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VOLTAGE BREAKDOWN IN A LOW-TEMPERATURE CESIUM-VAPOR DIODE

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16. Abstract

Breakdown voltages were determined experimentally for a cesium-vapor diode with electrode temperatures that varied from 350° to 900° C. The pressure-spacing product pd ranged from 10^{-2} to 1 torr-cm. The voltage at breakdown approximately followed Paschen's Law for constant cathode temperatures above 500° C and pd values greater than the pd minimum of about 1.5×10^{-2} torr-cm. The results indicated that the best combination of inverse characteristics coupled with desirable forward drive properties for high-temperature power conversion devices occurs at the higher cesium pressures.

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VOLTAGE BREAKDOWN IN A LOW-TEMPERATURE CESIUM-VAPOR DIODE

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SUMMARY

Breakdown voltages were determined experimentally for a cesium-vapor diode with electrode temperatures of 350° to 900° C. The pressure-spacing product pd ranged from 10^{-2} to 1 torr-centimeter. The breakdown voltage for this cesium-filled tube follows Paschen's Law for cathode temperatures in the range of 500° to 800° C and pd values greater than the pd minimum of about 1.5×10^{-2} torr-centimeter. For cathode temperatures below 450° C, the breakdown voltage was relatively independent of spacing and was approximately proportional to cesium pressure. The breakdown voltage exhibited a strong dependence on cathode temperature but only a weak dependence on anode temperature. Breakdown voltages in excess of 100 volts were obtainable only for cathode temperatures less than 425° C and with relatively high cesium vapor pressures (approx 1 torr).

For cathode temperatures less than 500° C, the discharge after breakdown resembled a glow discharge, with the sustaining voltage nearly equal to the breakdown voltage and with currents in the milliampere range. For higher cathode temperatures ($\gtrsim 600^{\circ}$ C), breakdown occurred at a voltage on the order of the ionization potential of cesium (3.89 eV), and the resulting discharge had currents in the ampere range with sustaining voltages less than the ionization potential of cesium. Current-voltage curves, together with visual observations, are shown to characterize the prebreakdown behavior and mode of discharge for the range of variables tested.

The results indicated that the best combination of inverse characteristics coupled with desirable forward drive properties for high-temperature power conversion devices occurs at the higher cesium pressures.

INTRODUCTION

Long-term space missions using nuclear power sources and thermionic energy converters will require lightweight, efficient power conditioning systems (refs. 1 and 2). Locating the power conditioning system near the power source and within the region of high temperature and nuclear radiation would reduce weight and electrical conduction losses. Gas- and vapor-filled discharge tubes inherently have a low susceptibility to radiation damage. This property leads to a study of their temperature characteristics for use as rectifiers and thyratrons in high-temperature power conditioning systems. Electrode temperatures and vapor pressures that yield high peak inverse voltages without sacrificing desirable forward capabilities must be determined. These capabilities, low voltage drop and high current density, are characteristic of alkali vapor tubes.

Since cesium has the lowest ionization potential (V_I = 3.89 V) of any element, it should be considered for use in high-temperature discharge devices. The low ionization potential of cesium coupled with its large cross section for ionization and its ability to lower the work function of electrode materials are most desirable for high-current, low-voltage-drop operation. However, these properties of cesium present difficulities for obtaining desirable high inverse voltages. They also lower the breakdown potential in the reverse direction, thereby reducing the inverse voltage capability of the tube. The purpose of this investigation was to determine parameters for operation of a cesium-vapor diode which relate inverse characteristics to desirable forward drive properties.

The determination of the breakdown potential across a gap in a gas or vapor and the dependence of this potential on the product of pressure p and electrode spacing d is important in the design of all electrical discharge apparatus. The pd product is proportional, in a sense, to the number of collisions that an electron undergoes with cesium atoms as it traverses the gap in the field direction. This fact is evident when one considers that the vapor pressure p is approximately inversely proportional to the average electron mean free path λ_e, or $pd \propto d/\lambda_e$.

Electrical breakdown in gases has been studied in considerable detail (refs. 3 and 4). Until recently, however, there has been only limited investigation of the breakdown in easily ionized vapors of the alkali metals such as cesium. Because of current interest in thermionic energy converters and in electrostatic thrusters, some cesium breakdown measurements have been reported (refs. 5 to 8).

Lebedev and Gus'kov (refs. 5 and 6) investigated breakdown voltages as a function of cathode temperature and cesium pressure. The discharge path is directed through a gap in a glass insulator interposed between two electrodes. Shimada and Luebbers (ref. 7) discuss discharge phenomena and anamalous electron currents at pd values below the pd minimum. A few breakdown voltages are given in connection with the determination of parameters for switching between the unignited and ignited modes of discharge. In a study of the behavior of the potential and plasma density in the development of the low-voltage arc in cesium vapor, Gus'kov et al. (ref. 8) present several curves of breakdown voltages and currents as functions of pd and electrode temperatures above 500° C. However, they present no data for lower electrode temperatures, nor do they attempt to correlate inverse with forward properties. The design and operating characteristics of a cesium-vapor thyratron are described by Coolidge (ref. 9).

EXPERIMENTAL APPARATUS

The diode used in this experiment was constructed with ceramic-metal seals in demountable tube sections. Two sapphire windows were provided to permit measurement of the interelectrode spacing with a cathetometer and to allow for direct visual observation of the discharges. Spacings were measurable to ±0.02 millimeter. A cross section of the diode is shown in figure 1.

Both electrodes were made of molybdenum with identical cross sections similar to the modified Rogowski-Bruce profile proposed by Harrison (ref. 10). One electrode was attached to the tube envelope through a bellows. Three adjustment screws spaced 120° apart around the tube provided alinement of the electrodes and allowed the spacing to be varied while the diode was in operation.

The electrodes were independently heated from the back side by radiation from a tungsten filament. Electrode temperature was measured by a Chromel-Alumel thermocouple inserted into the electrode from the filament side and penetrating to within 1.25 millimeter of the electrode surface. The filament chambers were evacuated by means of a vac-ion pump.

The cesium reservoir temperature was maintained to within $\pm 1^{\circ}$ C by an automatic air flow controller. A thermocouple attached to the reservoir provided the control signal. The reservoir and its surrounding air chamber were located within the oven that enclosed the entire diode assembly. The cesium vapor pressure was calculated from the reservoir temperature using the equation recommended by Heimel (ref. 11).

The oven temperature was automatically controlled from a Chromel-Alumel thermocouple attached to the center section of the tube envelope. All other temperature monitoring was provided by Chromel-Alumel thermocouples that printed out on a multipoint strip-chart recorder.

INSTRUMENTATION AND PROCEDURE

Current-voltage characteristics were obtained by applying a dc voltage across the electrode gap. The voltage was varied slowly through a selected range by means of a motor-driven potentiometer. Two power supplies provided voltage and current to span the wide range of conditions investigated. One supply was rated 0 to 1000 volts and 0 to 200 milliamperes, while the other supplied 0 to 36 volts and 0 to 10 amperes. Both

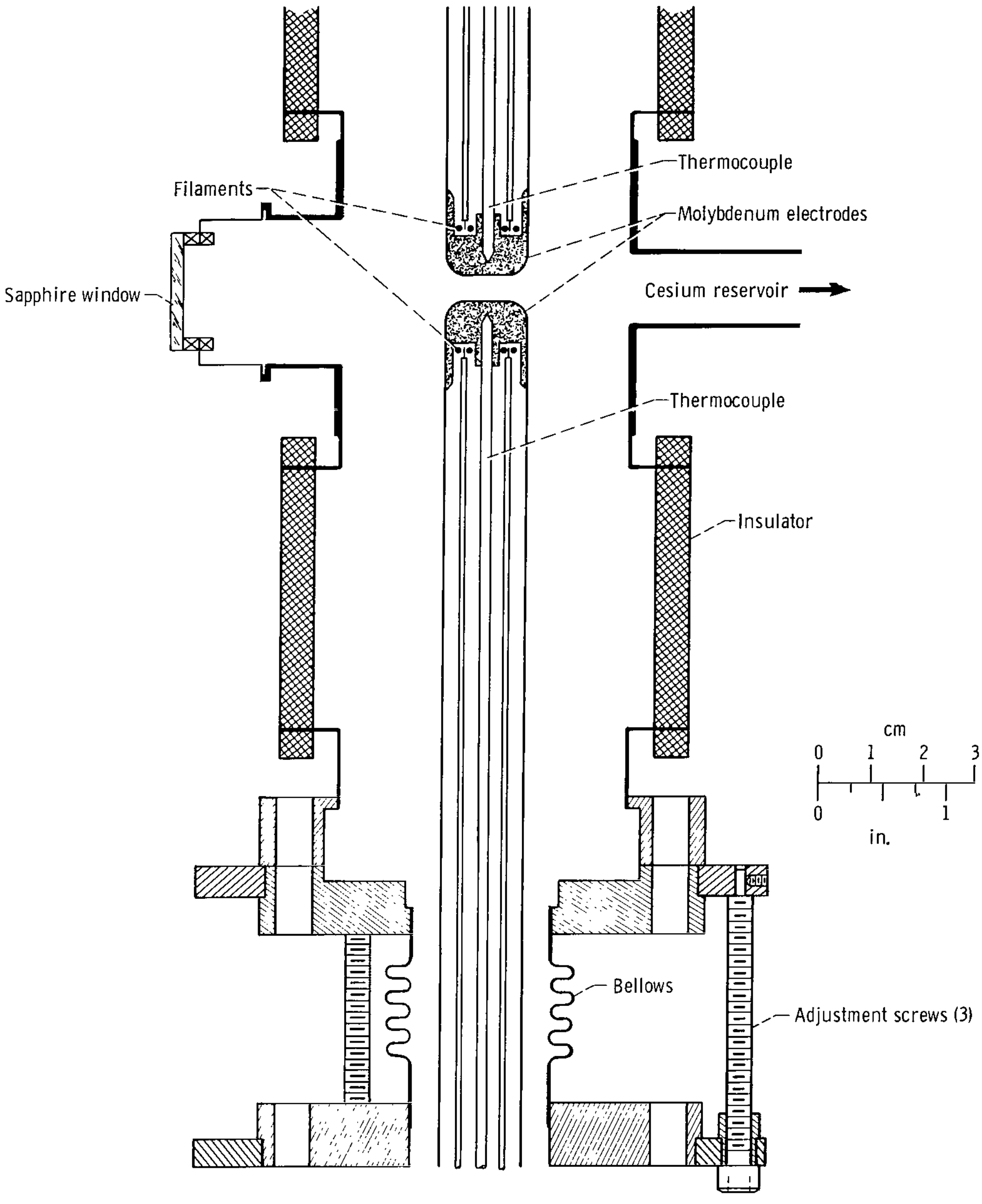


Figure 1. - Cross section of cesium-vapor diode.

supplies had negligible ripple. For regions of low current, the applied voltage was measured directly across the power supply. However, for currents greater than 10^{-3} ampere, the applied voltage was measured across the Alumel leads of the electrode thermocouples. This eliminated errors due to IR drops in the electrode shanks or in the discharge circuit.

In order to keep impedance low in the discharge circuit, current was measured as proportional to the voltage drop across a precision resistor inserted into the circuit. For currents less than 10^{-3} ampere, the voltage drop across a 100-ohm resistor was detected by a nanovoltmeter with an output connected to the y-axis of the recorder. For currents greater than 10^{-3} ampere, the drop across a 1-ohm resistor was measured directly on the y-axis of the recorder. Thus, the current-voltage (I-V) curves were obtained directly with current displayed as a function of applied voltage.

The center section of the tube envelope was included in the circuit to act, in effect, as a guard ring. This permitted checks of the leakage currents along the insulators during tube operation. This leakage current remained less than 0.1 percent of the current across the gap.

In this report, the terms cathode and anode will always refer to the relative voltages of the two electrodes regardless of their comparative temperatures. When voltage is applied across the electrode gap, the anode is positive with respect to both the cathode and the diode center section. The cathode is at a small positive potential (equal to the voltage drop across the current shunt) above the center section, which serves as the circuit ground.

The diode was constructed symmetrically, and the polarity of the electrodes could be interchanged by means of a switch. It was confirmed experimentally that the electrical characteristics were also symmetrical with the electrode polarity reversed.

Standard high-vacuum techniques were used throughout in the construction and initial conditioning of the cesium chamber. The cesium was introduced through copper tubulation that was then pinched off.

RESULTS AND DISCUSSION

Current-voltage characteristics at a pd value of 0.137 torr-centimeter and an anode temperature T_a of 350° C are shown in figure 2. The parameter is cathode temperature, which was varied from 420° to 900° C. Figure 3 shows current-voltage characteristics for a pd value of 0.013 torr-centimeter, which is near the pd minimum for cesium. It should be noted that, for the low pd value, the breakdown voltage for all cathode temperatures does not exceed 5 volts as compared with breakdown voltages up to 100 volts at the higher pd. The breakdown voltage is taken to be the point where the current-voltage

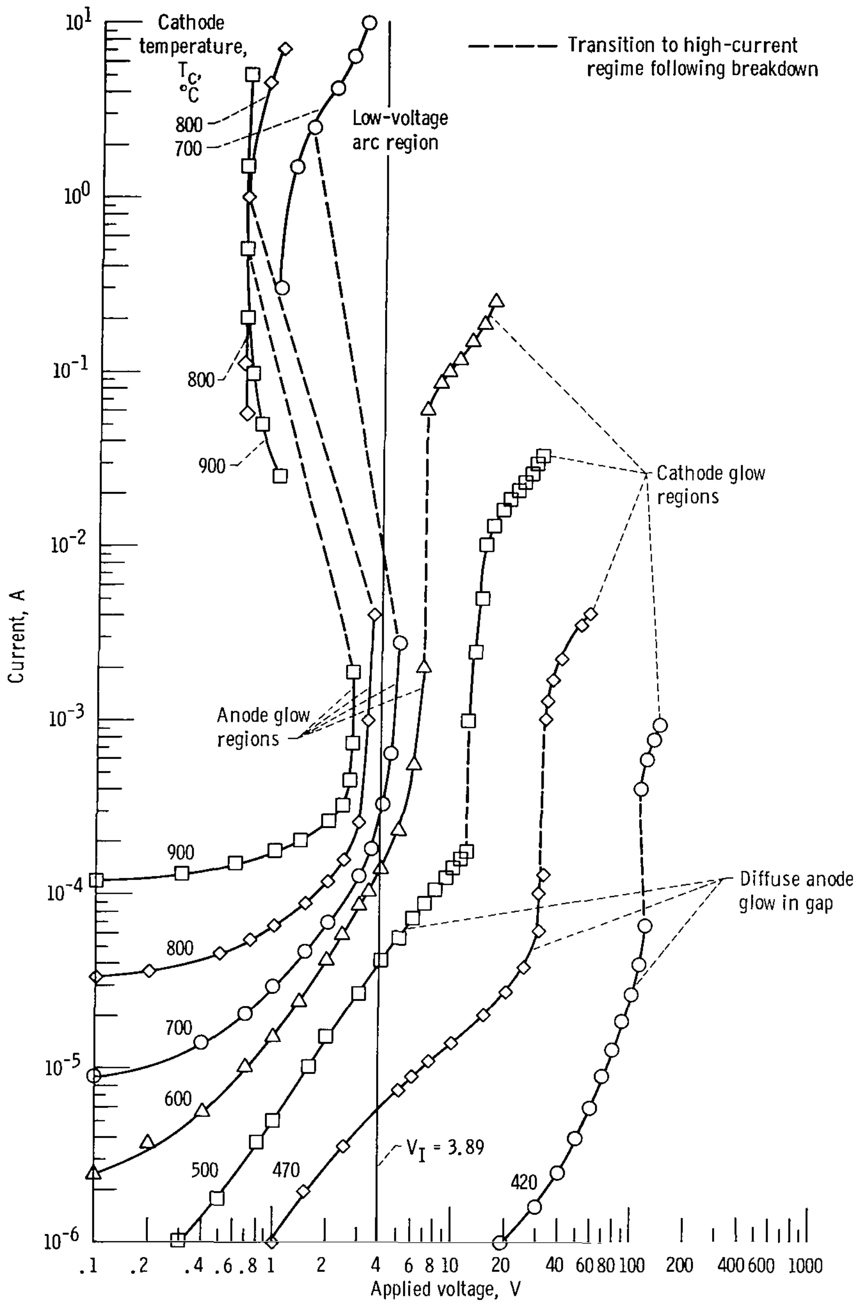


Figure 2. - Effect on cesium diode current-voltage characteristics of varying cathode temperature. Cesium temperature, 276° C; pressure, 1.09 torr; anode temperature, 350° C; electrode spacing, 0.126 centimeter; pressure-spacing product, 0.137 torr-centimeter.

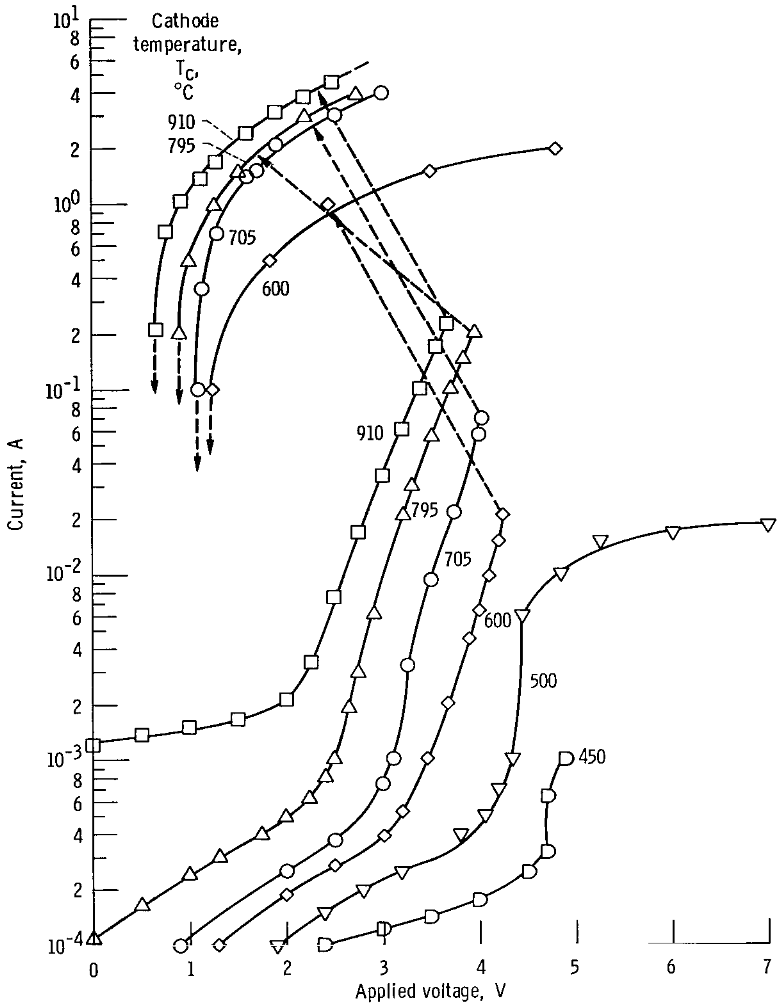


Figure 3. - Effect of varying cathode temperature on current-voltage characteristics near pressure-spacing product minimum. Cesium temperature, 206° C; pressure, 0.103 torr; anode temperature, 360° C; electrode spacing, 0.130 centimeter; pressure-spacing product, 0.013.

curve changes discontinuously as the voltage is increased. Where there is no discontinuity in the I-V curve, the breakdown voltage is taken to be the point of the steepest rise in current with increasing voltage. Figures 2 and 3 illustrate the I-V behavior of the development of the discharge, which is typical qualitatively of all the regions and conditions investigated. The behavior of these curves compares with the I-V curves of Lebedev (ref. 12) and follows the typical form of hot-cathode discharges in other gases.

The currents through the tube at breakdown were of the order of milliamperes, or less, for all conditions. The discharge currents after breakdown, however, varied from milliamperes for a low-temperature cathode to several amperes for a high-temperature cathode. This indicates the existence of two distinct types of discharges differing in cur-

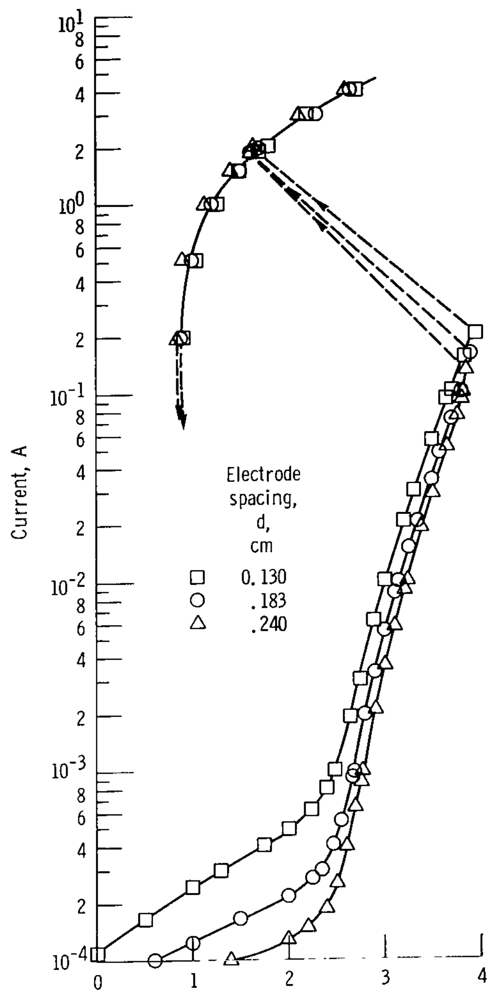


Figure 4. - Effect of variation in electrode spacing on current-voltage characteristics near pressure-spacing product minimum. Cesium temperature, 210° C; pressure, 0.119 torr; anode temperature, 365° C; cathode temperature, 795° C.

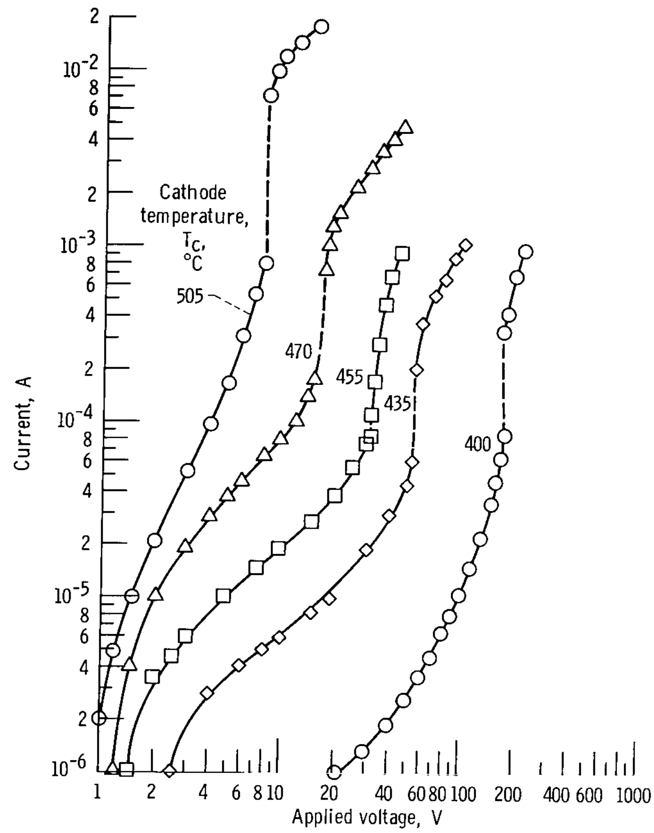


Figure 5. - Effect of varying cathode temperature on current-voltage characteristics for diode with hot anode. Cesium temperature, 276° C; anode temperature, 800° C; electrode spacing, 0.126 centimeter; pressure-spacing product, 0.137 torr-centimeter.

rent level by a factor of 100. The transition region between the two forms of discharge occurs for cathode temperatures around 500° C.

With the cathode temperature T_c less than 500° C, the discharge may be characterized as a glow, which is initiated around the electrodes and spreads to fill the volume of the tube as the voltage is increased. For T_c greater than 500° C, an anode glow was observed very near the anode just prior to breakdown. After breakdown, the more stable and higher current discharges, the ball-of-fire or the low-voltage arc, were obtained. Figure 2 has notations of the visual characteristics of the cesium hot-cathode discharge as they relate to various portions of the I-V curves. A comprehensive explanation of the

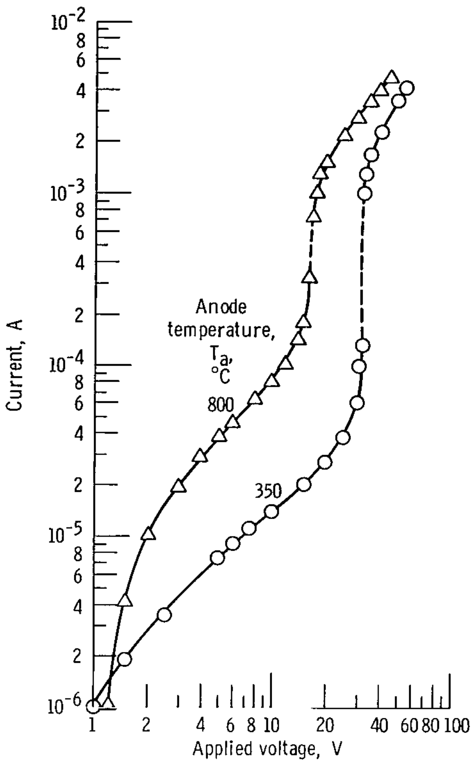


Figure 6. - Comparison of current-voltage curves for two anode temperatures and fixed cathode temperature. Cathode temperature, 470° C; cesium temperature, 276° C; pressure, 1.09 torr; electrode spacing, 0.126 centimeter; pressure-spacing product, 0.137 torr-centimeter.

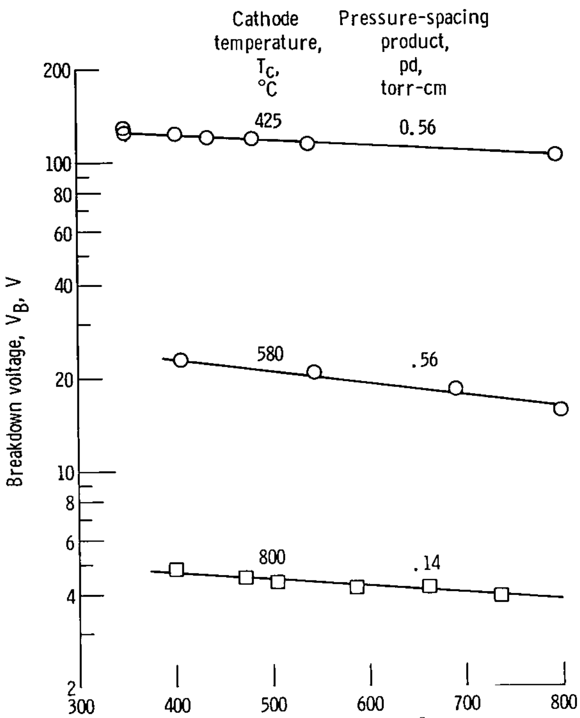


Figure 7. - Dependence of breakdown voltage on anode temperature for selected cathode temperatures and pressure-spacing product values.

modes of the hot-cathode discharge is given by Martin (ref. 13).

The I-V curves in figure 4 show the result of a variation in the spacing near the pd minimum. The shape of the curves is virtually unchanged, but the relative magnitudes of the currents and voltages are decreased as the spacing is increased. The I-V characteristics of the diode operated with an 800° C anode and low-cathode temperatures are shown in figure 5. A change in the anode temperature alters the I-V characteristics, as shown by the two curves in figure 6. Note that the voltage at breakdown decreases and the current increases for an elevated anode temperature. Figure 7 shows the typical dependence of breakdown voltage on anode temperature. The breakdown voltage, in general, decreases about 20 percent as the anode temperature is raised from 400° to 800° C.

Cathode and anode temperatures were monitored closely both before and after an I-V run to observe any variations caused by the discharge. At the higher current levels (the order of amperes), some anode heating and cathode cooling of 1° to 5° C was detected. Neither has an appreciable effect on the breakdown results. Cathode heating was observed

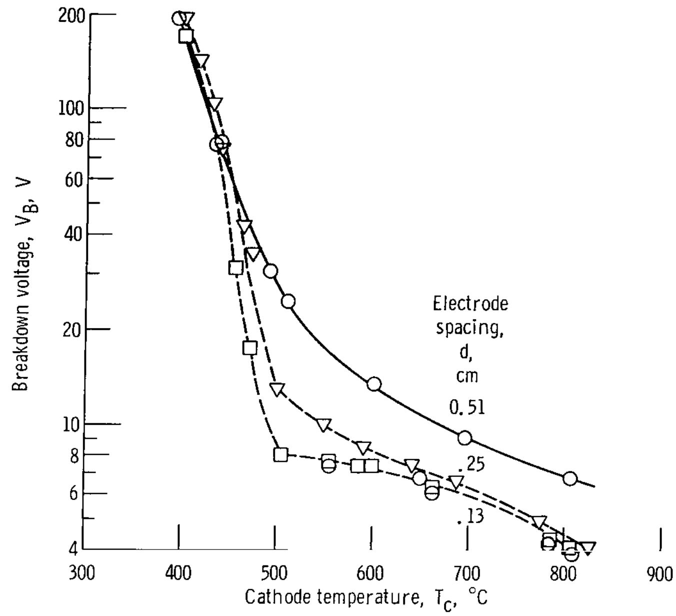


Figure 8. - Breakdown voltage as function of cathode temperature with hot anode and effect of variation in spacing shown. Cesium temperature, 276° C; cesium vapor pressure, 1.09 torr; anode temperature, 800° C.

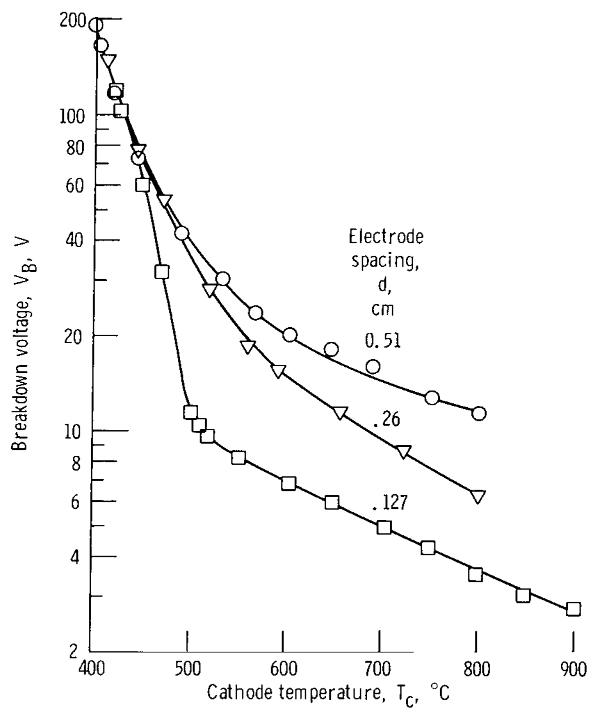


Figure 9. - Breakdown voltage as function of cathode temperature for low-temperature anode and effect of variation in spacing shown. Cesium temperature, 276° C; anode temperature, 365° C.

under conditions yielding high breakdown voltages of 100 volts or more. Positive ions from the plasma bombarding the cathode are a likely cause of this effect. Cathode heating tends to lower the observed breakdown voltage.

The breakdown voltage as a function of cathode temperature variation is plotted in figures 8 to 10. A comparison of figures 8 and 9 shows that the shape of the breakdown curves does not depend strongly on spacing or anode temperature. The magnitude, however, is proportional to spacing and inversely proportional to anode temperature, as previously mentioned. Two additional observations should be noted: (1) spacing had little or no effect on the breakdown for a cathode temperature T_c less than 450° C, and (2) a definite change in slope occurs at about $T_c = 500°$ C. This change in slope corresponds to changes in the shape of the I-V curves and the visual discharge characteristics. The breakdown voltages observed are in agreement with the maximum inverse voltage curves presented by Coolidge (ref. 14) for similar conditions.

The variation of breakdown potential with cathode temperature is shown in figure 10 for two values of cesium vapor pressure (P_{cs} = 0.107 and 1.09 torr). Note that at the lower cathode temperatures the breakdown potential is much greater for the higher cesium pressure. However, at the higher cathode temperature ($T_c \gtrsim 800°$ C), the breakdown voltage is less for the higher cesium pressure. This indicates that relatively high cesium

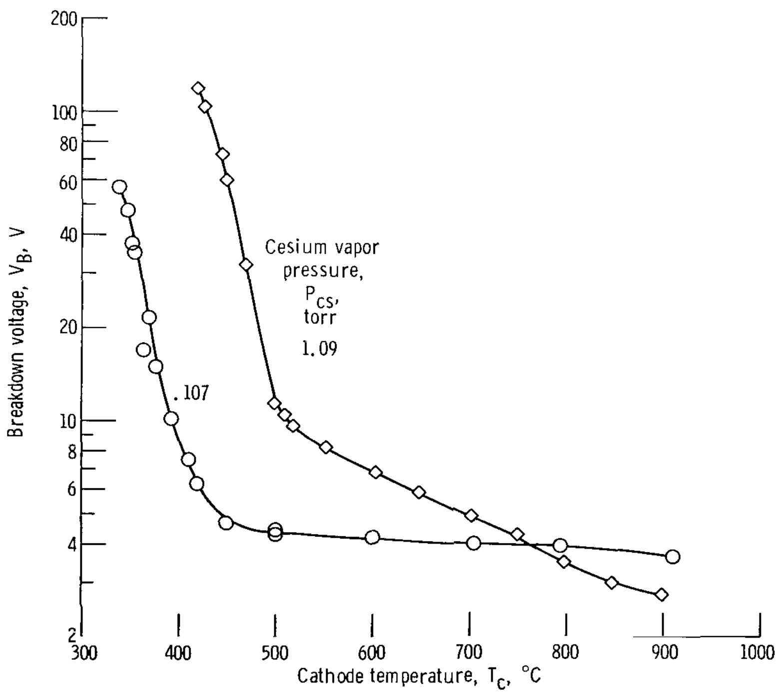


Figure 10. - Breakdown voltage as function of cathode temperature showing effect of variation in cesium pressure. Anode temperature, ≈365° C; electrode spacing, 0.125 centimeter.

vapor pressures (approx 1 torr) would yield both a higher inverse voltage and a lower forward breakdown voltage, which can be correlated to a lower forward voltage drop (cf. fig. 2).

The data from the curves in figures 8 to 10 are displayed in an alternate form by plotting the breakdown voltage as a function of pd in figure 11. These curves show the right arm of the Paschen curve that extends from a characteristic minimum to increasing values of pd. The pd minimum for cesium occurs at about 1.5×10^{-2} torr-centimeter for T_c of 500° C. This is lower than the value of 5×10^{-2} torr-centimeter mentioned by

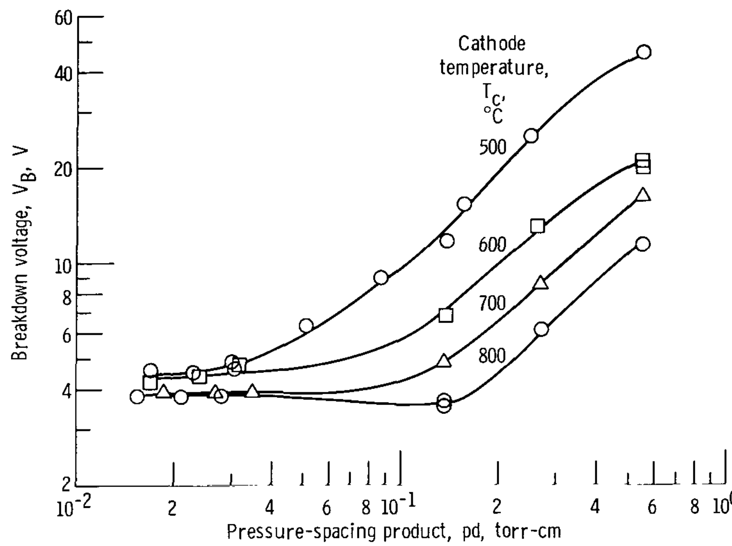
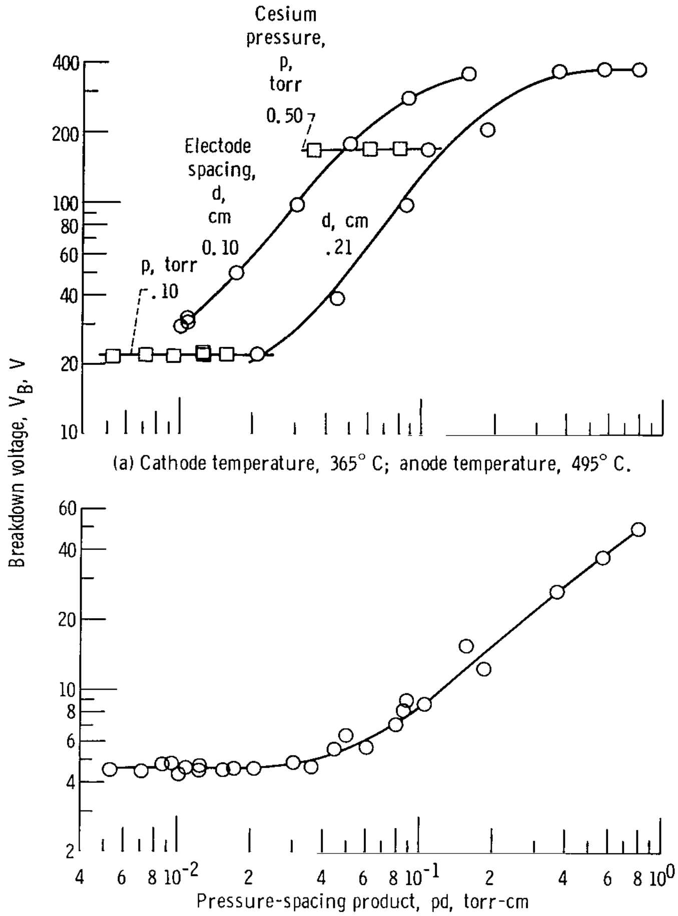


Figure 11. - Breakdown voltage as function of pressure-spacing product at various cathode temperatures. Anode temperature, 365° C.

Lebedev (ref. 5). There is some indication by the flattening of the curves that the breakdown voltage at the pd minimum decreases and the pd minimum shifts to higher pd values as the cathode temperature increases. Gus'kov (ref. 8) notes this effect, also. The region below the pd minimum could not be investigated with this diode. (Below the pd minimum, long-path breakdown effects were observed with the discharge path extending between the shanks of the two electrodes or from electrode to envelope rather than across the gap between the electrodes.)

The behavior of the breakdown voltage V_B as a function of pd is quite consistent for cathode temperatures greater than 500° C (i.e., Paschen's Law is followed). Below about 450° C, however, the values of V_B become scattered. This corresponds to the earlier observation concerning figures 8 and 9, that spacing had little or no effect for $T_c \leq 450°$ C and that the entire mode of the discharge had changed.



(a) Cathode temperature, 365° C; anode temperature, 495° C.

(b) Cathode temperature, 495° C; anode temperature, 365° C.

Figure 12. - Breakdown voltage as function of pressure-spacing product at two cathode temperatures. Breakdown voltage is independent of spacing for cathode temperature of 365° C.

Figures 12(a) and (b) show the curves of breakdown as a function of pd for two cathode temperatures, 365° and 495° C. In figure 12(a), for $T_c = 365^{\circ}$ C, spacing has no effect. A change in spacing at constant p produces a constant V_B. However, with d constant and p varied, V_B does change and exhibits the normal dependence on pressure. Figure 12(b) shows the behavior of V_B for $T_c = 495^{\circ}$ C, where Paschen's Law is more closely followed. All the points from figure 12(a) were replotted in figure 13 as a function of pressure only. Since the spacing varies from 0.05 to 0.21 centimeter, this figure shows that the breakdown voltage in this diode is dependent only on the pressure for this low cathode temperature.

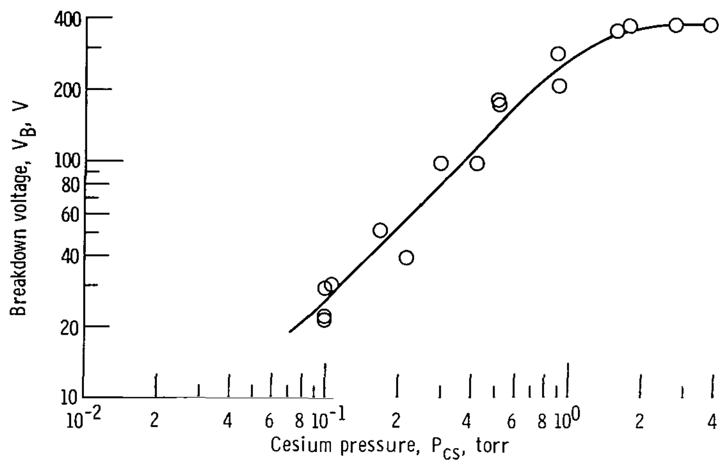


Figure 13. - Breakdown voltage as function of cesium pressure at low cathode temperature. Cathode temperature, 365° C; anode temperature, 495° C.

CONCLUDING REMARKS

The results of the study indicated that cesium-filled devices for power conditioning applications (rectifiers, thyratrons, etc.) could be developed for use in environments with ambient temperatures up to about 400° C. For maximum inverse voltage capability, the cesium vapor pressure should be relatively high (approx 1 torr). This cesium pressure also permits high current densities ($\gtrsim$3 A/cm^2) with cathode temperatures $\gtrsim$800° C.

The data presented herein may be used as a guide in determining the maximum hold-off voltages in high-temperature rectifiers and thyratrons by assuming that the temperature of the electrode with positive polarity has only a slight effect on the breakdown voltage. (Herein it was shown that the breakdown voltage generally was lowered by about 5 percent per 100° C increase in the temperature of the anode.) It should be noted that different electrode materials (molybdenum was used here) and geometries may change the values of the breakdown voltages from those given in this report.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 10, 1970,
120-27.

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