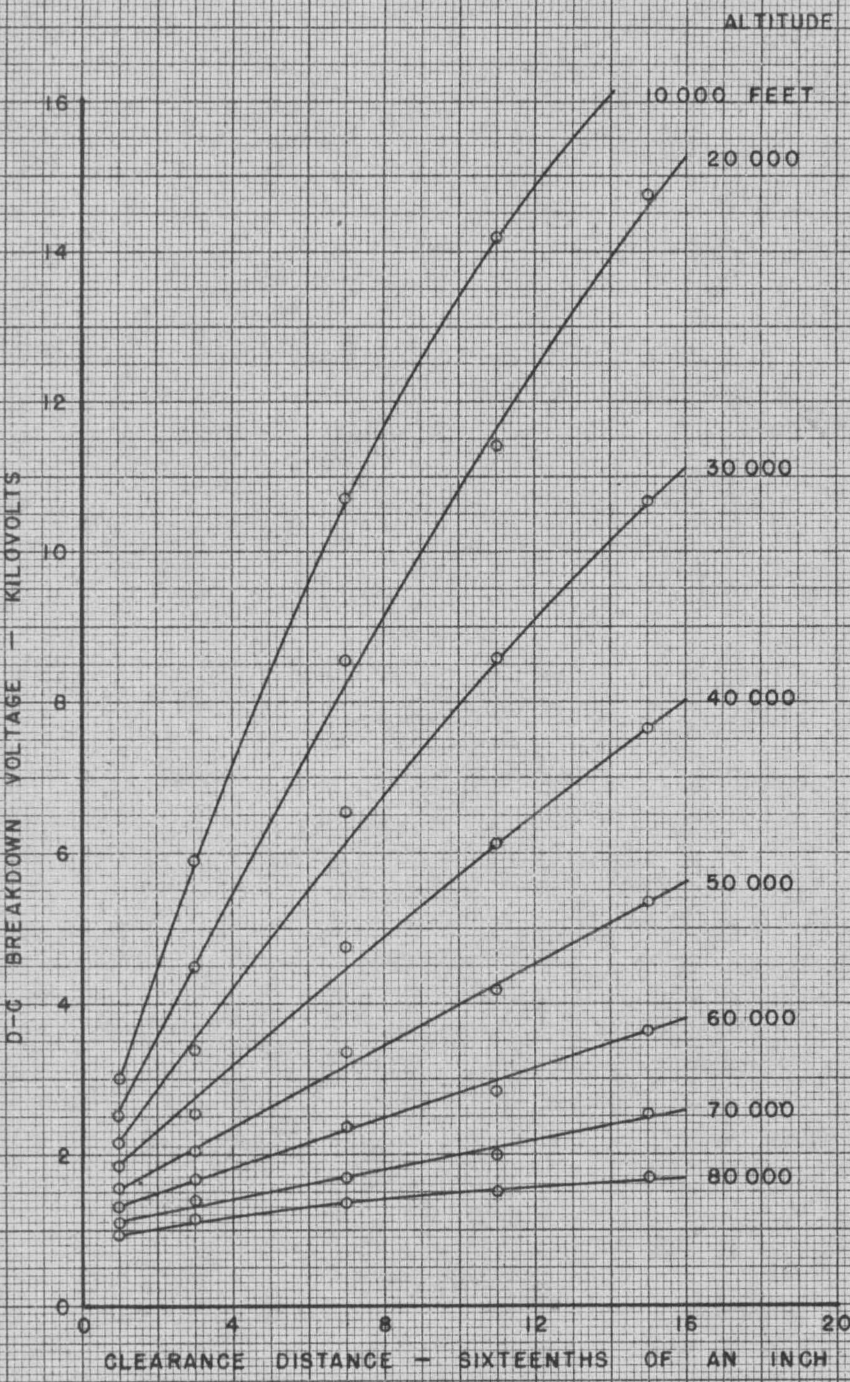

FIG. 9

D-C BREAKDOWN VOLTAGE VS. CLEARANCE

FOR BARRIERS $\frac{1}{16}$ INCH THICK

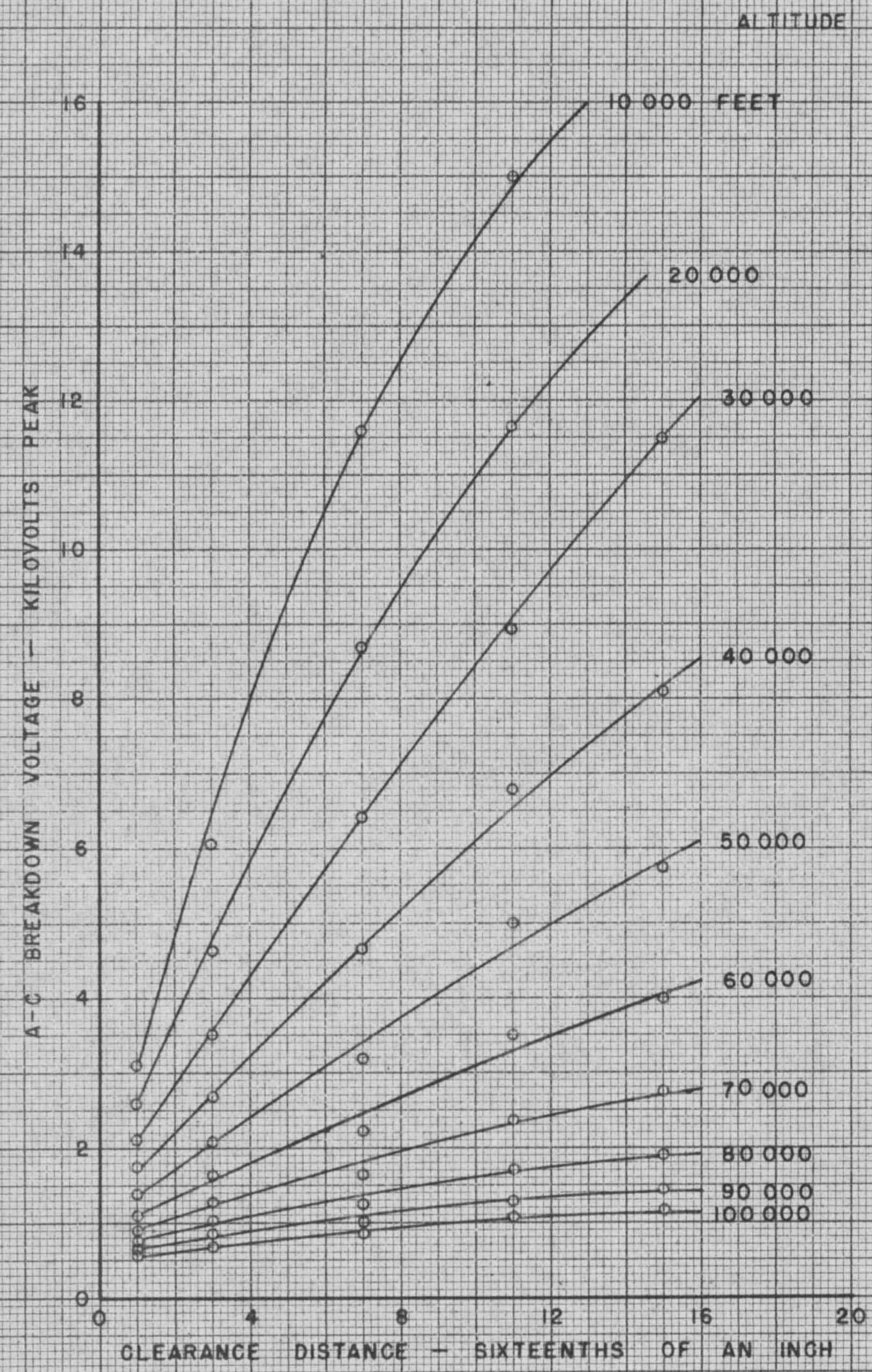

FIG. 10
A-C BREAKDOWN VOLTAGE VS. CLEARANCE
FOR BARRIERS $\frac{1}{16}$ INCH THICK

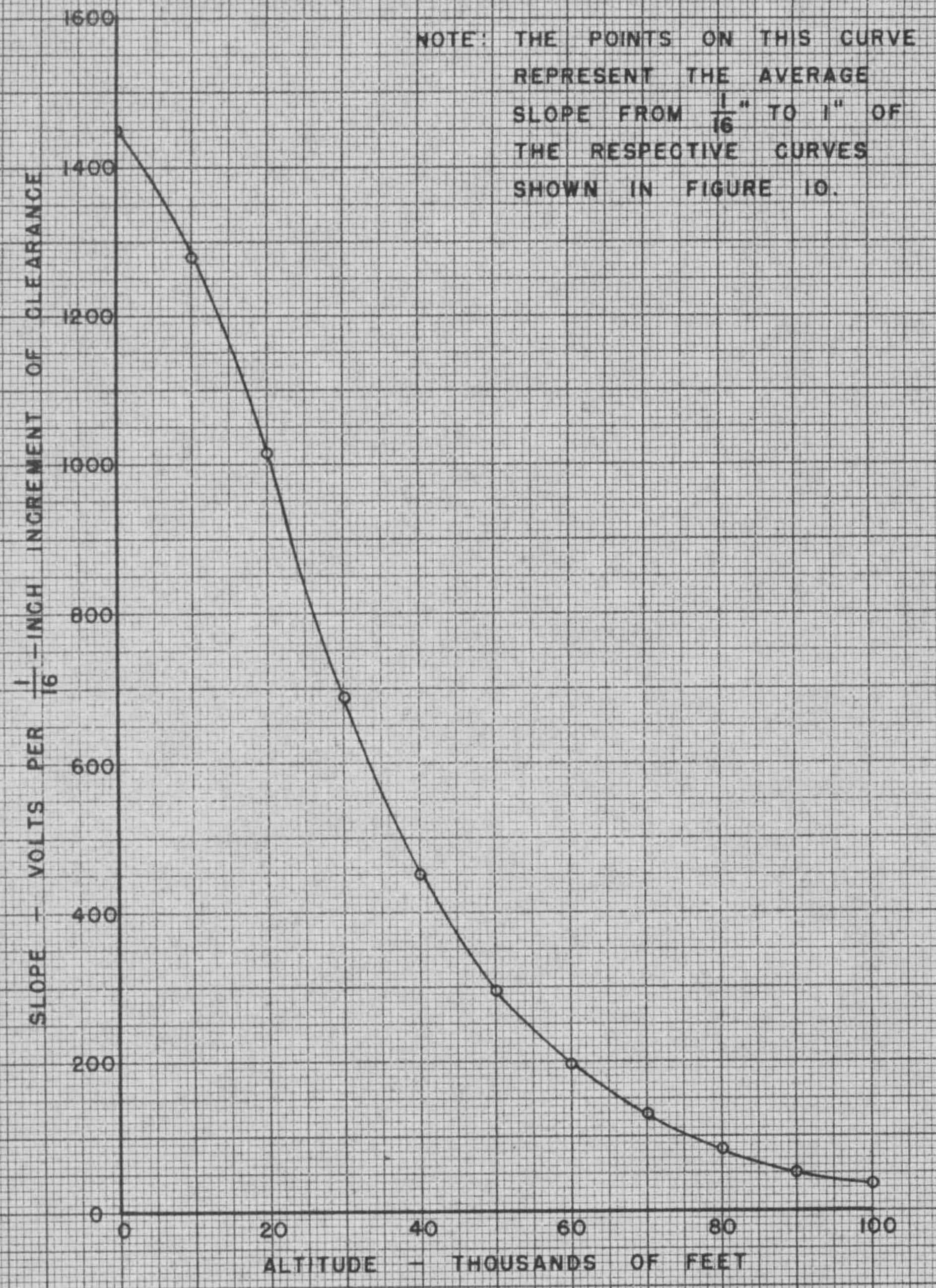

FIG. 11

SLOPE VS ALTITUDE CURVE ILLUSTRATING THE RELATIVE EFFECT AT VARIOUS ALTITUDES OF AN INCREASE OF CLEARANCE DISTANCE voltage which may be expected for each additional 1/16 inch of clearance distance more than the first 1/16 inch. From design considerations, it is the higher-altitude portion of this curve that is most significant. The knee of the curve at 50,000 feet marks the lower limit of this critical region.

To illustrate this point, consider the following example. At 100,000 feet, the breakdown voltage is 700 volts peak for 1/16 inch clearance and 1200 volts peak for 15/16 inch clearance (Figure 10). This represents a 500-volt increase of breakdown voltage for a 14/16 inch increase of clearance distance or 35 volts per sixteenth inch increase of clearance distance. This latter value may be read directly from the slope vs. altitude curve (Figure 11). In this example, the voltage required for breakdown is raised only 71 percent by increasing the clearance distance to 15 times its original value.

As the operating altitude of modern aircraft steadily increases, the design of aircraft electrical equipment becomes more difficult. Unfortunately, the insulating properties of air become dangerously ineffective at the low densities found at high altitude as illustrated in the preceding example. The necessary increase of creepage distance to meet breakdown voltage specifications may become impractical because of space limitations. The use of hermetically-sealed equipment solves this problem inside the seal, but outside connections may be surrounded by the rarified air. In any case, the use of insulating barriers seems to be the most feasible method of increasing creepage distance with negligible loss of space.

It is known, however, that the insulating qualities of air never disappear entirely. For uniform fields, a minimum breakdown voltage of approximately 350 volts peak exists for air at some critical product of air density and electrode spacing.[1] For any product of density and spacing other than the critical product, the breakdown voltage will be greater than 350 volts peak. For uniform field conditions, then, this critical product defines the worst possible condition of protection from breakdown in air. For non-uniform fields, it is probable that a potential somewhat less than 350 volts peak would overstress air along a certain path such that breakdown might occur. However, it is well to recall that a minimum breakdown potential does exist, for any given electrode configuration, which is independent of the air density.

Fortunately, the insulating properties of solid insulation are not materially affected by altitude. If terminals normally exposed to the air were sealed in plastic or were painted heavily with an insulating material after installation, adequate protection against breakdown at extreme altitude might be obtained with relatively short creepage paths.

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1. Knowlton, A.E. STANDARD HANDBOOK FOR ELECTRICAL ENGINEERS. Seventh Edition, 1941, Section 4-654, page 405.

BARRIERS OF SIMILAR CREEPAGE DISTANCE

All tests discussed so far were made with barriers of uniform thickness. At this point the question arises whether breakdown voltage is a function of the thickness of a barrier. The second series of barriers was designed to study this question. See Photograph 122033. The electrodes were mounted tight against the barriers as for the first series so the terms "creepage distance" and "clearance distance" may again be used interchangeably. The specific dimensions of the barriers were chosen so that each electrode-barrier configuration would have a common clearance distance of 15/16 inch. See Appendix III for barrier dimensions. Data obtained from this block could then be compared with the data recorded for the 1/16 inch wide by 9/16 inch-high barrier which has a similar clearance distance. The similarity of clearance distance for these configurations is dependent upon the use of terminals 1/8 inch high mounted flush against the barrier.

The close resemblance of the breakdown vs. altitude curves for these barriers is shown in Figure 12. It is clearly seen that d-c breakdown voltage is not a function of barrier thickness for this configuration. The corresponding curve of 60-cycle a-c voltage vs. altitude for the 1/16 x 9/16 inch barrier is shown as a dashed line in Figure 12. It seems reasonable to assume from previous results that 60-cycle a-c breakdown voltage are also independent of barrier thickness for the configuration used.

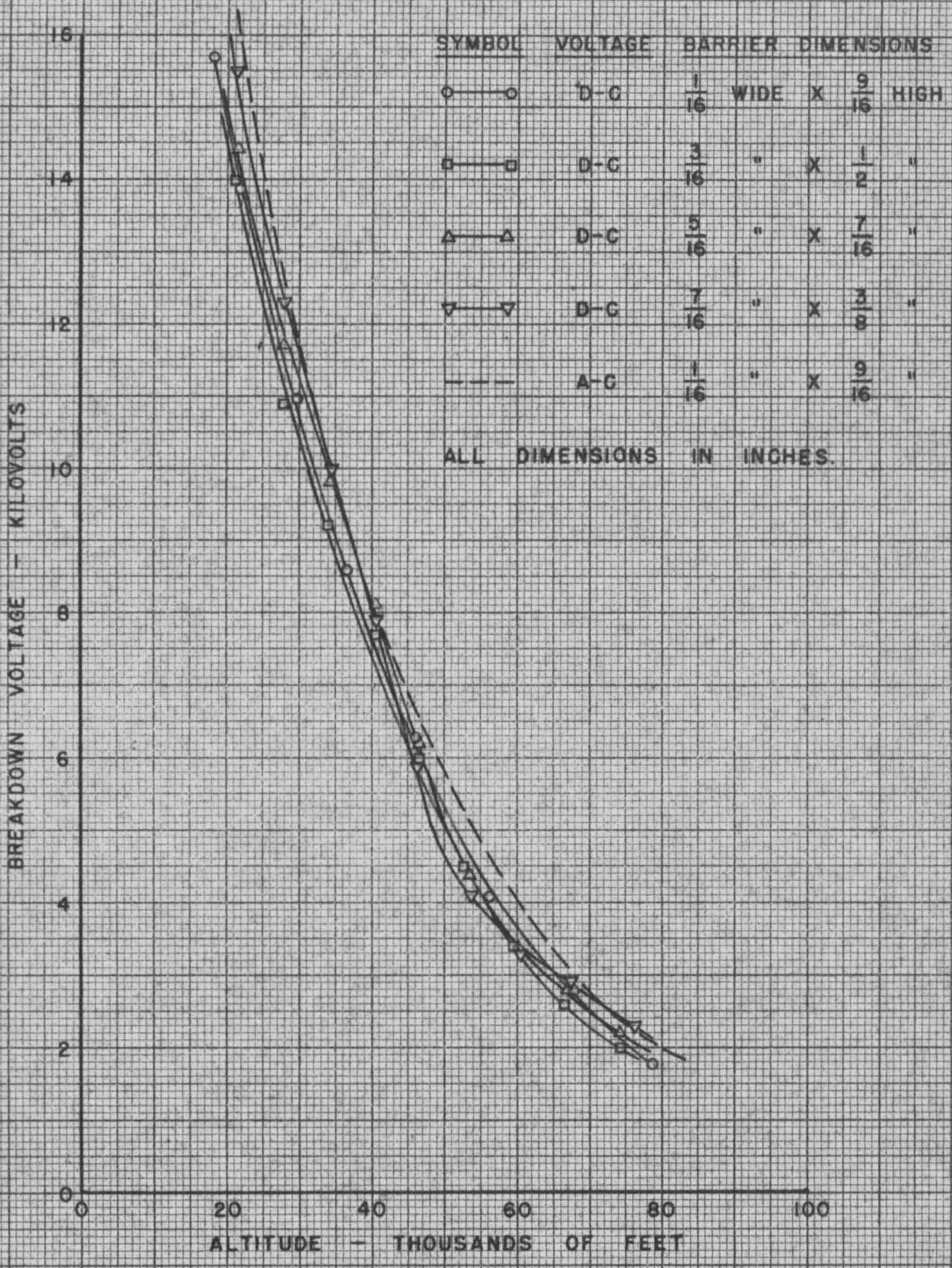


FIG. 12
BREAKDOWN VOLTAGE VS. ALTITUDE
FOR BARRIERS WITH SAME CLEARANCE

VARIOUS CONFIGURATIONS USING SIMILAR BARRIERS

The third series of barriers were all 1/16 inch thick and 1/2 inch high. The purpose here was to determine the most accurate method for calculating the actual length of the breakdown path for electrode-barrier configurations in which the electrodes were set back from the barrier. The nine configurations used in this series are illustrated and labelled in Table I. (Block B-8A in Photograph 122032 illustrates four of these configurations.) Three different methods of determining the length of the breakdown path between electrodes are listed in Table I. The creepage and clearance distances have been defined previously. It is evident that the creepage distance is greater than the clearance distance for any configuration in which one or both electrodes are set back from the barrier. The method using the shortest perpendicular distance is included as a compromise between the creepage distance and the clearance distance. Each distance listed in Table I is referred to the creepage distance of configuration No. 1 on a percentage basis to facilitate comparison.

The curves for the nine configurations in Table I are shown in Figures 13 and 14. Curve No. 1 is drawn in both figures to provide a common reference for the two sets of curves. At a given altitude, the breakdown voltages of the nine configurations should vary with the actual length of the breakdown path. The breakdown voltage for all configurations is within 20 percent of the breakdown voltage of configuration No. 1 at any altitude up to 50,000 feet. For some altitudes above 50,000 feet, the breakdown voltage from curve 9 is as much as 145 percent of the

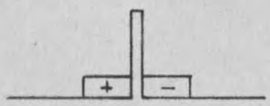
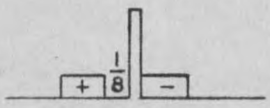
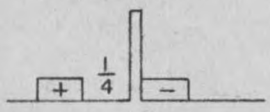
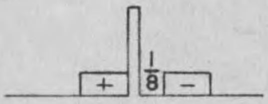
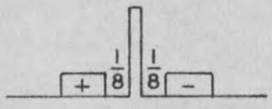
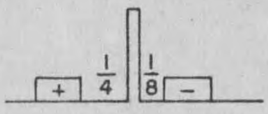
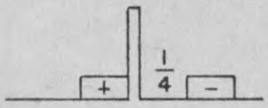
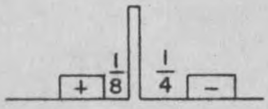
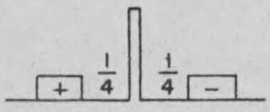
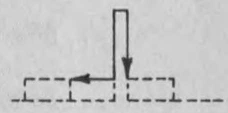
NUMBER	CONFIGURATION	CREEPAGE DISTANCE		CLEARANCE DISTANCE		SHORTEST PERPENDICULAR DISTANCE	
		INCHES	PERCENT OF NO. 1	INCHES	PERCENT OF NO. 1	INCHES	PERCENT OF NO. 1
1		0.813	100	0.813	100	0.813	100
2		1.063	131	0.832	102	0.938	115
3		1.188	146	0.888	109	1.063	131
4		1.063	131	0.832	102	0.938	115
5		1.313	162	0.852	105	1.063	131
6		1.438	177	0.917	113	1.188	146
7		1.188	146	0.888	109	1.063	131
8		1.438	177	0.917	113	1.188	146
9		1.563	192	0.963	118	1.313	162
	METHOD USED FOR CALCULATING DISTANCE						

TABLE I

COMPARISON OF THREE METHODS OF CALCULATING THE EFFECTIVE DISTANCE BETWEEN ELECTRODES

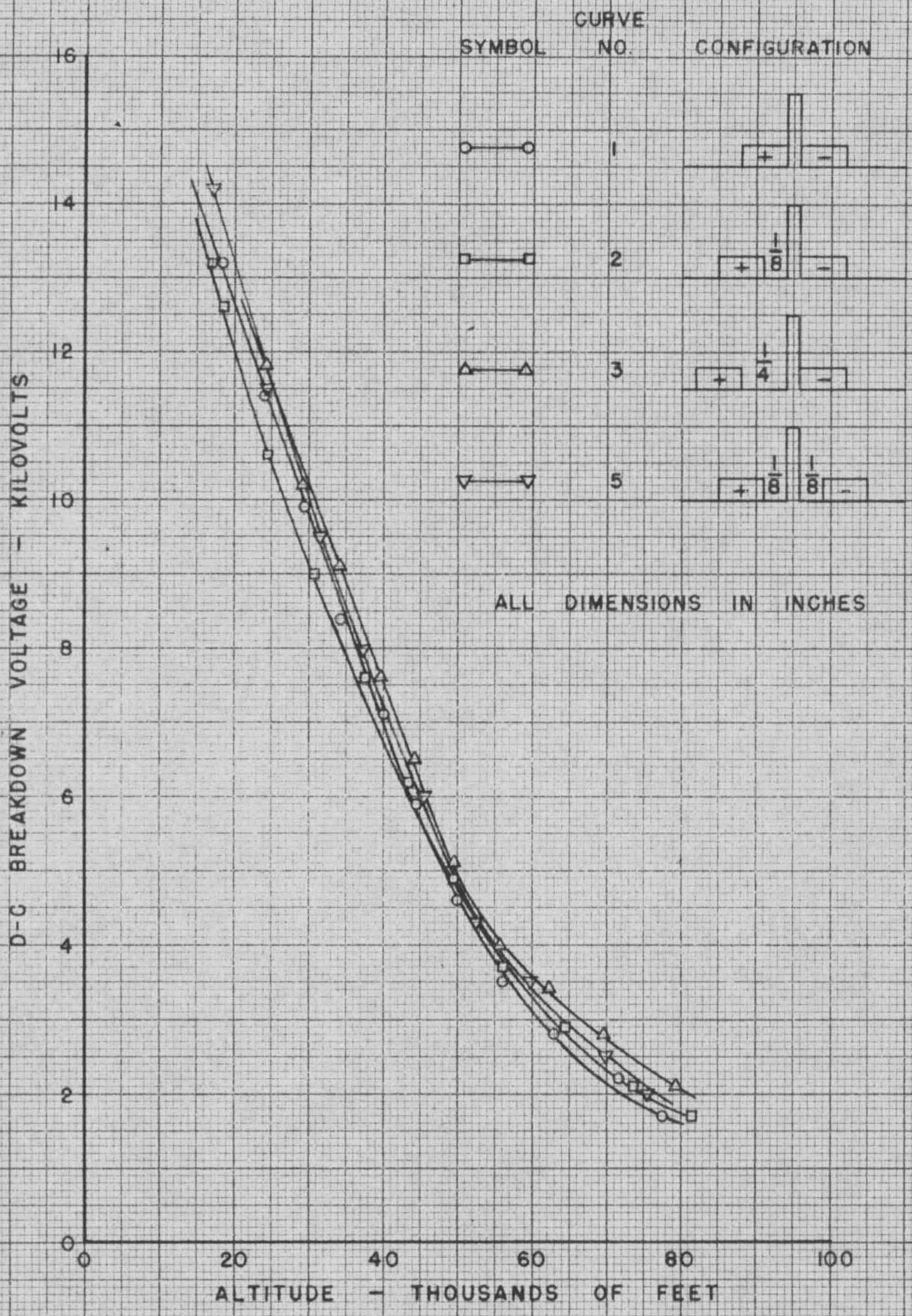


FIG. 13
D-C BREAKDOWN VOLTAGE VS. ALTITUDE
FOR VARIOUS CONFIGURATIONS (TABLE I)

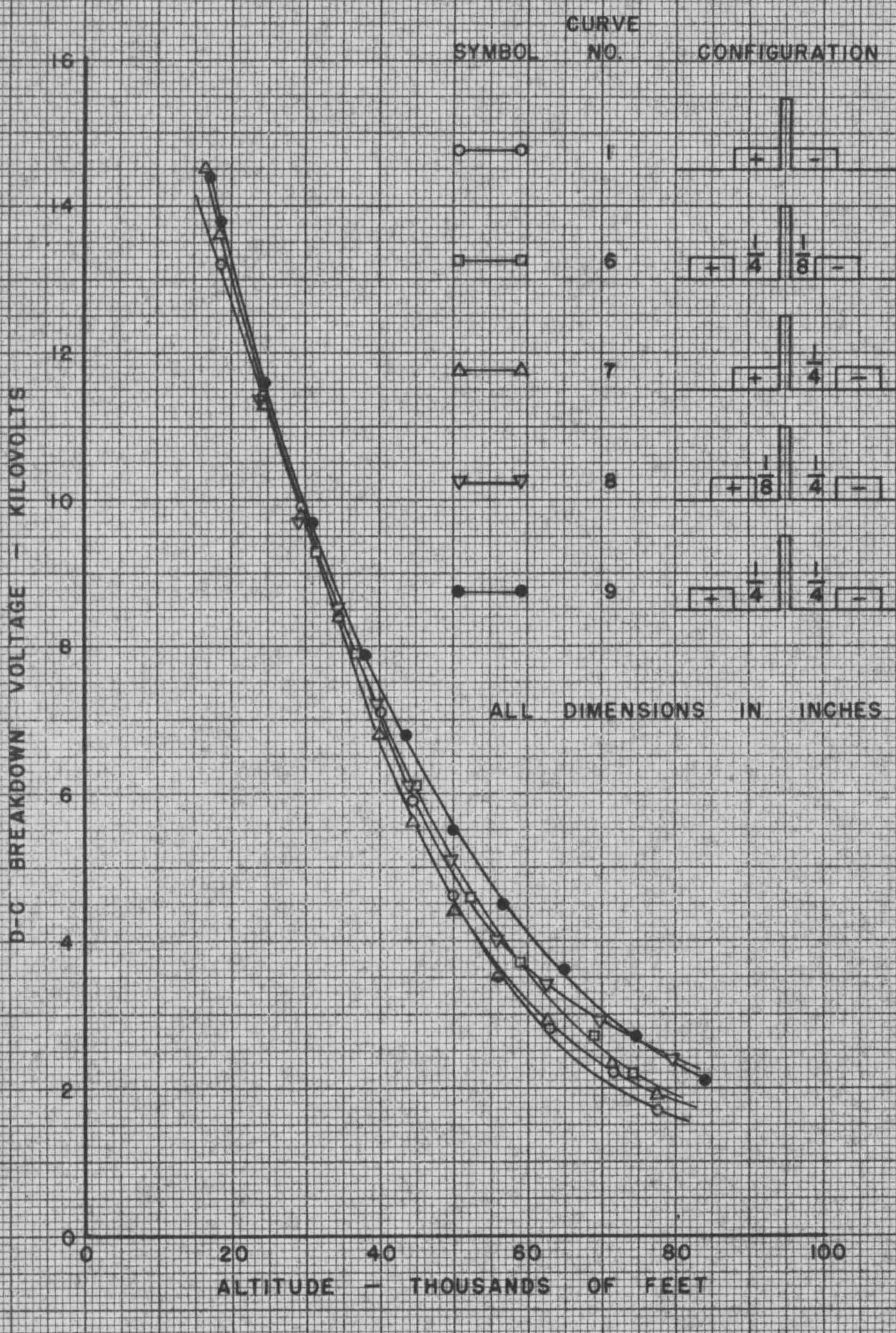


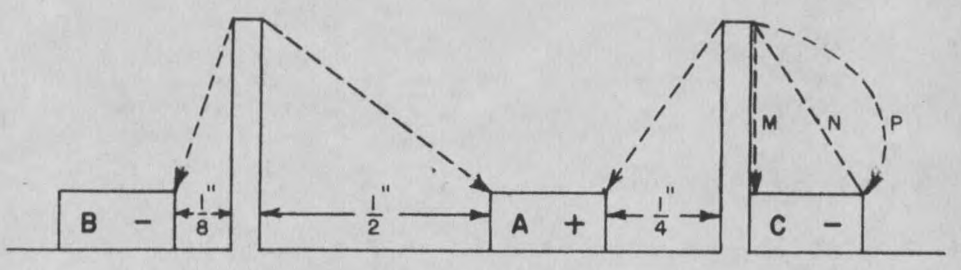
FIG. 14
D-C BREAKDOWN VOLTAGE VS. ALTITUDE
FOR VARIOUS CONFIGURATIONS (TABLE I)

corresponding voltage from curve 1.

The variation of clearance distance in column 2 of Table I is seen to correspond well with the variation of breakdown voltage for the major portion of the altitude range. The use of the creepage distance or the shortest perpendicular distance cannot account for the relative proximity of the nine curves. Therefore, the actual breakdown path over a barrier may be expressed with reasonable accuracy as the clearance distance.

The practical advantage of moving the electrodes away from the barriers is slight. The resulting increase of clearance distance is negligible compared to the loss of space in the design. It is evident then, that the most practical design of high-altitude aircraft electrical equipment, in terms of space and weight considerations, is the use of barrier configurations with terminals mounted close to the barriers.

One additional observation was made during this series of tests which may be of interest here. The configuration illustrated in Table II was being tested. It was discovered that arcing would occur at the same breakdown voltage from the high voltage (+) terminal to either ground (-) terminal. This phenomenon was observed for a range of altitude from sea level to 50,000 feet. The arc from A to C terminated on the outside corner of C as shown by path n in Table II. Since the breakdown voltage is the same, the actual length of the breakdown path must be similar over either barrier. The clearance distance from A to C (path m) does not apply here because the arc did not follow this path. The distance along



BREAKDOWN PATH	CREEPAGE DISTANCE		CLEARANCE DISTANCE		SHORTEST PERPENDICULAR DISTANCE	
	INCHES	PERCENT OF A-B DISTANCE	INCHES	PERCENT OF A-B DISTANCE	INCHES	PERCENT OF A-B DISTANCE
FROM A TO B	1.688	100	1.082	100	1.438	100
FROM A TO C ALONG PATH "M"	1.188	70	0.888	82	1.063	74
FROM A TO C ALONG PATH "N"			0.963†	89		
FROM A TO C ALONG PATH "P"			1.082†	100		

† THIS IS NOT A CLEARANCE DISTANCE. IT IS INCLUDED HERE FOR COMPARISON WITH CLEARANCE DISTANCE FROM A TO B.

TABLE II

COMPARISON OF VARIOUS BREAKDOWN PATHS FOR A CERTAIN TEST CONFIGURATION path n is 11 percent shorter than the clearance distance from terminal A to terminal B. Therefore, the actual length of the breakdown path must be measured along a path similar to path p. This is supported by the fact that brush corona was observed at the outside corner of terminal C extending out a short distance along a path similar to path p.

This test is described here to point out that the actual breakdown path may be dependent upon the exact configuration employed. No single method of determining the actual length of breakdown path will be accurate for all electrode configurations. The use of the clearance distance will be reasonably accurate in most barrier design. If the clearance distance is incorrect in a given case, the resulting design must be on the conservative side since the clearance distance is the shortest air path from metal to metal.

EFFECT OF ELECTRODE SHAPE

The fourth condition of electrode-barrier configuration employs a slightly modified electrode shape. The conclusions drawn to this point are based upon electrodes equipped with flat-head screws countersunk level with the top surface of the electrode. In this section, round-head screws were used in place of the former for purposes of comparison. The results of this comparison show that allowance must be made for any parts of the electrode which would tend to decrease the clearance distance. In the practical design of relays, terminal strips, switches, etc., such allowance must be made for lugs, washers, and screw heads which lie above the plane of the metal connecting strap. That is, the clearance distance should be determined with all connections assumed to be in place.

EFFECT OF HUMIDITY

Throughout the testing of the various electrode-barrier configurations, some factors were studied which are independent of the configuration used. Some data were obtained to determine the effect of air humidity upon breakdown. There is no significant difference between the d-c breakdown voltages obtained with saturated air or with dry air provided no moisture is condensed on the test block. Results obtained with condensation of moisture on the electrodes and barrier were not consistent. However, breakdown voltages are significantly lowered by moisture condensation on the barrier under test. In this case, the breakdown voltage rises with continued sparking because the heat of the arc rapidly removes the condensed moisture in the region of the test. The results agree favorably with previous work of this nature.[1,2]

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1. Berberich, L.J., Moses, G.L., Stiles, A.M., Veinott, C.G. EFFECT OF ALTITUDE ON ELECTRIC BREAKDOWN AND FLASHOVER OF AIRCRAFT INSULATION. AIEE Transactions, Volume 63, 1944, pages 345-53.

2. Delerno, M.J. POTENTIAL BREAKDOWN OF SMALL GAPS UNDER SIMULATED HIGH-ALTITUDE CONDITIONS. AIEE Transactions, Volume 63, 1944, pages 109-12.

EFFECT OF OZONE

The effect of ozone concentration was studied on a qualitative basis. A Westinghouse WL-794 ozone-producing lamp was mounted inside the bell jar close to the barrier under test. The lamp provided a continuous supply of ozone in the region of the test electrodes. It would seem that the presence of ozone in the test region would promote a higher degree of ionization in the air thereby lowering the voltage required to cause breakdown. Data obtained with the lamp seemed to yield smoother curves, but no significant change of d-c breakdown voltage was noted as a result of its use. However, even without the lamp, ozone is present in the bell jar as soon as the air is broken down in test. Therefore, all tests recorded here were made in the presence of some ozone. A small blower unit was mounted inside the bell jar which directed a blast of air to the test region. This effectively kept the air in constant motion past the test configuration. Again no significant change of breakdown voltage could be observed.

An attempt was made to obtain breakdown voltages for fresh air by evacuating the air and replacing it with fresh air after each data point. The data obtained in this attempt did not plot into smooth curve. The breakdown voltages measured in this test were within 25 percent of the corresponding voltages obtained with the ozone lamp, but individual points were both high and low. The readings obtained with the d-c tester are questionable because of the test procedure required here. Consistent results were obtained with the Takk tester throughout this study by using the method described in the Test Procedure. However, the test with fresh air required that the breakdown voltage be determined at the first arc. Time would not allow repetition of points because the test chamber was evacuated twice between each voltage readings. Inconsistent results may be expected with this eqipment in any test if the breakdown voltage must be determined from the first arc. It is the opinion of this writer that breakdown voltages are lowered by the presence of ozone in the test region, but additional data is required for proof of this statement.

HIGH-VOLTAGE TESTS OF AIRCRAFT EQUIPMENT

Electrical equipment intended for use at high altitude must meet various requirements of an electrical and mechanical nature. One of the most important of these is the requirement of adequate clearance distance to insure against failure caused by arc-over. Specifications for aircraft electrical equipment usually state the minimum allowable clearance distance, but do not require an adequate high voltage test to check the clearance distances used. For example, the specification used for aircraft relays (AN-R-20b[1]) specifies a minimum clearance of 1/8 inch from live terminals to ground and a minimum clearance of 1/16 inch between live terminals. This specification also requires a 1000-volt (rms) sea level test to check the adequacy of the solid insulation.

It has been demonstrated earlier in this report that clearance distance may become critical in the region of altitude from 50,000 feet to 100,000 feet. The relay specifications cited above do not insure adequate protection against breakdown for altitudes above 50,000 feet. The 1000-volt (rms) insulation test does imply that the solid insulation will not breakdown under 1414 volts peak at any altitude. For the specified minimum clearance of 1/16 inch, however, the surrounding air will break down at 52,000 feet if 1414 volts peak were applied (Figure 6). At 80,000 feet, air breakdown will occur at 870 volts peak (Figure 6) which is far below the requirements specified for the solid insulation.

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1. AMERICAN STANDARD DEFINITIONS OF ELECTRICAL TERMS, AIEE. Section 20.10.415-420, page 85.

It is recommended here that specifications for electrical components, which are intended for use above 50,000 feet, include a high-voltage test to determine the adequacy of clearance distance. Such a test cannot be made at normal pressure because the insulating properties of air will be most critical at the maximum design altitude. The only conclusive single test which will guarantee adequate clearance distance would be the application of the minimum allowable breakdown voltage at an air density corresponding to the maximum altitude of the design. If no breakdown occurs in this test, the clearance distance is definitely adequate at any altitude lower than the simulated test altitude.

The voltages recorded here are based on complete breakdown of air. At high altitude, this breakdown was in the form of a glow discharge. For lower altitudes, only a visible spark was considered to constitute breakdown. A brush corona discharge was observed in some tests at voltages one to ten percent below the breakdown voltage. This effect was noted only from sea-level to about 30,000 feet for larger clearance distances. In practice, corona discharge may be objectionable even though actual arcing does not occur. However, this brush corona effect is not a limiting factor in the design of high-altitude aircraft used at 50,000 feet or higher. If equipment will not breakdown at a given voltage at 50,000 feet or above, this voltage is not high enough to cause brush corona under 30,000 feet.

CONCLUSIONS

1. The measurement of clearance distance between electrodes should be made along the shortest air path from metal to metal. All lugs, washers, and fasteners should be in place for this calculation.
2. The use of barriers to increase clearance distance is found to be most practical. Most effective use of a barrier may be made if terminals are mounted close to the barrier on each side. Clearance distance is then determined by the height of the barrier above the terminals. A clearance distance measured over a barrier is just as effective for protection against arc-over as the corresponding plane-surface creepage distance. This statement is true for direct voltage and 60-cycle alternating voltages and for any shape of barrier.
3. The beneficial effect of increasing creepage distance for protection against arcing becomes limited at altitudes above 50,000 feet. The properties of air as an insulating material becomes questionable above this altitude. Results obtained here indicate that solid or liquid insulation may be required in place of air at extreme altitudes.
4. It is recommended that specifications for electrical equipment intended for use above 50,000 feet, include a test to determine the adequacy of clearance distance. In this test, the minimum allowable breakdown voltage should be applied to the configuration under test in an air density equivalent to the maximum altitude used in the design. High-voltage tests performed in normal atmosphere will not assure adequate protection from breakdown at high altitude.

5. Breakdown voltage is not a function of the relative humidity of air provided that no actual moisture condensation exists. Breakdown voltages are lowered significantly if moisture is condensed on the barrier and electrodes.

APPENDIX I

Reduction of Laboratory Data to Standard Atmosphere

A. Sample reduction using U-tube manometer.

Data: Temperature: 77°F. or 25°C.
Manometer readings: 14.20 and -13.33 in. Hg.
Barometer reading: 29.82 in. Hg.
D-C breakdown voltage: 3.2 kilovolts

The height, H, of the mercury column represents the difference between the air pressure in the bell jar and atmospheric pressure:

$$H = 14.20 - (-13.33) = 27.53 \text{ in. Hg.}$$

The height, H, is corrected to 0°C by multiplying by the ratio of the density of mercury at 25°C to the density of mercury at 0°C.

$$H \text{ (corrected)} = (27.53) \frac{(0.9971)}{(0.9999)} = 27.42 \text{ in. Hg.}$$

The air pressure in the bell jar, P, is obtained by subtracting H (corrected) from the barometric pressure

$$P = 29.83 - 27.53 = 2.29 \text{ in. Hg.}$$

The density of the air is calculated from the formula

$$\text{Air density} = \frac{0.205}{1 + (0.00367)(25)} \; \frac{2.29}{76} = 0.00598 \text{ pounds/cu.ft.}$$

The simulated altitude may be read from the NACA density vs. altitude curve (Figure 2)

Simulated altitude = 64,000 ft.

B. Sample reduction using Wallace and Tiernan manometer

This manometer is temperature compensated and was connected so that the absolute pressure in the bell jar was obtained by direct reading. Consequently, the air density could be calculated from direct temperature and pressure readings. Simulated altitude was obtained from the same curve (Figure 2).

APPENDIX II

List of Equipment

1. High Voltage Insulation Tester (D-C); The Takk Corporation. Model 5C; Serial 31.

2. Crest Voltmeter (M_1); General Electric. Type A3; Cat. 5993877G6; Serial 1287278. Battery operated.

3. Vacuum Tube Voltmeter (M_2); General Radio. Type 726-A; Serial 3972; BAC 6699. Reads rms of sine wave or 0.707 of peak of complex wave. Calibrated with voltage divider to read peak value directly.

4. Voltmeter (M_4); Westinghouse. Serial 2016060; U.S. 4SFB 62896.

5. Vacuum Tube Voltmeter (M_3); Hewlitt-Packard. Model 400A; Serial F691; U.S. 4SFB 62127.

6. Vacuum Tube Voltmeter (M_5); General Radio. Type 727-A; Serial 379; U.S. 4SFB 63090. Battery operated.

7. Vacuum Pump, Duo-Seal; W.M. Welch Mfg. Co. Serial 5842-O; BAC 35032.

8. Manometer, Reservoir-Type; Wallace and Tiernan. Type FA135; Serial WP51515; BAC 62140.

9. Potential Transformer (T_1); Westinghouse. Type PT; 11500/115 volts; 50-60 cps; 400 va; Style 958997-A; Serial 2299858.

10. Potential Transformer (T_2). Same as above expect Serial 2299859.

11. Induction Regulator; General Electric. 1.2 kva; Form HK; Serial 7571361. Connected for 110/110 volt operation.

APPENDIX III

Description of Test Electrodes and Test Blocks

Test Electrodes:

All electrodes were cut from 1/8 inch brass sheet stock.

Type A: Ground Electrode - 1 x 1 inch; sharp corners.
High-Voltage Electrode - ½ x ½ inch; sharp corners.

Type B: Ground Electrode - ¼ x 4 inch; sharp corners.
High-Voltage Electrode - ¼ x 1 inch; sharp corners.

Type C: Ground Electrode - Same as type B except that two #4 flat-head brass screws were mounted at one end of the electrode and two #4 round-head brass screws were mounted at the opposite end of the electrode. The electrodes were countersunk for the flat-head screws so that the screw heads were level with the top of the electrode. See Photographs 122031 and 122032.

High-Voltage Electrode - Same as type B except that two #4 flat-head brass screws were mounted in some of the electrodes and two #4 round-head brass screws were mounted in the others. See Photographs 122031 and 122032 for mounting configurations.

Test Blocks:

The test blocks were labelled B-1, B-2, B-3, etc., according to the design of the test block. In some cases duplicate test blocks were made to replace defective blocks (barriers cracked, chipped, or punctured). Duplicate blocks were distinguished from each other by using capital letters: for example, B-2A, B-2B, B-2C, etc.

All test blocks were made of 1 inch black laminated micarta except B-1, which was made from 1/4 inch black laminated micarta. See Photographs 122031, 122032, and 122033 for sample configurations.

B-1 Barriers - None.
Electrodes - Type A. See Photograph 122032.

B-2 Barriers - 1/16 inch wide x 1/8; 3/16; 1/4 inch high.
Electrodes - Type C.

B-3 None.

B-4 Barriers - 1/16 inch wide x 5/16; 3/8; 7/16; 1/2 inch high.
Electrodes - Types B and C.

B-5 Barriers - 1/16 inch wide x 9/16; 5/8 inch high.
Electrodes - Type C.

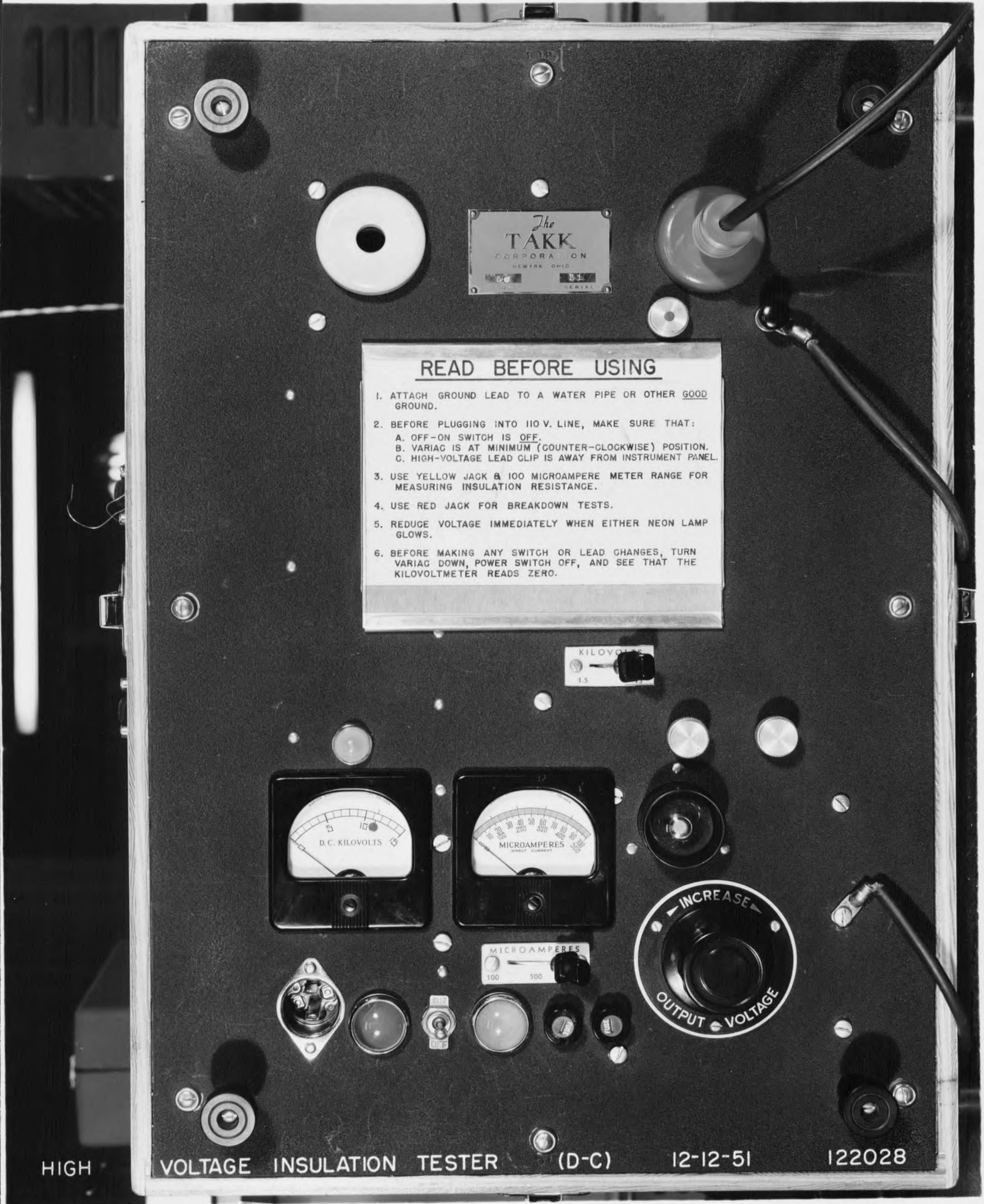
B-6 Barriers - 1/16 inch wide x 11/16; 3/4 inch high.
Electrodes - Type C.

B-7. Barriers - None. Plane-surface creepage distances only.
Electrodes - Type C. The ground electrode was movable so that the plane-surface creepage distance could be adjusted as desired.

B-8 Barriers - 1/16 inch wide x 1/2 inch high (4 barriers).
Electrodes - Types B and C.

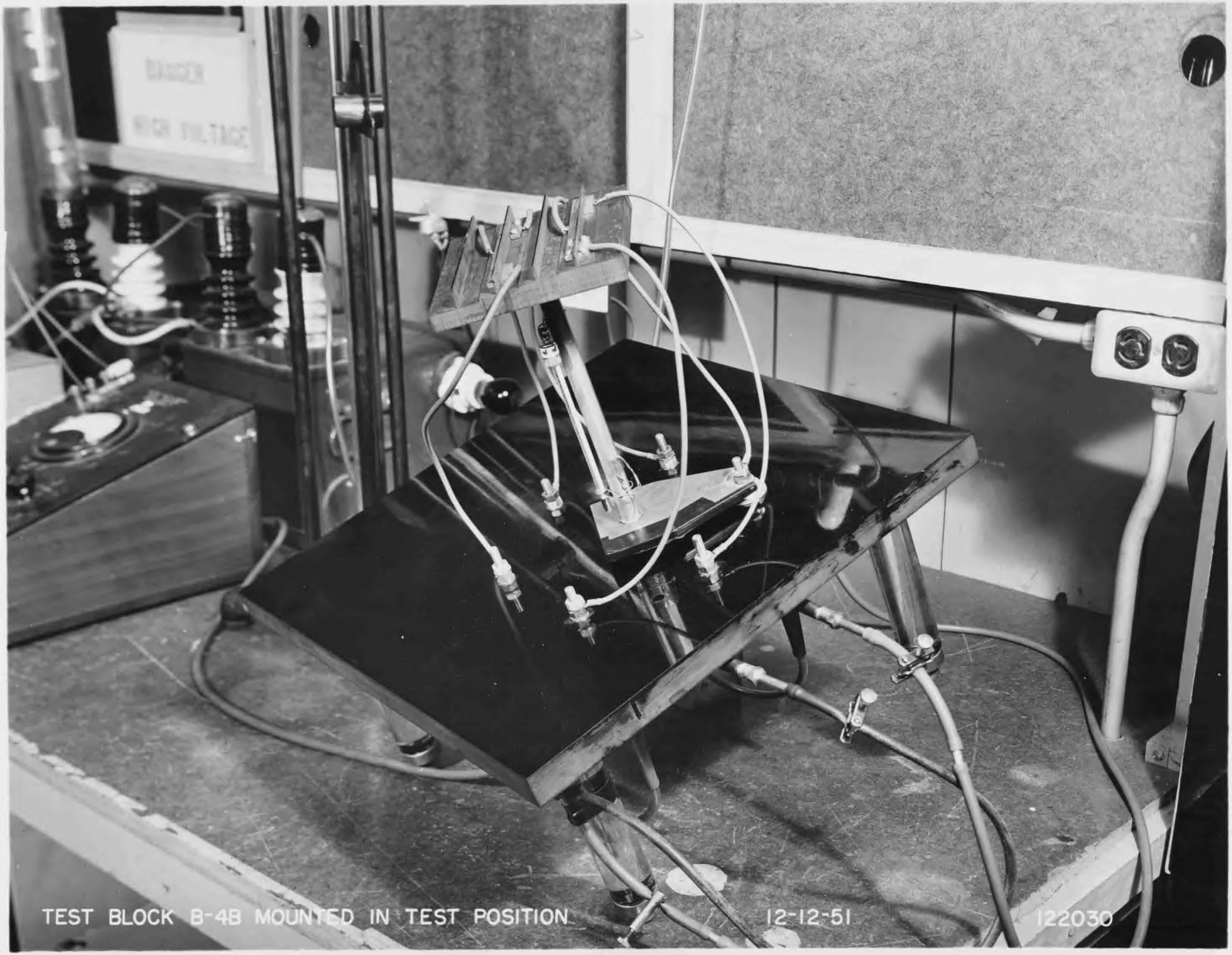
B-9 Barriers - 3/16 inch wide x 1/2 inch high; 5/16 inch wide x 7/16 inch high; 7/16 inch wide x 3/8 inch high.
Electrodes - Type C.

GENERAL ELECTRIC CREST VOLTMETER 2-21-44 46859-B

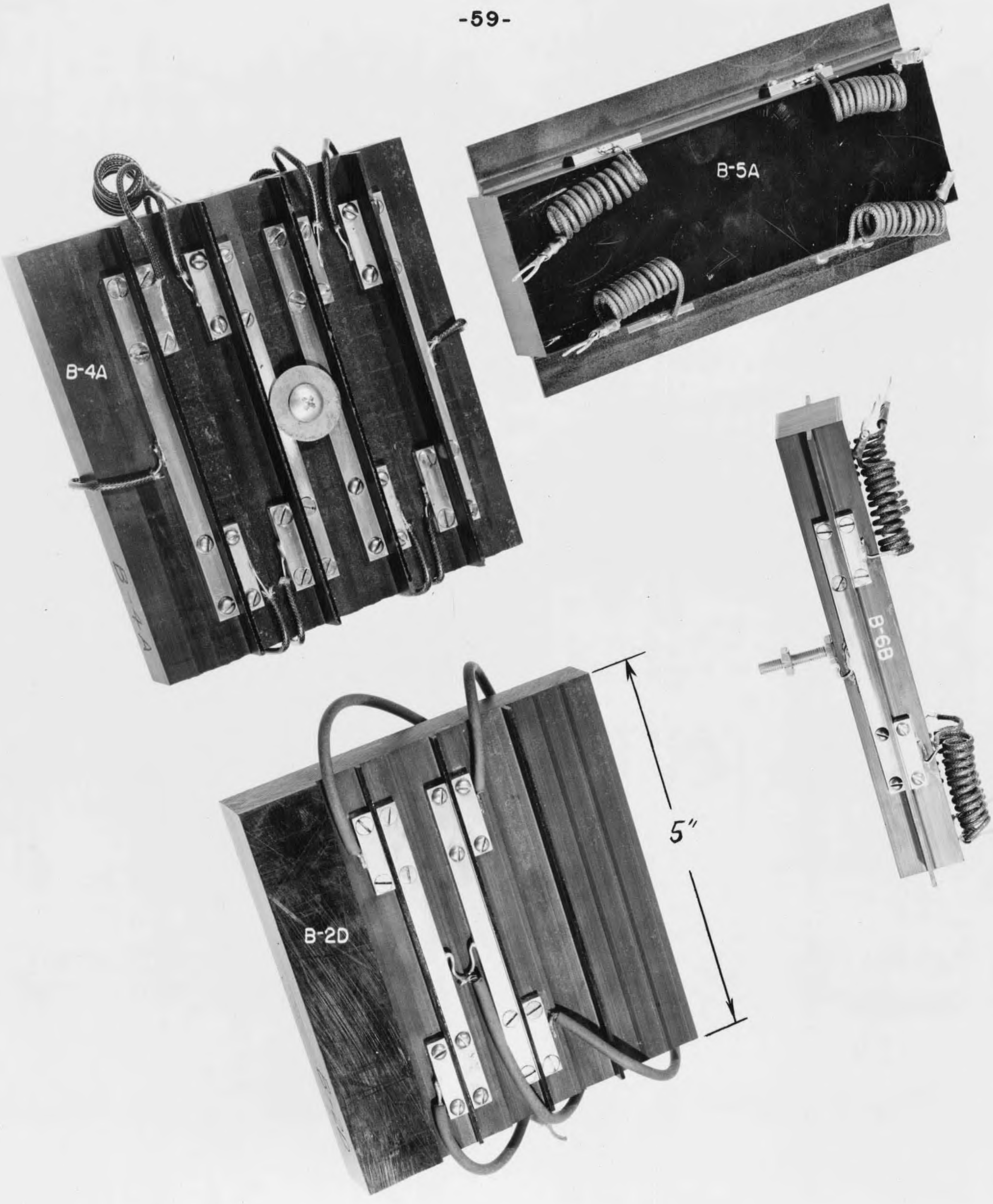


HIGH VOLTAGE INSULATION TESTER (D-C) 12-12-51 122028

HIGH VOLTAGE TEST EQUIPMENT (A-C) 12-12-51 122029

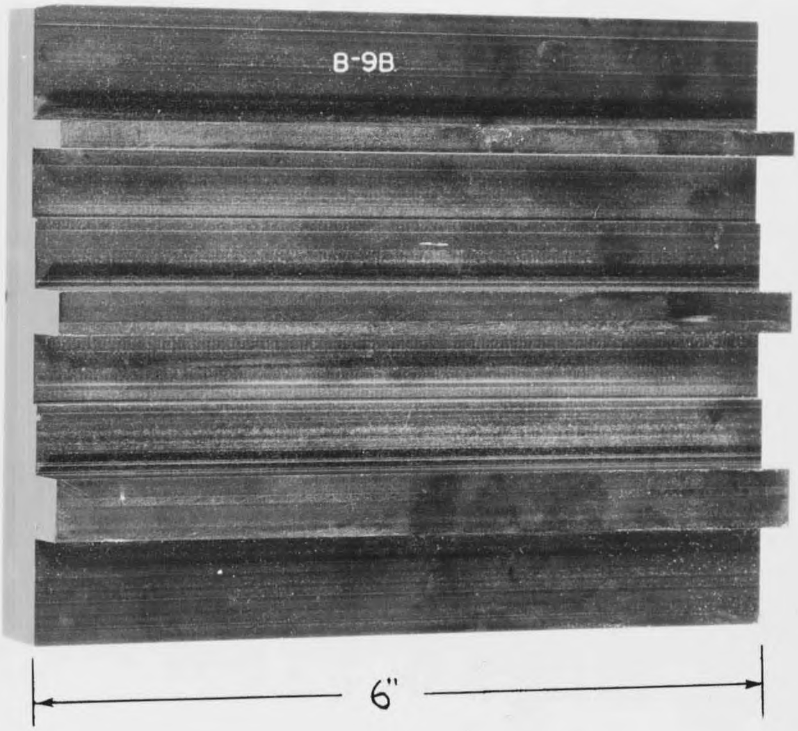


TEST BLOCK B-4B MOUNTED IN TEST POSITION 12-12-51 122030



TEST BLOCKS 12-12-51 122031

TEST BLOCKS 12-12-51 122032



TEST BLOCK 12-12-51 122033

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