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UV Induced Insulator Flashover *

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***Abstract*- Insulators are critical components in high-energy, pulsed power systems. It is known that the vacuum surface of the insulator will flashover when illuminated by ultra-violet (UV) radiation depending on the insulator material, insulator cone angle, applied voltage and insulator shot-history. A testbed comprised of an excimer laser (KrF, 248 nm , ~2 MW/cm^2, 30 ns FWHM,), a vacuum chamber (low 1.0E-6 torr), and dc high voltage power supply (<60 kV) was assembled for insulator testing to measure the UV dose during a flashover event. Five in-house developed and calibrated fast D-Dot probes (>12 GHz, bandwidth) were embedded in the anode electrode underneath the insulator to determine the time of flashover with respect to UV arrival. A commercial energy meter were used to measure the UV fluence for each pulse. Four insulator materials High Density Polyethylene, Rexolite® 1400, Macor™ and Mycalex with side- angles of 0, ±30, and ±45 degrees, 1.0 cm thick samples, were tested with a maximum UV fluence of 75 mJ/cm^2 and at varying electrode charge (10 kV to 60 kV). This information clarified/corrected earlier published studies. A new phenomenon was observed related to the UV power level on flashover that as the UV pulse intensity was increased, the UV fluence on the insulator prior to flashover was also increased. This effect would bias the data towards higher minimum flashover fluence.**

I. INTRODUCTION

The purpose of this work was to measure the critical UV fluence (energy per unit area) required to induce surface flashover of vacuum insulators for some candid insulator materials: High Density Polyethylene (HDPE), Rexolite, Macor™ and Mycalex. This work was also a clarification of studies performed by C.L. Enloe, et. al. in 1982 [1]. The critical fluence has importance in the area of UV-switching technology, however was important to us in designing the power flow channel for explosively driven magnetic flux compression generators where the UV presence can be detrimental to power flow. The enormous currents produced at the vacuum power flow channel of these generators heats surfaces to temperatures where significant UV radiation is produced. Baffles and UV absorbing surfaces must be used to limit the UV fluence illuminating the insulator to avoid flashover and suboptimum performance.

We measured the critical UV fluence utilizing a 248 nm impinging on a 1.0-cm thick insulator, with varying angles, and materials held between two electrodes. A variable dc voltage supply was used to charge the cathode up to -60 kV. Fast capacitive probes, i.e., D-dots, embedded into the anode (ground) electrode were used to determine the arrival time of flashover with respect to the laser pulse.

A photodiode registered the temporal shape of the pulse and an energy meter determined the energy of the pulse. Integrating the laser pulse from the start of illumination until flashover yielded the critical energy. This was divided by the insulator cross section for critical fluence.

Our work supports the higher fluence values given in References 1 and 3. We had very good agreement with Reference 3 for Rexolite (a polystyrene based material), both negative and positive angles, and for polyethylene with negative angles, as described below. We did not observe the differences between negative and positive angles for polyethylene shown in Reference 3. We did note however a possible relationship between critical fluence and the UV surface power density.

We also experimented with two ceramic based insulator material, namely Macor™ and Mycalex and report of the findings.

II. EXPERIMENTAL SETUP

A. Insulator Teststand

The 1.0-cm thick insulator was placed between two electrodes in a vacuum chamber and was illuminated over a 1-cm^2 area by a Lambda Physik LPX 325i excimer laser in single pulse mode. The light was transported from the output of the 248-nm (~5.0 eV) laser operated at by highly reflective (HR) dielectric coated 2” diameter mirrors to the chamber. A diagram of the optical system used is shown in Figure 1. A one-to-one projection optical system was used to illuminate a uniform 1-cm^2 onto the sample. The antireflective (AR) coated silica lens used had a nominal focal length of 150-mm. The mask and the part were placed each approximately 300 mm from the lens with an AR coated silica window between the part in the vacuum chamber and the lens. A process shutter was placed before the mask so that the laser could be fired without delivering energy on target. There were two locations used for to insert neutral density (ND) filters Inconel™ brand.

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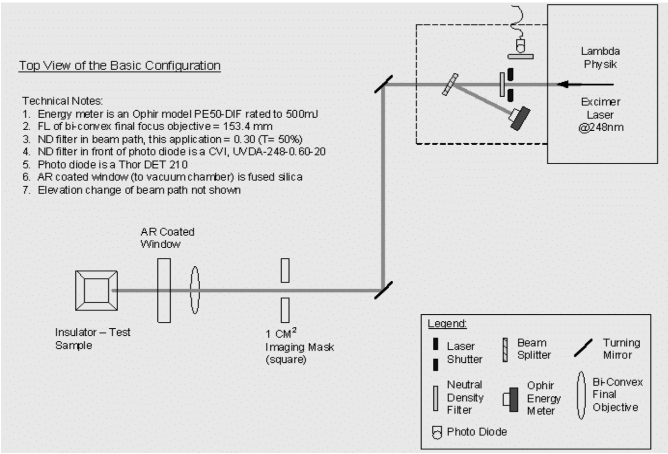

Fig 1. Diagram of the optical system.

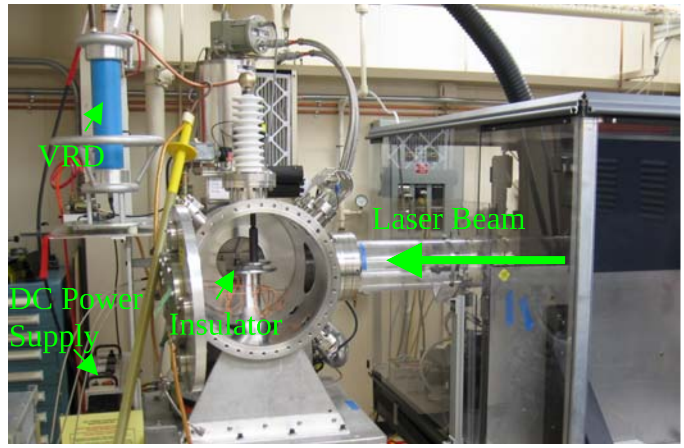

Fig 3. Photo of testbed.

The second was just before the imaging mask after the process shutter.

Laser diagnostics included a photodiode (Thor Labs DET210) that measured diffuse reflected light from the mechanical safety shutter to measure temporal pulse properties and to establish a jitter free trigger of the laser pulse. Another ND filter was used to attenuate the signal to prevent saturation. An energy meter (Ophir PE50-DIF) measured light reflected from a pick-off that was calibrated to energy readings inside the chamber.

The laser UV energy is variable and is set by the voltage at its thyratron output switch (13 kV to 19 kV) and is capable to deliver up to 75 mJ/cm^2 on the surface of the insulator – corresponding to 2.0E+06 Watt/cm^2 waveforms. The laser nominally operated at 18 kV and single pulse mode. Figure 2 shows three typical laser power output waveforms and the corresponding UV energy at the insulator. The total energy deposited on the insulator varied from 60 mJ/cm^2 to 75 mJ/cm^2 (laser at 18 kV) depending on length of time since the laser gas was recharged.

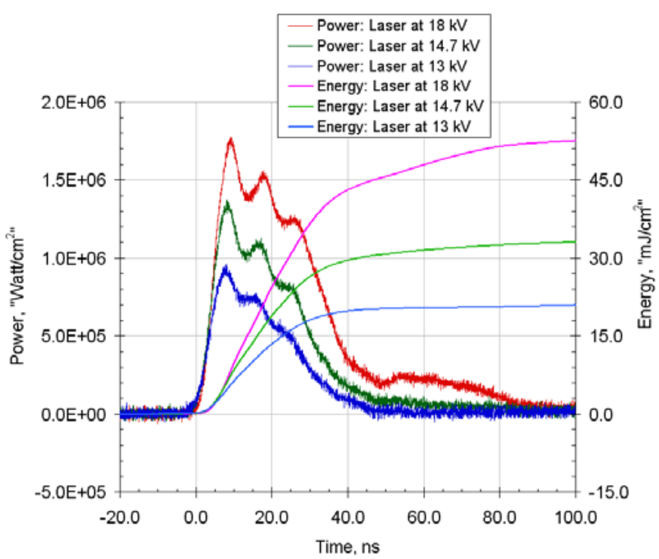

Fig 2. Laser output waveforms; power and energy.

A variable DC power supply connected through a 5 MΩ isolation/limiting resistor. The power supply was disabled electronically at the time of the laser pulse. A photograph of the open vacuum chamber with electrodes and insulator visible is shown in Figure 3. The vacuum system consisted of a small mechanical roughing pump and a CTI™ cryopump (CTI Cryogenics/Helix, Model: Cryo Torr 8) that maintained a pressure of ~1x10-6 torr.

B. Insulator Material

Four dielectric materials were used as insulators: High Density Polyethylene (HDPE), Rexolite® 1400 (cross linked polystyrene), Macor™ and Mycalex. A summary information of each insulator material is given below:

1) High Density Polyethylene (HDPE); Polyethylene is a polymer consisting of long chains of the monomer ethylene (CH2 = CH2). It is also harder and more opaque and can withstand somewhat higher temperatures (120^{o}C for short periods). HDPE has a dielectric constant of 2.25.

2) Rexolite® 1400; Cross linked polystyrene (CH2 = CH = CH2) was originally developed for use in coaxial cable connectors. Rexolite has a dielectric constant of 2.53.

3) Macor™; Macor is a machinable glass-ceramic material. Glass-Ceramic, 55% mica crystal and 45% matrix glass, it is melted and cast using conventional glass making techniques. Macor is a fluorine rich glass with a composition close to trislicic fluorphlogopite mica ($KMg_3AlSi_3O_{10}F_2$). Macor has a dielectric constant of 6.0.

4) Mycalex; High performance ceramic is a union of finely powdered electrical quality glass and precisely defined classified mica (a group of sheet silicate minerals $XY_{2–3}Z_4O_{10}(OH, F)_2$ with X = K, Na, Ba, Ca, Cs, (H_3O), (NH_4); Y = Al, Mg, Fe^{2+}, Li, Cr, Mn, V, Zn; and Z = Si, Al, Fe^{3+}, Be, Ti). The tiny glass globules absorb the mica flakes, join with one another and weld the particles into a single mass. Mycalex has a dielectric constant of 6.7.

The insulators were truncated pyramids 1 cm in height and with a 2.54 square base with cut angles of 0, 30 and 45.

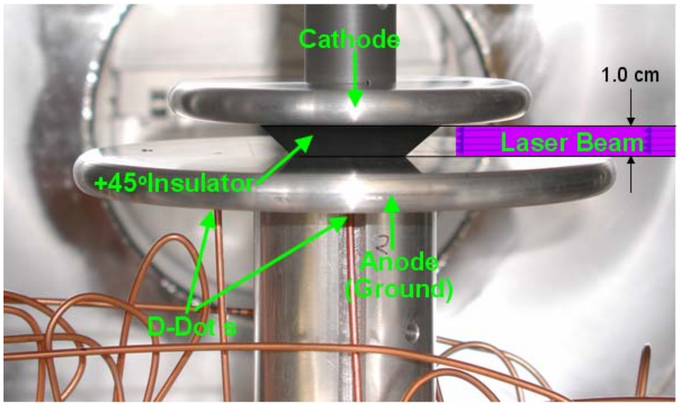

Fig 4. Photo shows a close view of insulator under test and the D-dot probes.

C. Diagnostics

A precision VRD (North Star™ VD-60) was used for monitoring the charging voltage. In-house designed, fabricated and calibrated capacitive pick-up probes (D-dots) were embedded in the anode electrode to determine the initial arrival time of surface flashover. In Figure 4, the semi-rigid copper coaxial cables visible below the electrodes connect the D-dots to a Tektronix TDS6124C, 12 GHz scope. The D-dot probe was developed by author, T.L. Houck, and is discussed extensively in reference [4]. The probe located below the UV illuminated, being closer to the flashover site (for +45 degree) gave highly resolved signals. For example; we could easily differentiate a self-break signal from a UV-induced flashover.

Although these probes were mainly used to give time fiducial of the flashover, as shown in Figure 5, their integrated signals can be calibrated to obtain the charge on the insulator during flashover and the transient electric field. For example; a typical value of the measured UV induced electron charge on the insulator was ~280 pC [4]. This is much less than the 10.4 nC reported in reference [3].

III. Measurements

Measurements of UV energy to induce flashover were taken for insulator angles of 0, ±30, and ±45 degrees for HDPE, Rexolite® 1400, Macor™ and Mycalex. Over 2000 shots were recorded. A precision 1-cm square mask in the beam path was used to define the area illuminated on the insulator surface. Up to 75 mJ energy was deposited on the insulator. Electrode charging voltage was varied up to a maximum of 60 kV.

A typical test-run started with first establishing the self-break voltage on the insulator. If there were no self-break up to 60 kV of cathode charge then we collected flashover data reducing voltage in steps of 2.5 kV to the point of no flashover – a ramp down. In our earlier testing we had taken the ramp up approach where we started low on electrode voltage and ramped up in step of 2.5 kV, the problem with this approach was that the insulator collected charge and held to that charge until this residue charge took part in the subsequent shot thus resulting in non-reproducible data. The insulator that has experienced flashover loses all of its charge, so that it has no residue charge to part take in the next shot.

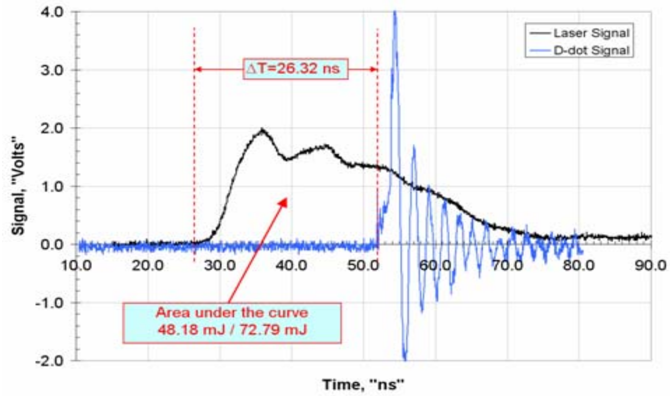

Fig 5. Photo-diode signal and D-dot raw signals during flashover of a +45° HDPE insulator with 45 kV/cm of applied field.

Thus, there is no UV conditioning of the insulator on any of the reported data.

The digitizing oscilloscope was triggered by the signal from the photo diode. Signals from the D-dot probes were also recorded on the oscilloscope to permit the determination of time to flashover after arrival of the UV pulse at the insulator. The temporal shape, $f(\tau)$, of the laser pulse was relatively constant from shot to shot. To calculate the critical fluence we normalized the integrated diode pulse, i.e.,

$$\int_0^\infty f(\tau)\,d\tau = 1 \qquad (1)$$

and then defined the critical fluence, F_C, as;

$$F_C \equiv \frac{E}{A}\int_0^{t_f} f(\tau)\,d\tau \qquad (2)$$

Where E is the total pulse energy, A is the cross sectional area of the beam, and t_f is the time delay from first illumination until flashover. Thus, the critical fluence is the total energy deposited on the insulator before flashover divided by the area of the beam. Note this area is only equal to the illuminated area for the 0° insulator. Figure 5, shows the time corrected raw signals of the photo diode and the D-dot during flashover for the case of +45° insulator illuminated by a 72.79 mJ laser pulse. In that case the Critical fluence, F_c, was 48.18 mJ.

A. Critical Fluence as a Function of Electric Field for HDPE

Results for 1.0-cm thick HDPE for different angles are shown in Figure 6. These HDPE measurements did show some deviation from Reference 3. The -45 degree angle required about 20% more fluence for flashover and we were limited to maximum fields of 50 kV/cm before the insulator would self-break. The positive angle critical fluence continued to decrease as the negative angle fluence leveled off until it was approximately 10% lower. This is the improved performance for the unconventional geometry described in [3].

The -30° angled insulator showed slightly lower critical fluence than +30° but less breakdown strength without UV. For zero degrees the insulator would not flashover for applied fields of less than 10 kV/cm for the maximum, ~75 mJ/cm^2, fluence available. For 25 kV/cm and above, the insulator would self-break.

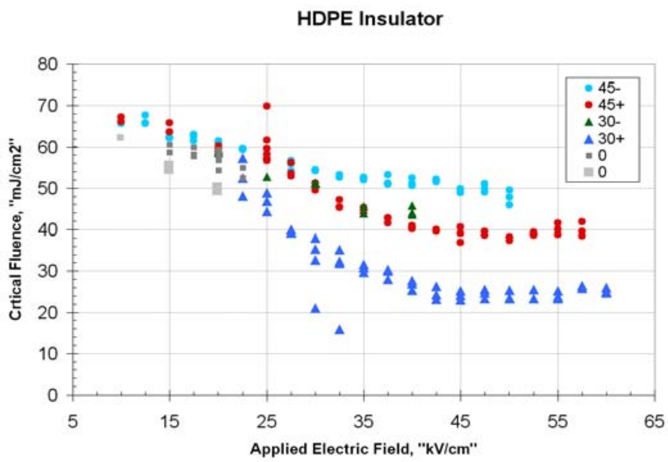

Fig. 6. HDPE critical fluence results; different angles.

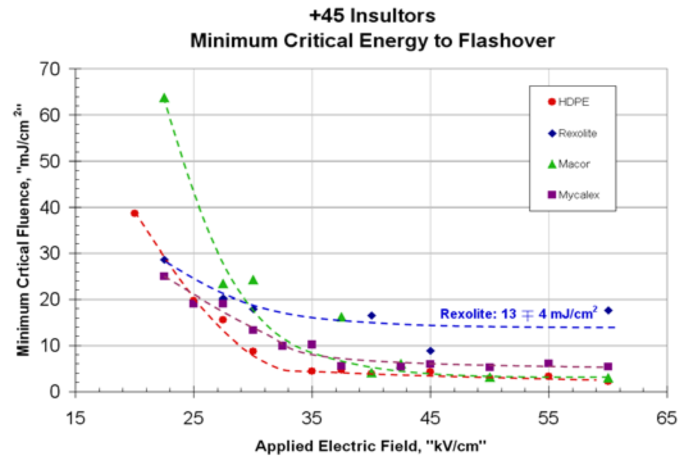

Fig. 8. Minimum critical fluence results; +45^o angles.

The Critical Fluence vs. Applied Electric Field plots were obtained for each of the candid materials – but due to limited space only results for HDPE reported here.

B. Critical Fluence for +45^o Insulators

Of all insulator angles, +45^o, is probably the most commonly designed insulator. Figure 7 shows how the four insulator materials fair against each other. Rexolite seems to be most resistive to UV-induced flashover among all the candid insulator materials. At low applied electric field, i.e., below 20 kV, would not flash with all the power of the laser impinging on it. At high applied electric fields it needed ~ 45 mJ to flashover.

D. Effect of Reduced Power Level

An unexpected effect that was noted during measurements involved reducing the laser pulse power, using a combination of ND filters in the beams path or/and lowering the laser operational voltage. What we expected was that the time delay from start of illumination until flashover would increase resulting in the same critical fluence as for the unattenuated cases, but this was not the case!

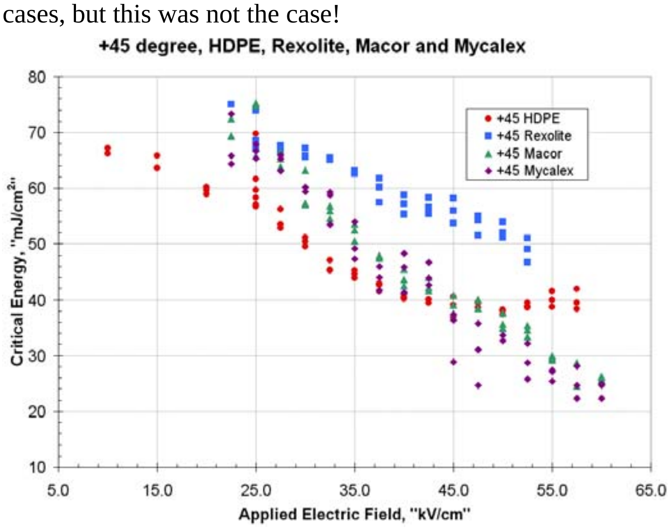

Fig. 7. Critical fluence results; different insulator materials, all +45^o

These results could indicate an illumination time dependence for flashover, i.e. the energy of the applied UV pulse is not as significant as the length of the pulse. Attenuated shots taken show a minimum critical fluence independent of power level. Figure 8 shows the minimum critical fluence measurements for the four 45^o insulator materials. Rexolite as before shows a greater resistance to UV flashover, i.e., ~13µ 4 mJ/cm^2, at higher applied electric fields.

IV. SUMMARY

An excimer laser was used to illuminate dielectric vacuum insulators with UV (248 nm) fluence of up to 75 mJ/cm^2 to determine the critical fluence for insulator flashover for different electrical field stresses. HDPE, Rexolite® 1400, Macor™ and Mycalex, 1.0 cm thick samples, with various angles were used as insulator materials. Critical fluence of UV to induce flahover was measured by the use of fast D-Dot probes and UV energy meter. Rexolite® 1400 showed the best UV hold off properties for surface flashover when measuring the Critical Fluence and the newly established minimum critical energy of ~~13µ 4 mJ.

ACKNOWLEDGMENT

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