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DETERMINING THE MODE OF HIGH VOLTAGE BREAKDOWNS IN VACUUM DEVICES

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ABSTRACT

We constructed devices which were essentially vacuum diodes equipped with windows allowing observation of high voltage breakdowns. We then used photography, recording the waveform of the applied voltage, and monitoring the X-ray output to investigate electrical breakdown in these vacuum diodes. Our results indicate that breakdowns may be divided into two types: (1) vacuum (interelectrode) breakdown - characterized by a diffuse moderately bright discharge, a relatively slow and smooth voltage collapse, and a large burst of X-rays, and (2) surface (insulator) flashover - characterized by a bright discharge with a very bright filamentary core, a relatively fast and noisy voltage collapse and no X-ray burst. Therefore, we conclude that useful information concerning the type of breakdown in a vacuum device can be obtained by monitoring the voltage (current) waveform and the X-ray output.

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INTRODUCTION

High voltage breakdowns (HVBs) occur in many vacuum devices. It frequently is of great practical interest to know the type (or mode) of such HVBs, since this can indicate weak points in the device. Post-mortems can sometimes be useful, but it would be quite desirable to have a technique which would allow the HVB mode to be determined in an operating device. Photography can be quite helpful, but unfortunately many devices do not permit optical access to the region of interest. However, the idea of using photography in conjunction with other diagnostic techniques to establish the validity of these techniques seemed promising, since these techniques could then be used to determine the mode of HVBs in opaque devices.

In this paper we shall limit ourselves to techniques utilizing electrical or electromagnetic phenomena. Within this limitation, we will consider possible diagnostic techniques (parameters to measure) applicable to the HVB mode identification problem. We shall show that a literature search strongly suggests the usefulness of these techniques, then present experimental evidence confirming their validity.

Two obvious (interrelated) parameters to measure are the voltage applied to the device and the current through the device. Many vacuum devices also emit X-rays when voltage is applied to them, which X-rays are sufficiently energetic to be detected outside the device. A literature search resulted in much useful information concerning the possible suitability of these parameters as diagnostic tools.

Upon looking in the published literature for information pertinent to using these parameters to distinguish between types of HVBs, it quickly became apparent that the breakdown time was quite important, but that careful distinctions had to be made between the various times associated with breakdowns in the literature. Frequently there is a delay (t_d) between the application of voltage (or attainment of maximum voltage) and the beginning of breakdown. The actual time it takes for complete breakdown to occur once it has started is t_{brk} (also referred to as the voltage collapse time t_c or current rise time t_r).

Unfortunately, the time for an HVB to occur may be defined by an author as $t_{HVB} = t_d + t_{brk}$, or as $t_{HVB} = t_{brk}$, or sometimes it is not defined at all. In this latter case the reader must try (with more or less confidence) to decide exactly which t_{HVB} the author is using. If $t_d \ll t_{brk}$ the distinction isn't important, but in many cases $t_d \approx t_{brk}$ or even $t_d \gg t_{brk}$. It is necessary to stress this distinction because we noted that t_{brk} seemed to correlate much better with the type of breakdown than did t_d.

Several investigators have found that the time for an HVB to occur along an insulator (surface flashover) is relatively short, of the order of a few nanoseconds. This voltage collapse time was found to be a linear function of gap length which implies that the voltage collapse propagates along the surface with a constant velocity. For surface flashover this velocity seems to be of the order of 10^7 m/s.[1-4]

Many investigators have measured t_{brk} for vacuum breakdown. Again, a linear relationship seems to exist between the collapse time and the gap length. However, the implied collapse velocity is considerably slower for vacuum breakdown, being 10^4 to 10^5 m/s.[5-9] Thus, the expected voltage collapse times for HVBs are predicted to be significantly different for surface flashovers as compared to vacuum breakdowns. Therefore measuring the voltage collapse time offers promise as a means of determining the mode of breakdown.

Baksht et al[10] investigated the production of X-rays during breakdown of 1- to 5-mm vacuum gaps. They found that a burst of X-rays was emitted at the time the current through the gap increased sharply (voltage collapsed). The duration of this X-ray burst was approximately the same as the rise time ($I = 0.1$ to 0.9 of I_{max}) of the current. The X-ray burst duration was thus proportional to the gap length. Therefore, measuring the X-ray output of a device also seems promising as a means of determining the mode of an HVB.

PROCEDURE

We used two separate experimental setups. The first setup was designed to monitor the applied voltage waveform and X-ray output of a vacuum device. A single camera was used to take photographs of HVBs. We found that the light intensity from an HVB varied greatly, so it was very difficult to obtain satisfactorily exposed photographs of HVBs with a single camera. Therefore, we used a second setup, which was designed primarily to obtain photographs of HVBs. This second setup is shown in Figure 1. The two-camera arrangement worked very well enabling us to photograph satisfactorily both bright and dim HVB phenomena. We used 3000 ASA speed Polaroid* film, with about a three or four stop difference in sensitivity between the cameras. Most of this difference was attributed to the disparity between transmission and reflection of the pellicle beam splitter, with fine adjustments being made with the camera apertures. X-ray measurements were not made in this second setup because it was located in an area designed for optical investigations and the X-ray detector was in use elsewhere.

*Trademark, Polaroid Corp.

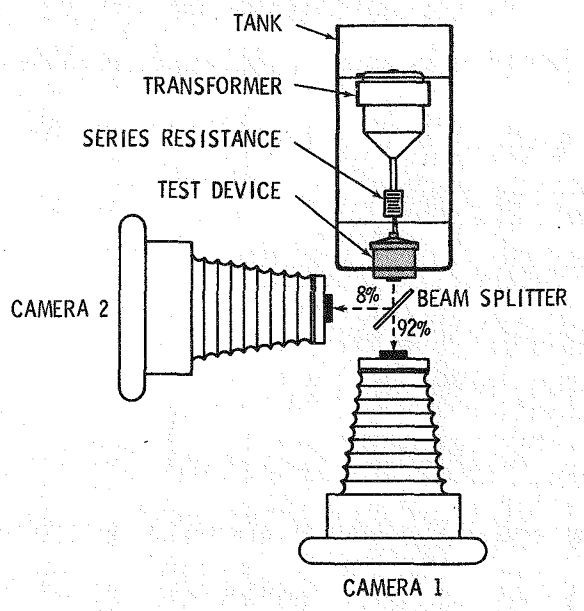

Figure 1. Layout of Second Experimental Setup

The length of the applied voltage pulse had to satisfy two conflicting requirements: a pulse length of at least a few microseconds would be desirable to ensure that both surface and vacuum HVBs could occur readily. However, the longer the pulse, the larger and heavier the required transformer and PFN line would have to be. We used a 12-μs pulse, moderately trapezoidal, but with the voltage rising slowly throughout most of the pulse. The 12-kΩ series resistance was used to reduce the stress of an HVB on the transformer.

Our test devices were vacuum diodes, with a single insulator separating the electrodes either longitudinally (first setup) or coaxially (second setup). These vacuum diodes were fabricated using standard ultrahigh vacuum techniques.

RESULTS AND ANALYSIS

In our first experimental setup we observed breakdown in a vacuum diode using a hollow cylindrical alumina insulator, which is described elsewhere.[11] Two distinct types of breakdown occurred as seen by differences in the voltage and X-ray waveforms. These results are shown in Figure 2. The fast breakdown was defined by a very rapid decrease in the voltage waveform, too fast to be seen on the oscilloscope trace. The probable voltage collapse time is less than 0.1 μs. The trace became visible again near the original baseline, appearing at first as a very noisy (ringing) signal. No appreciable X-ray signal was seen, but a burst of noise appeared at the time of voltage collapse, presumably from pickup. Photographically, a bright track along the insulator surface extended from cathode to anode. The slow breakdown was defined by a relatively slow (~ 1/3 μs) voltage collapse. Simultaneously, a large burst of X-rays was produced. No bright track was seen.

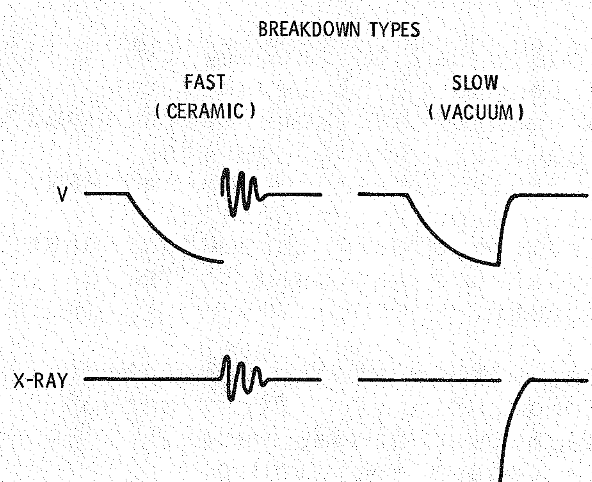

Figure 2. Voltage and X-ray Waveforms for Two Types of HVBs

In our second setup we observed breakdown in a vacuum diode with a coaxial geometry. Usually the center electrode was positive, so we could observe the entire triple junction (the cathode-insulator-vacuum interface) at the cathode (outside) electrode. The center electrode is slightly reentrant, so the center electrode-insulator boundary is not visible. Again HVBs mainly fell into two distinct classes. An example of the first class is shown in Figure 3. Note that because of the beam splitter the right-hand photograph is reversed left to right.

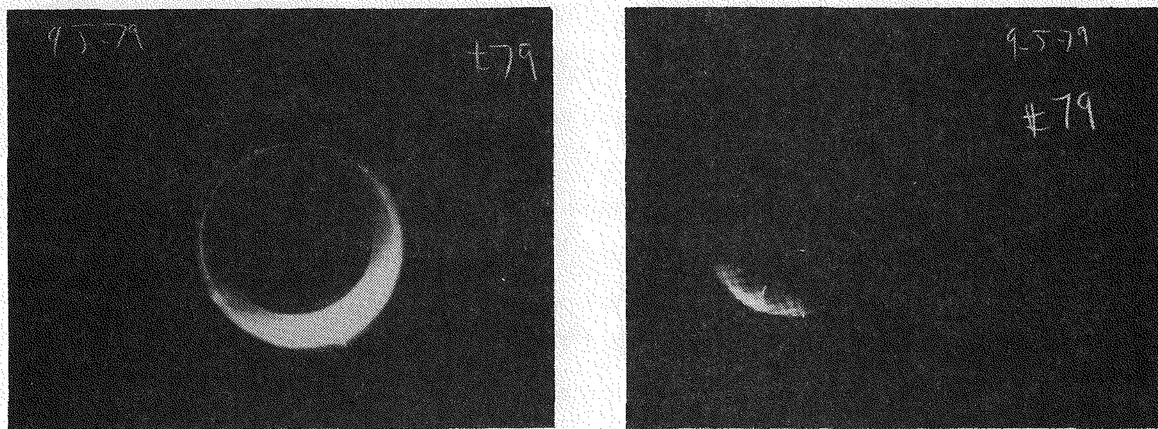

Figure 3. A Surface Flashover HVB

The discharge is bright, with a very bright filament and a glow near the cathode. It is quite localized and appears to be close to the surface of the insulator. The bright filament tends to be centered in the cathode glow. The associated voltage waveform indicates a quite noisy collapse.

A member of the second class of HVBs is shown in Figure 4. The discharge is moderately bright, but dimmer than the first class. It is diffuse and appears to fill much of the device volume, as is shown by the appearance of the cross in the center of the center electrode (anode). This cross is located well below the edge of the anode. It can be used as a support for various components, but for our HVB investigations serves as a convenient focus point and as an indicator of a discharge which is located above the anode. A similar type of discharge is shown in Figure 5. This appears much like Figure 4, except that the discharge is significantly more localized, being toward one side of the device and mostly in the cathode-anode region below the top of the anode. In both cases the voltage waveforms are comparatively noise free.

These results complement those obtained with the first experimental setup. They again indicate that HVBs in vacuum devices may be divided into two categories:

(1) Vacuum (interelectrode) breakdown - The discharge is moderately bright, diffuse, and fills much of the device volume. It frequently covers the entire cross section of the device. The voltage collapse is noise free and relatively slow.

(2) Surface (insulator) breakdown - The discharge is bright with a very bright filamentary core and a cathode glow. The discharge is very near or at the insulator surface. The voltage collapse is very noisy and relatively fast.

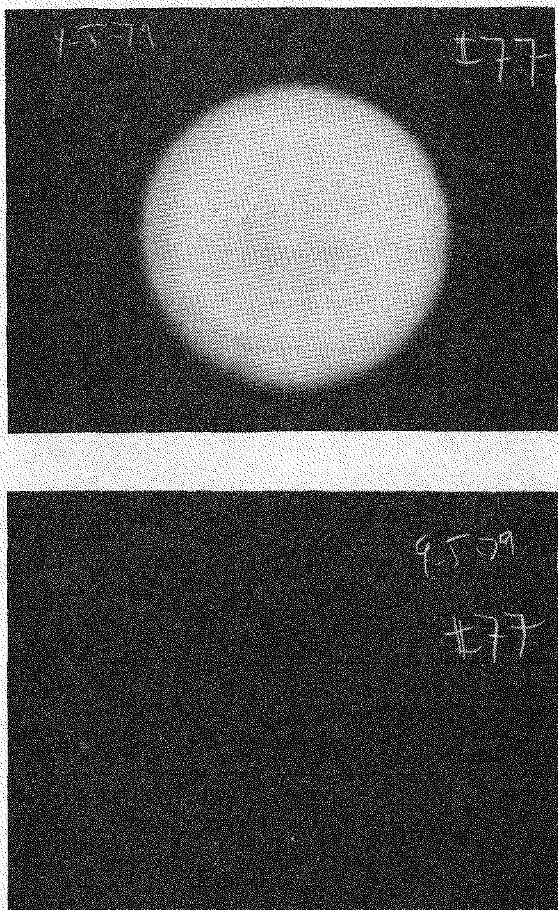

Figure 4. A Vacuum HVB

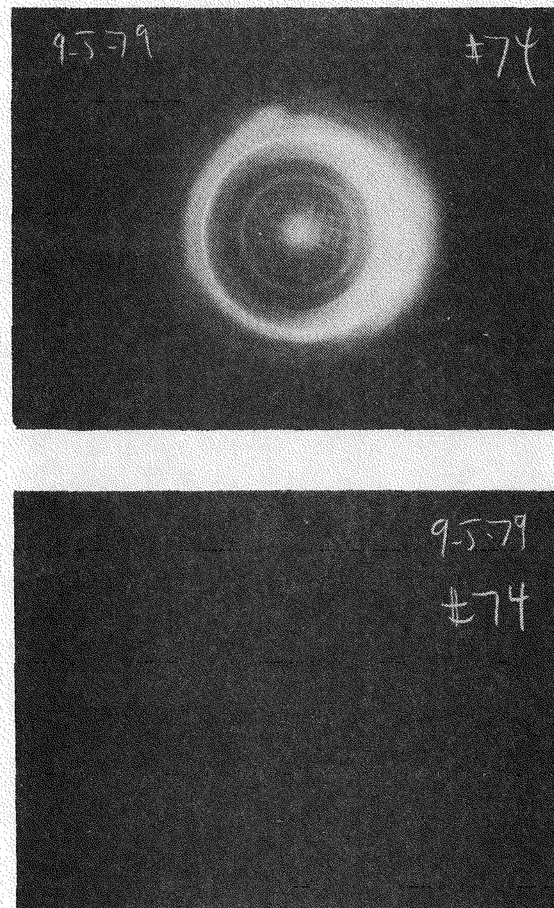

Figure 5. A Localized Vacuum HVB

SUMMARY AND CONCLUSIONS

HVBs occur in vacuum devices. It would be useful to know the mode of breakdown, since this could indicate weak points in the device. We have investigated breakdowns in vacuum devices by using photography, by recording the applied voltage waveform, and by monitoring the X-ray emission from the device. Our results indicate that HVBs may be divided into two types:

(1) Vacuum (interelectrode) breakdowns - characterized by a diffuse moderately bright discharge, generally covering a large region of the device; a relatively slow and smooth voltage collapse, and a large burst of X-rays.

(2) Surface (insulator) flashover - characterized by a bright localized discharge with a very bright filamentary core; a relatively fast and noisy voltage collapse, and no X-ray burst.

Therefore, we conclude that by monitoring the voltage (or current) waveforms and the X-ray output of vacuum devices which suffer from HVBs, the type of HVB can be determined.

FUTURE PLANS

We plan to continue our investigations, looking for additional correlations between the photographic and voltage waveform observations.

ACKNOWLEDGMENTS

F. D. Ansell and W. S. Forshay helped with the measurements. C. W. Wiltshire has shown the advantage of using a digital waveform recorder for similar voltage measurements.

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