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LOW-VOLTAGE ARC AND BREAKDOWN EFFECTS IN XENON-FILLED THERMIONIC DIODES

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16. Abstract

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SUMMARY

Breakdown phenomena and the low-voltage xenon arc have been studied in xenon-filled thermionic diodes. These measurements were made at gas pressures ranging from 1 torr (133 N/m^2) to atmospheric pressure and with diodes having interelectrode spacings of 0.05, 0.1, and 0.75 centimeter. Most of the results were obtained on tubes with a unipotential, thoriated tungsten cathode operating at approximately 1700° C.

The results showed that breakdown in xenon leading to the low-voltage arc can occur at voltages even lower than the first excitation potential of xenon. No minimum spacing effect was observed, the low voltage arc occurred for interelectrode spacings down to 0.05 centimeter. At a spacing of 0.05 centimeter and a cathode temperature of 1700° C, the low-voltage xenon arc could be induced over the pressure range of 1 to 500 torr (133 to 6.67×10^4 N/m^2). Under some conditions of pressure and spacing the low-voltage xenon arc could be sustained at voltages as low as 1 to 2 volts.

INTRODUCTION

Low-voltage arc and breakdown effects are associated with studies in hot-cathode discharges. The low-voltage arc is a discharge mode which exists at voltages below the first excitation level of the filling gas (ref. 1); whereas low-voltage breakdown is a phenomenon associated with the ignition of a discharge at voltages below the ionization potential of the gas (refs. 2 and 3). These phenomena occur in the rare gases, alkali metals, and mercury. A historical review of studies in rare-gas low-voltage arcs is given in reference 1.

In some recent work on the low-voltage arc, Martin and Rowe (ref. 1) have made Langmuir probe measurements on a planar thermionic diode filled with either a rare gas or mixture of gases. They were able to distinguish three different hot-cathode-arc discharge modes and characterize them as (1) the low-voltage arc, (2) the ball-of-fire mode, and (3) the Langmuir mode. Their results also showed that the peak plasma potential in the low-voltage arc could be considerably lower than the first excitation level of the gas. In addition, they reported that it was always necessary to apply voltages greater than ionization potential of the gas in order to obtain breakdown to the low voltage arc and ball-of-fire modes of discharge. They also found that the low voltage arc mode could not be obtained at relatively low pressure-spacing values (below 4 to 5 torr cm (5.3 to 6.7 N/m) in neon).

The purpose of this investigation was to study the low-voltage arc and breakdown effects in a cylindrical xenon-filled thermionic diode over a wide range of pressure-interelectrode distance values. Most of the measurements were made using an unipotential, thoriated tungsten cathode, which operated at about 1700° C, but some were made at an operating temperature of 1100° C using a Philips cathode. In this study the low-voltage ignition phenomenon was measured at applied voltages below the lowest resonance potentials for xenon, and the low-voltage xenon arc measurements were made at pressure-interelectrode space values as low as 0.05 torr-centimeter (0.07 N/m).

EXPERIMENTAL TECHNIQUES AND RESULTS

The type of gas-filled diode used in most of these measurements is shown in figure 1. The tube envelope is 304 stainless steel. There are two separate parts to the device. The evacuated lower volume is used for electron bombardment heating of the thoriated tungsten cathode 2. The upper portion contains the filling gas. The outside diameter of the thermionic emitter is about 1.0 centimeter and its effective emitting length about 1.3 centimeters. Different tubes were constructed having interelectrode spacing of 0.05, 0.10, and 0.75 centimeter. The copper pinch-off tube for the lower sealing volume and the gas inlet tube for the upper volume are not shown in figure 1.

The tube was processed on a vacuum system identical to that illustrated in figure 2. The structure is of stainless steel and the system is evacuated by a turbomolecular vacuum pump. Xenon was introduced into the valved-off gas system by breaking the glass seal on the gas bottle, condensing the gas into cold finger, and then sealing off gas bottle. The gas pressure in the system is controlled, over the range of 1 torr (130 N/cm^2) to approximately atmospheric pressure, by controlling the temperature of the cold finger. The pressure is accurately measured to ±0.25 torr (33 N/m^2) by the capacitance manometer. This instrument is used as a null indicating device in conjunction with helium gas and a mercury manometer in an auxiliary system. The maximum impurity levels reported in the xenon gas bottle were nitrogen at 5 ppm and hydrogen at less than 5 ppm.

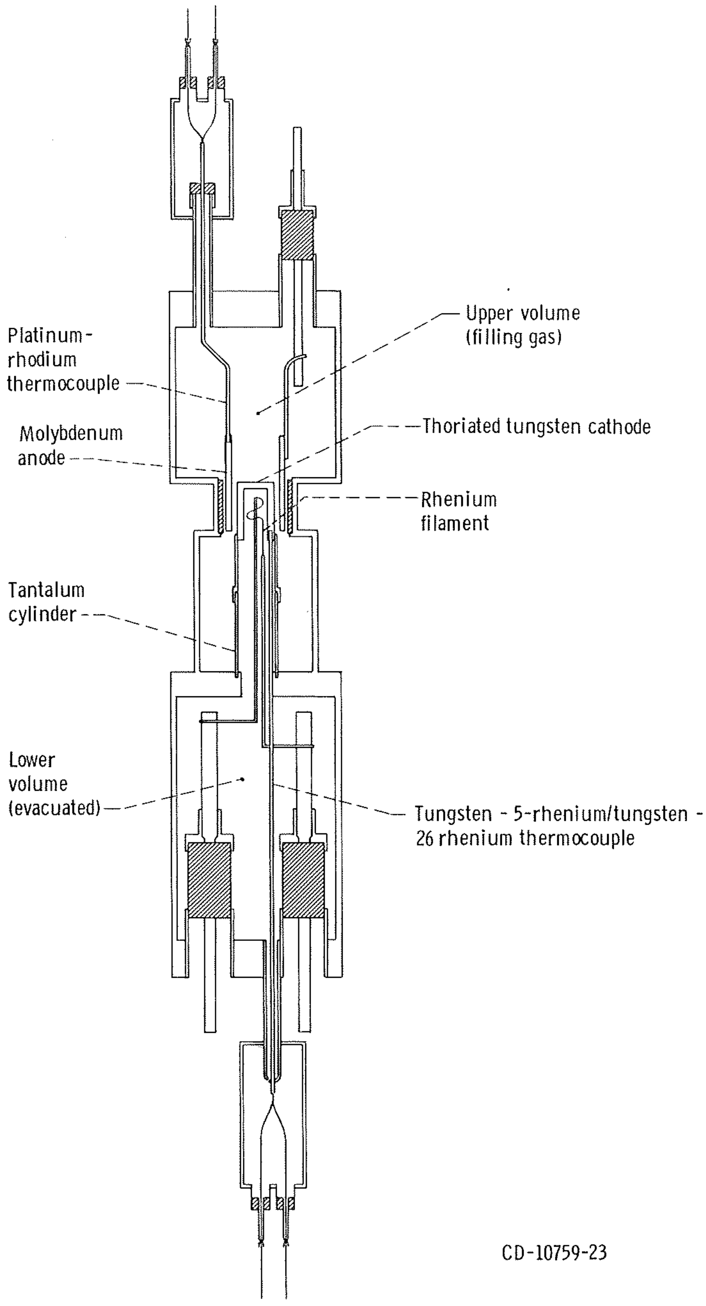

Figure 1. - High-temperature gas-filled thermionic diode.

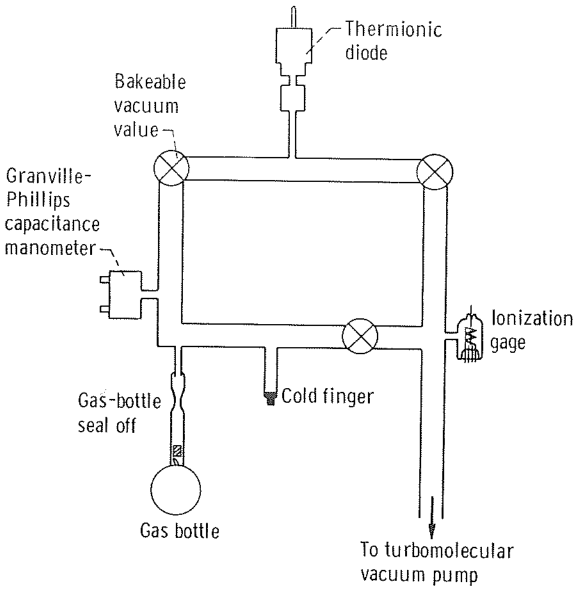

Figure 2. - Vacuum system for processing diode.

Prior to the introduction of the gas, the thoriated tungsten cathode tube was processed. It was baked out at 400° to 450° C for 24 to 32 hours. The cathode was then degassed at approximately 1750° to 1800° C for about 7 to 9 hours and finally aged for a few hours with relatively high direct currents being drawn. As an example, a tube with an 0.05-millimeter interelectrode spacing was run for 7 hours with an anode voltage of about 55 volts and a corresponding anode direct current of 1.6 amperes. During this run, the cathode temperature was 1720° C, and the anode temperature about 1380° C. After this type of process, the pressure in the system was in the range of 10^{-9} with the tube cold and 10^{-8} with the tube hot.

Low-voltage arc data were also obtained from a diode using a Philips cathode as the thermionic emitter. The design and processing prescription for this type of tube have been previously described (ref. 4).

Electrical measurements were made with a simple direct-current circuit using a 0- to 20-volt and a 0- to 30-ampere regulated power supply. The current was read across a 0- to 30-ampere shunt (100-mV drop at 30 A), and the current voltage characteristics were recorded on an X-Y recorder.

EXPERIMENTAL RESULTS AND DISCUSSION

The discharge data obtained from a thoriated tungsten cathode tube with an interelectrode spacing of 0.05 centimeter, at different xenon pressures, is shown in figure 3.

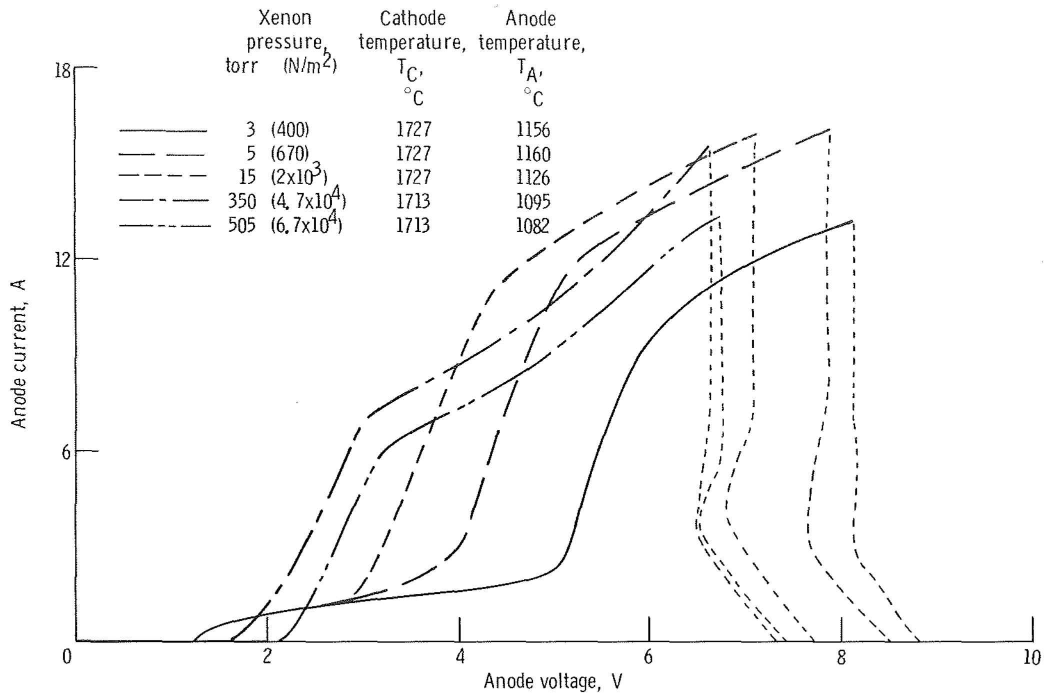

Figure 3. - Discharge characteristics of thermionic diode. Interelectrode spacing, 0.05 centimeter. Temperature in key were taken before ignition.

The short dashed portion of the curves at breakdown is a transient, instantaneous response. It should be noted in all these curves that breakdown occurs at voltages considerably lower than the ionization potential (12.1 eV). In fact, at pressures above 5 torr, breakdown occurs at a voltage below that corresponding to the lowest excited state (8.3 eV). After breakdown, the current rises to a point determined by the external resistance in the circuit, and the stable discharge current associated with the applied voltage minus the IR drop in the external circuit. The discharge characteristics are stable but the anode temperature rises on discharge. When 10 to 15 amperes are drawn continuously, the anode temperature rises a few hundred degrees Celsius. Each value of anode temperatures noted in the figure are all measured before breakdown. Although the discharge was not visually observed, the nature of the characteristic indicates that the arc is the low voltage arc. The currents are in the ampere range (corresponding to A/cm^2 from the cathode) and the arc is sustained at voltage values much lower than the first excitation potential.

Figure 3 also illustrates that the low-voltage arc occurs at a pressure-spacing value of 0.15 torr-centimeter (0.20 N/m) (note 3 torr curve). Another measurement on this tube (not shown in fig. 3) at 1 torr (130 N/m^2) showed that the low voltage characteristic was similar to that shown for the 3-torr (400 N/m^2) curve of figure 3 except it was initiated at 10.2 volts (well above the excitation potential). These data for xenon are different from those reported for the neon low-voltage arc by Martin and Rowe (ref. 1). They stated that they were unable to ignite the low-voltage arc without the application of voltages greater than the ionization potential of the gas and that the low-voltage arc in xenon could not be obtained at pressure-spacing values below 4 and 5 torr-centimeters (5.3 to 6.7 N/m). Although they experimented with the xenon low-voltage arc (refs. 1 and 5), they had considerable difficulty with cathode emission problems, and did not publish any xenon data. Cathode poisoning was not a problem in the present study for either thoriated tungsten or the Philips cathode tubes. Discharge currents were stable and could be maintained in the amperage range.

One interesting feature of the data in figure 3 should be noted: the characteristic shape of a curve at given pressure. At some voltage, for a given pressure, the slope of the curve will change abruptly, an indication of a mode change in the discharge. These characteristic shapes are a stable feature of the curves. One can reproduce these features by either increasing or decreasing the voltage.

Since the relative difference in work function between cathode and anode is important for an interpretation of these data, an experiment was run to determine this difference. Before xenon was introduced to one tube with an interelectrode spacing of 0.05 centimeter, retarded and accelerated field data were taken on the thoriated tungsten cathode at a temperature of 1725° C. The anode work function was graphically determined from observed current density in the retarding field range and was found to be within 0.2 electron volt of the cathode work function. In addition, saturated thermionic emission from the anode could be measured at anode temperatures of about 1125° C. When similar measurements were made on the cathode at this temperature, the same saturated emission value was found. This value corresponds to a work function value of 3.0 electron volt (assuming $A = 120\ A/cm^2\ K^2$). The most obvious explanation for the similarity of work function for the two electrodes is that the deposition of thorium on the anode from the cathode results in a thoriated molybdenum surface having approximately the same work function as thoriated tungsten.

This evidence confirms the fact that early breakdown at voltages below the lowest xenon excited state (8.3 eV) is an empirical result which cannot be attributed to large-contact potential differences between electrodes. One possible explanation for the phenomenon is that long-lived excited states are generated by electrons in the Maxwellian tail of the emitted distribution when voltages in the range of 7 volts are applied. Increases in voltage lead to further ionization of these long-lived species (metastables and resonant states whose populations are maintained by trapping of radiation), increasing the ion-electron concentration in the gas. This finally results in ignition and the generation of the low-voltage arc.

Figure 4 illustrates the discharge results obtained on another tube with an interelectrode spacing of 0.05 centimeter and an xenon pressure of 2 torr (270 N/m^2) where

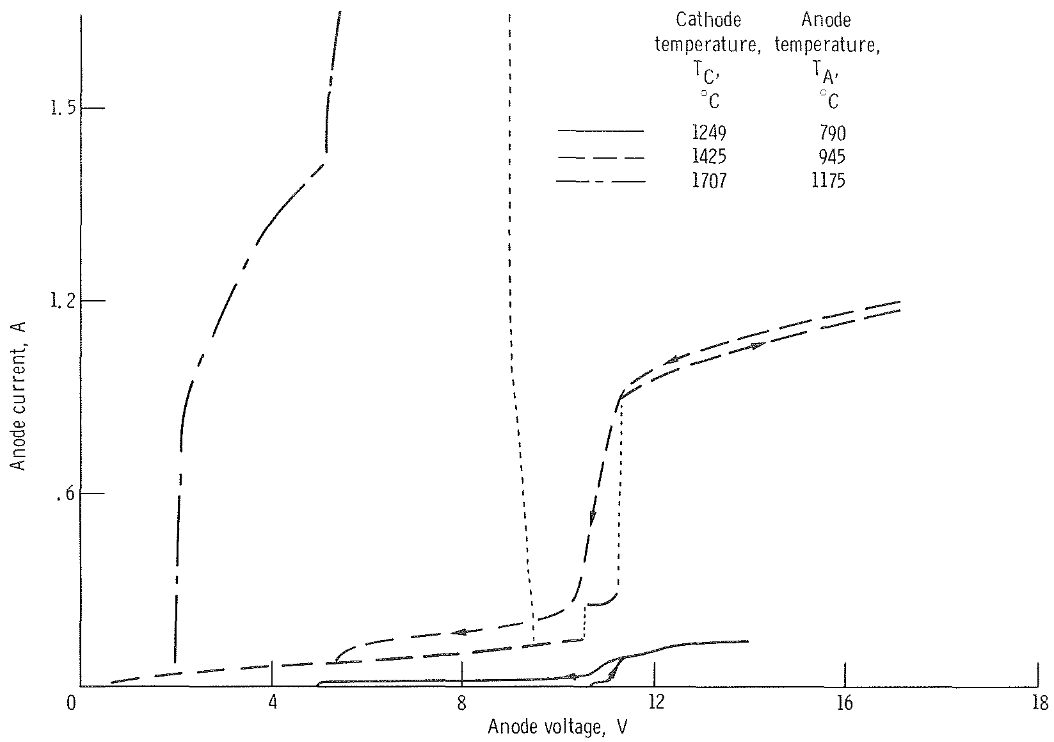

Figure 4. - Discharge characteristics of thermionic diode. Interelectrode spacing, 0.05 centimeter; xenon pressure, 2 torr (270 N/m^2). Temperatures were measured before ignition.

the cathode temperature is the variable parameter. At low temperatures breakdown occurs at voltages slightly lower than the ionization potential (12 eV). The current rises to an apparent saturation value that corresponds quite well to the calculated saturated cathode emission current for that temperature. This corresponds to a Langmuir discharge mode at low temperature as distinguished from the low voltage arc which occurs at the higher temperature of 1707° C. Again, it should be noted that all these breakdown curves have characteristic shapes which are reproducible.

Data at the other extreme of relatively high interelectrode spacing are illustrated in figure 5. These results, at spacings of 0.75 centimeter show characteristics similar to those illustrated in figure 3, except that early ignitions that are generated at voltages lower than the first excitation potential occur at lower pressure values. At a pressure of 187 torr (2.5×10^{4} N/m^2), breakdown occurs at the ionization potential, and at 55 torr (7.3×10^{3} N/m^2) it occurs at about the value of the lower excitation potential. At 1 torr (130 N/m^2) ignition occurs again at 12 volts (data not shown).

An experiment was also run to determine the influence of cathode temperature on breakdown and low-voltage arc characteristics. This was accomplished by studies on a cylindrical diode, similar in geometry to that of figure 1, with a Philips cathode and an interelectrode space of 0.05 centimeter. The tube used is identical to that described

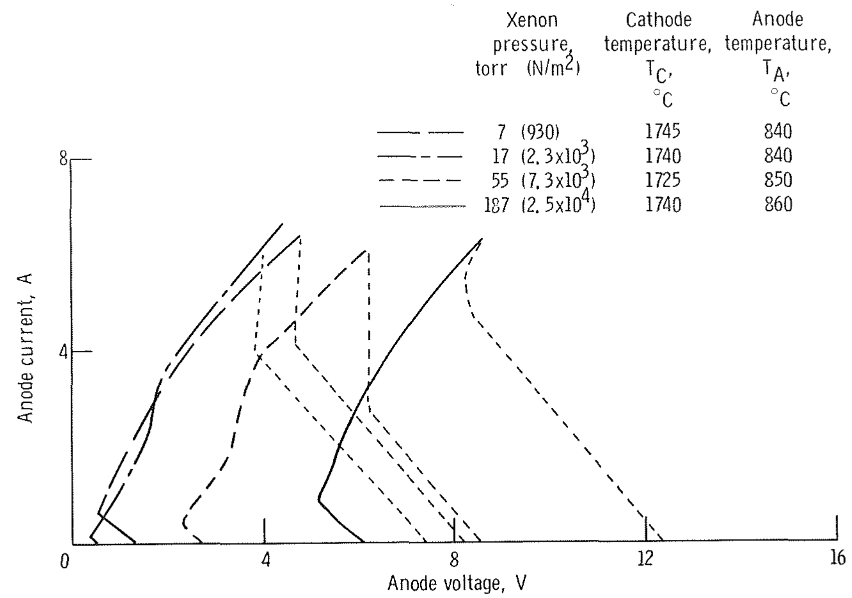

Figure 5. - Discharge characteristics of thermionic diode. Interelectrode spacing, 0.75 centimeters. Temperatures were measured before ignition.

previously (ref. 4), and it was mounted on the vacuum system shown in figure 2. After processing in vacuum, xenon gas was introduced and current-voltage characteristics obtained as a function of gas pressure. These data are shown in figure 6. The low-voltage arc currents measured were lower than observed in the thoriated tungsten tube data. The Philips cathode tubes seemed to have a relatively large internal resistance effect (approximately 0.6 ohm), which was not present in the high-temperature diodes. Ignition in all these measurements always occurred at voltages greater than the first ex-

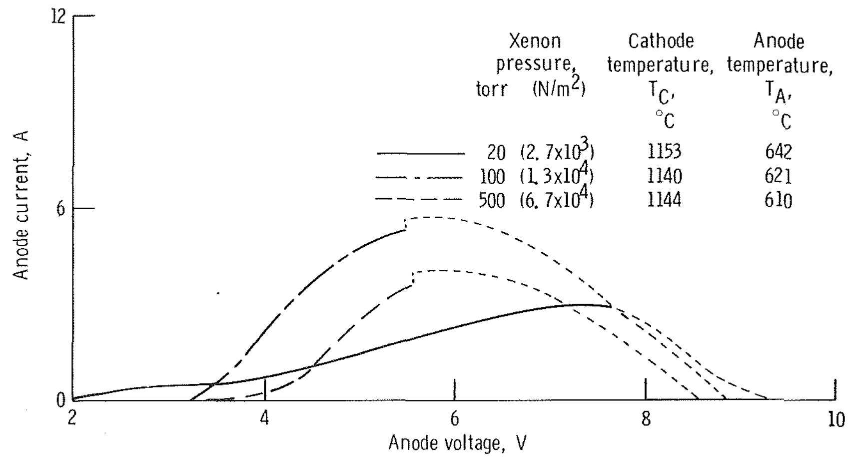

Figure 6. - Discharge characteristics of diode with Philips cathode. Interelectrode spacing, 0.05 centimeter. Temperatures were taken before ignition.

citation potential but below ionization potential. These characteristics have quite different shapes in the low-voltage arc region than those shown in figures 3 to 5. The low-voltage arc mode was stable, and the characteristics were reproducible with time. After the measurements were made at various xenon pressures, the gas was condensed in cold finger of figure 2, the appropriate valve closed, which isolated the gas system, and the tube evacuated again. The thermionic capabilities of the cathode were then determined by pulse emission testing and found to be unchanged.

CONCLUDING REMARKS

Data obtained in this investigation of the low voltage arc in a xenon discharge can be summarized as follows:

1. The low-voltage arc occurred over a wide variation of pressure-interelectrode spacing. The range of pressure-spacings encompassed by this study varied from 0.05 to 150 torr-centimeter (0.07 to 200 N/m).

2. The low-voltage arc occurred in xenon at interelectrode spacings as low as 0.05 centimeter. There was no apparent minimum spacing effect as was reported in reference 1.

3. Ignition of the low-voltage arc occurred at breakdown voltages below the ionization potential of xenon over a wide range of pressure-spacing values.

4. Ignition at voltages even lower than the first excited state of xenon were observed under some conditions in thermionic diodes with thoriated tungsten cathodes.

Phenomenologically, the xenon low-voltage arc is similar to that of the cesium ignited mode (refs. 6 and 7). It can be sustained at very small interelectrode spacings and breaks down at ignition voltages below its first excitation potential. It has generally been assumed that the ionization mechanism for the ignition of inert gas discharges is one of direct ionization from the ground state (ref. 8). However, the data obtained in this investigation indicate that the ignition mechanism of the xenon low-voltage arc is a stepwise process similar to that of the cesium low-voltage arc. Electrons in the tail of the Maxwellian distribution gain energy falling through the applied ignition voltage and populate excited levels of the rare gas atoms by collisions. These excited states can then be readily ionized by further electron collisions since they have large inelastic cross sections.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 27, 1970,
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