

# ULTRA-VIOLET INDUCED INSULATOR FLASHOVER AS A FUNCTION OF MATERIAL PROPERTIES

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## Abstract

Previous work has shown that a small fluence of UV photons is sufficient to initiate flashover at the insulator/vacuum interface of a vacuum insulated transmission line.<sup>1</sup> In this paper we examine the behavior of polyethylene, polystyrene, and teflon insulators in which the dielectric/vacuum interface was oriented at a 45-degree angle to the applied electric field. Field stress was varied over the range 10-70 kV/cm, both positive and negative polarity. The insulators were exposed to various UV spectra with photon energy up to 12 eV. All insulator materials were unaffected by radiation with photon energy 3 eV or less regardless of power. The geometry which withstood the greatest photon fluence was, for every material, the inverse of the geometry suggested as preferable by applying conventional DC breakdown criteria. A model explaining the polarity phenomena as well as the insulators' behavior under various spectra is proposed.

## Experimental Setup

An apparatus was devised to test insulators of several materials while varying the parameters of interest. A small plasma focus device was constructed to serve as a UV source. The energy for this device was provided by a single, 6-microfarad high energy density capacitor typically charged to 35 kV, making available approximately 3.5 kJ of electrical energy. The total photon energy radiated by the device was on the order of 20 J. The focus chamber was prefilled with 5 Torr Helium, while windows of quartz or magnesium fluoride provided an interface between the Helium atmosphere and a vacuum chamber in which the test insulators were mounted. The quartz window passed UV radiation up to 6 eV photon energy, while the magnesium fluoride passed radiation up to 12 eV. The pressure in the vacuum chamber was  $2-4 \times 10^{-5}$  Torr. The insulators were 5 cm wide, 0.5 cm thick, and were held between two bare aluminum electrodes, one of which was held at ground potential while up to 35 kV positive and negative DC bias was applied to the other electrode, providing up to 70 kV/cm average field stress across the gap. A diagram of the experiment is shown in Figure 1.

## Insulator Geometry

One purpose of this experiment was to determine the effect of electric field polarity on UV-induced insulator flashover. Milton<sup>2</sup> has shown empirically

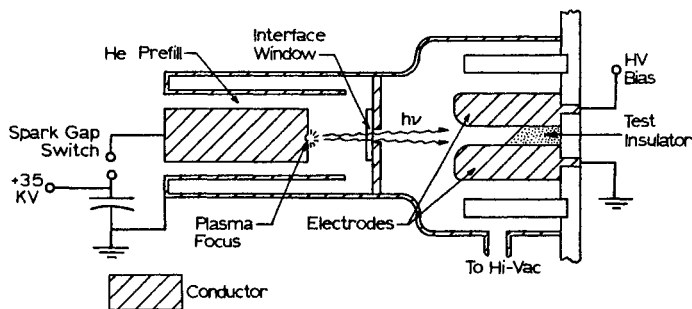


Figure 1. Experimental apparatus.

that the worst (electrically weakest) geometry for plastic insulators is one in which the electric field is tangential to the insulator surface (Figure 2a). In such a configuration, a free electron appearing in the gap receives the greatest acceleration before returning to the insulator. Milton found that the greatest voltage holdoff is obtained when insulators are angled at what is commonly termed "positive angle", so that electrons are accelerated away from the insulator surface (Figure 2b) minimizing their chance of returning to the surface and producing secondary electrons. In this paper this will be called "conventional" geometry. A geometry such that electrons tend to be pulled into the insulator surface (Figure 2c) will be referred to as an insulator at "negative angle" or as the "unconventional" geometry. Milton found that this geometry is somewhat inferior to the conventional geometry in terms of voltage holdoff in the absence of UV illumination, but still far superior to the insulator at zero angle. In this experiment, insulators at both  $\pm 45$  degrees were tested.

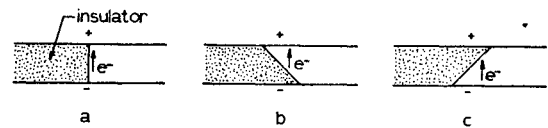


Figure 2. Insulator geometry: a. zero angle b. positive angle c. negative angle.

## Irradiation Spectrum

The spectrum of the illumination was determined by observing the source with a photomultiplier through various bandpass filters in the 200-700 nm range. Each PMT/filter combination was absolutely calibrated versus a standard of spectral irradiance. Absolute radiometry was used to extrapolate the spectrum into unmeasured regions. The equivalent brightness temperature of the source varied from 1.4 eV at 700 nm to 1.8 eV at 200 nm. The inferred spectrum was verified by observing the source with a spectrometer and film which, although not absolutely calibrated, returned the same qualitative spectrum as the PMT/filters. The spectrum is shown in Figure 3. The time of illumination was 25 microseconds, consisting of five pulses of decreasing amplitude.

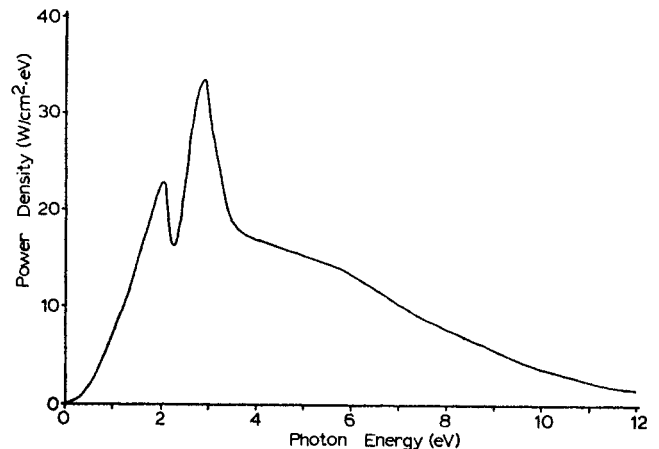


Figure 3. Illumination spectrum.

## Report Documentation Page

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## Experimental Procedure

The experiment was conducted by assembling the vacuum chamber containing the insulator to the focus chamber with a selected window as the interface between the two chambers. A series of shots was fired and the voltage across the insulator was monitored with a V-dot probe. Insulator behavior was observed as a function of time, as a function of the number of shots fired with a particular window in place, and as a function of electric field stress and polarity. The time from initiation of the light source until the insulator gap flashed was measured, if flashover occurred. A solid metal "window" was used on several shots, confirming that it was UV radiation and not circuit coupling which initiated the flashover. A plastic window passing radiation below 3 eV was also employed. Flashover was never observed whenever the plastic window was in place.

To understand the experiment it is crucial to realize that the window was in close proximity to the plasma focus, so that debris was deposited on the window as the number of shots increased. The increasing amount of debris altered the transmission of the window, attenuating light at all wavelengths, but preferentially attenuating short wavelengths. The effect of the buildup of debris was to modestly alter the UV spectrum with which the insulator was illuminated. Spectral transmission of the windows were measured before and after each series of shots, and intermediate transmission functions were inferred. The spectra passed by clean quartz and by quartz plus the debris from twenty shots are shown in Figure 4.

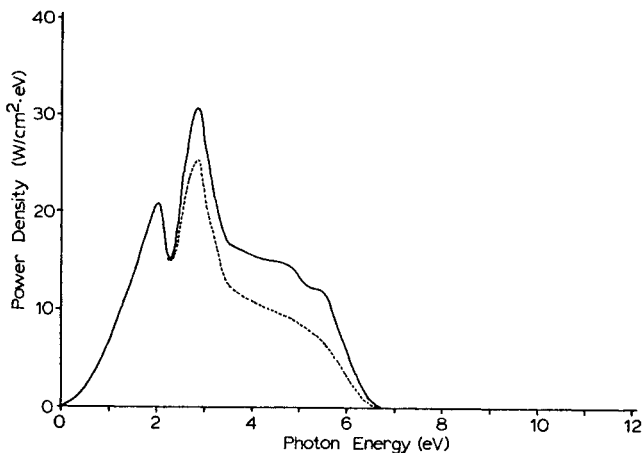


Figure 4. Illumination spectrum filtered by quartz windows: clean (solid) and with deposited debris (dashed).

## Voltage Dependence

Two series of shots were conducted with conventional and unconventional geometries with polyethylene insulators while randomly varying the magnitude of the field stress from shot to shot in order to eliminate window transmission and "conditioning" effects. In one series, positive voltage stress was varied over the range 20-70 kV/cm, while in the other negative voltage stress ranged from 10-60 kV/cm. In neither case could a trend of time to flash as a function of field stress be established. Therefore, the remainder of the shots were made with 50 kV/cm field stress (both positive and negative) for the sake of comparison between materials. The series of shots in the negative 10-60 kV/cm range is included in the data in Figure 5.

## Observations

The results of the tests with polyethylene, polystyrene, and teflon insulators through quartz windows

in both conventional and unconventional geometries are shown in Figures 5 and 6. The difference between the two geometries is dramatic. For all materials, flashover could be reliably and predictably induced during the time of the UV pulse with insulators at positive angle, while with insulators at negative angle, flashover occurred long after the UV pulse was over, if it occurred at all. Furthermore, this polarity dependent behavior could be reliably reproduced at will by changing polarity of the applied field between shots in a particular shot series. This polarity dependent behavior is the reverse of the expected results, but agree with the results reported by Avdienko,<sup>3</sup> whose results are in a different time and spectral regime.

We assume that the basic effect of UV illumination of the insulator is the liberation of photo-electrons in single photon events on or near the surface of the insulator. Therefore, photons striking the insulator surface with less photon energy than the work function for the insulator should be ignorable. The insulators under consideration were either fluoro- or hydrocarbons, so that for simplicity the work functions of all materials could be approximated by the work function for carbon, 4.7 eV.<sup>4</sup> This is a reasonable approximation; for example, in the band structure of polystyrene presented by Sorokin and Blank<sup>5</sup> the electron nearest the Fermi level is 4.4 eV away. Since a large electric field exists within the insulator, it is sufficient to excite the electrons above the Fermi level before they are stripped away. This assumption is consistent with the observation that a large number of photons of energy below 3 eV (the plastic window cut-off) were incapable of initiating breakdown, and with the results of previously reported experiments.<sup>1</sup> Therefore for single photon photo-ionization events the

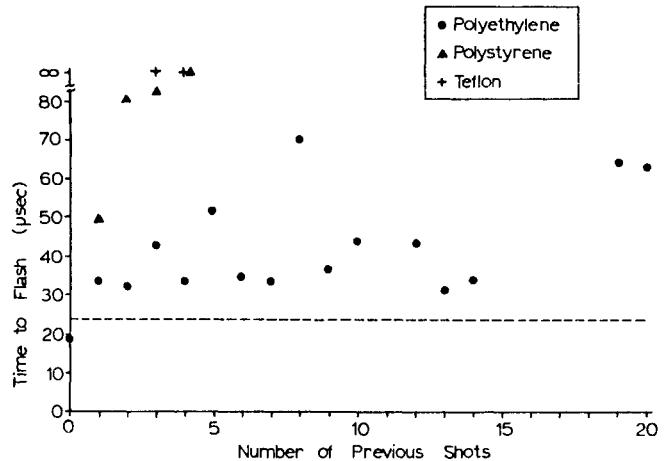


Figure 5. Behavior of insulators at negative angle. Polyethylene data taken for  $E = 10-60$  kV/cm. Other data taken for  $E = 50$  kV/cm. Dashed line is the end of the illumination pulse.

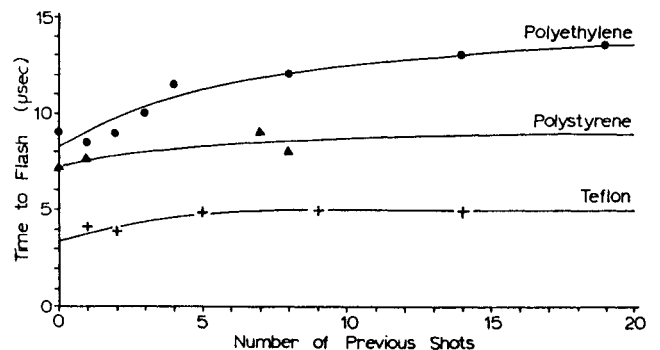


Figure 6. Behavior of insulators at positive angle. All data taken for  $E = 50$  kV/cm.

photon flux, rather than the energy flux, is important in analyzing the results. The spectrum emitted by the plasma focus in units of photon flux is shown in Figure 7. Table I shows the number of photons of energy 4.7 eV or greater falling on the insulator before the time flashover occurred. Energy values are also shown. As shot sequences progress and window transmissions change, the photon flux drops, and the time to flash increases, as one would expect. But while we expect the total number of photons required to initiate flashover to be roughly constant, the total number of photons above 4.7 eV seen by the insulator decreases modestly but consistently.

Insulators at negative angle which did not flash when exposed to UV illumination through quartz windows were exposed through magnesium fluoride windows to see if they could be induced to flashover during the time of the illumination pulse. Magnesium fluoride windows essentially passed the entire available spectrum through 12 eV. The fluence required to flash these insulators through magnesium fluoride is shown in Table II. Since the net photon fluence is less in these tests than when the same materials were exposed to more, lower energy photons and did not flash, we suggest that higher energy photons are more likely to produce photoelectrons than photons with energy barely greater than the work function.

#### Model of UV-Induced Flashover

We now attempt to develop a model which explains the curious relationship of time to flash versus total UV fluence illustrated in Table I as well as the effect of changing polarity of the applied field. We note an important difference in the case of insulator flashover under UV illumination versus unilluminated flashover. In the unilluminated case, the initial source of free electrons are assumed to be those electrons field-emitted from the triple junction,<sup>6,7</sup> whereas under UV illumination photoelectrons may be emitted everywhere on the insulator surface, in numbers large enough to have significant impact on the gross applied electric field.

TABLE I

MATERIAL POSITIVE ANGLE	MICROJOULES PER CM <sup>2</sup> TO FLASH	PHOTON FLUENCE PER CM <sup>2</sup> TO FLASH	WEIGHTED PHOTON FLUENCE
Poly-ethylene			
Clean	44.2	$5.21 \times 10^{13}$	1.00
Debris	32.3	$3.83 \times 10^{13}$	0.89
Poly-styrene			
Clean	41.2	$4.85 \times 10^{13}$	1.00
Debris	26.9	$3.19 \times 10^{13}$	0.71
Teflon			
Clean	24.9	$2.93 \times 10^{13}$	1.00
Debris	18.7	$2.21 \times 10^{13}$	0.93

TABLE II

MATERIAL NEGATIVE ANGLE	MICROJOULES PER CM <sup>2</sup> TO FLASH	PHOTON FLUENCE PER CM <sup>2</sup> TO FLASH
Poly-styrene	9.2	$0.88 \times 10^{13}$
Teflon	59.0	$2.39 \times 10^{13}$

It would seem that a geometry in which photoelectrons are accelerated away from the insulator surface, as in the conventional geometry, would be impervious to UV-induced flashover. However, since each electron which leaves the insulator surface leaves behind a net positive charge and since charges are not free to move in an insulator, the surface charge builds up as more and more electrons are taken away. In unilluminated flashover the available free charge is limited by secondary electron yields while in the illuminated case the UV provides an almost unlimited supply of electrons leading to vastly increased surface charging. As sufficient charge is built up, the electric field near the insulator surface may be grossly distorted to have a significant tangential component, so that the insulator is effectively at zero angle to the applied field, which is the weakest possible configuration.

In the unconventional geometry, by contrast, photoelectrons from the insulator are immediately accelerated back into the insulator surface and while experiencing a large number of electron impacts (compared to the unilluminated case), the surface of the insulator remains net neutral, resulting in no net distortion of the gross field and hence displaying breakdown at average fields which are lower (but not dramatically lower) than the vacuum, unilluminated case.

Calculation shows that if a small fraction of incident photons of proper energy actually produce free electrons, the insulator in conventional geometry can achieve sufficient charge to cause major changes in the local electric field. Calculations were made for the case of a polyethylene insulator illuminated through a clean quartz window. It was assumed that two tenths of one percent of the photons with energy greater than 4.7 eV which illuminated the insulator surface prior to flashover actually caused the emission of an electron which was removed from the surface. The electrons were assumed to have been accelerated away from the insulator surface, and the resulting surface charge density was assumed to exist on a thin layer near the insulator surface. The field-solving code JASON<sup>8</sup> was used to calculate the electric fields near the insulator before the beginning of illumination and at the time immediately prior to flashover. The results of these calculations are shown in Figure 8. The plots show that after illumination the electric fields have a large component tangential to the insulator interface.

In the unconventional case the angle of the applied vacuum electric field to the insulator surface before illumination is somewhat greater than the critical angle described by Pillai and Hackam.<sup>7</sup> Above the critical angle the probability of secondary electron emission from electrons which are accelerated in the field and which reimpact the surface falls below unity.

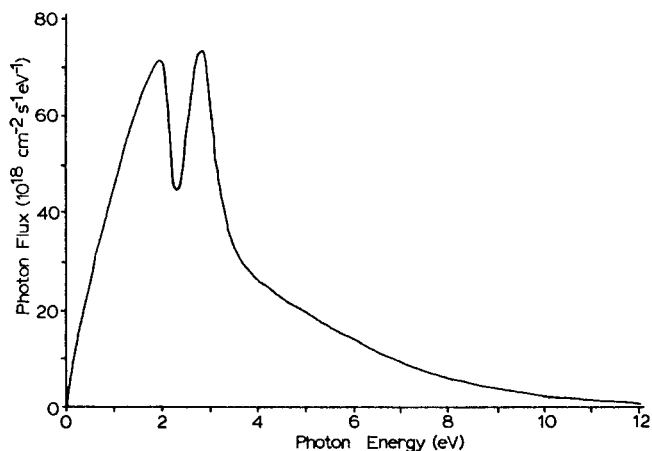


Figure 7. Illumination spectrum (units of photon flux)

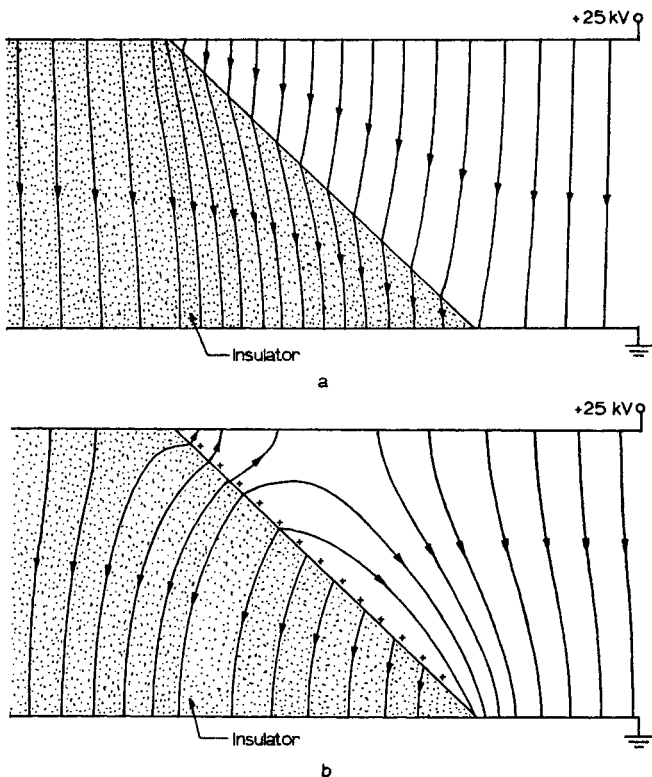


Figure 8. Electric field configurations calculated by JASON for polyethylene insulators and a 0.5 cm gap: a. before illumination b. with net positive surface charge.

Furthermore any net charging which does take place will tend to increase the angle of the field to the surface. Therefore, the electrons are not likely to avalanche due to secondary electron emission. Rather, the situation will be similar to that in which a saturated current is flowing on the surface, with each emitted photoelectron contributing to this current, but without the current's increasing. Thus the magnitude of the current is proportional to the total fluence onto the insulator surface. It is then possible for this current to desorb gas from the surface of the insulator and create a path for macroscopic current flow. Such a process, initiated by UV illumination but persisting long after the end of the light pulse could explain the relatively late breakdown of the negatively sloped insulators.

A closer examination of the apparent disparity in the photon fluence required to induce flashover in insulators exposed to different spectra illustrated in Table I lends credence to our model of flashover in conventional geometry. In the conventional case, if each photoelectron which is accelerated away from the surface affects the field which is seen by photoelectrons which are emitted later, it follows that each liberated photoelectron is more likely to initiate flashover according to the number of photoelectrons which have been emitted before it. Clearly, this increasing probability relationship could be complex, but if we take the simplest weighting, such that the probability of causing flashover at any time is proportional to the integrated number of photons which have illuminated the insulator prior to this time (i. e., to the net surface charge), then the weighted number of photons arriving on the insulator is the same for the first shot as for the 21st shot within ten percent, as shown in Table I.

The observation that in the irradiated case breakdown is enhanced by rapid buildup of surface charge has

interesting implications for the case where a large magnetic field is present. In such cases, geometries are usually chosen to ensure that electrons are swept away from the surface by the  $\vec{B}$  field. This, of course, leads to even more effective surface charging and perhaps greatly enhanced breakdown.

We note incidentally that the presence of a small prebreakdown current in the unconventional geometry corresponds to a small conductivity over the surface of the insulator. Other experimenters<sup>9</sup> have noted that the presence of a thin, slightly conductive layer on an insulator tends to improve breakdown strength. Hence, by our model, those insulators which most readily give up secondary electrons and perform most poorly in a conventional geometry might well be expected to perform best in an unconventional geometry. This is indeed the observed trend.

### Conclusions

We caution that these experiments are conducted for DC potentials only, and note that electrical breakdown at various points in the apparatus prevented us from approaching static breakdown across the insulator. For pulsed systems near electrostatic breakdown, other effects may dominate, but under the conditions specified, we conclude that a very small amount of UV illumination is required to initiate insulator flashover, that the reverse of conventional geometry is most resistant to UV-induced flashover, and that of the materials tested, teflon in the preferable material in the unconventional geometry.

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