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HIGH-VOLTAGE ATMOSPHERIC BREAKDOWN ACROSS INTERVENING RUTILE DIELECTRICS *

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Abstract

The electrical power grid, aircraft, and defense systems are potentially subject to damage from lightning strikes. Surge arresters are high-voltage safety components used to mitigate damage to many critical systems by diverting transient currents to ground via breakdown. Some arresters utilize high-permittivity dielectric materials, such as rutile (TiO_2), to ensure breakdown occurs at a prescribed voltage and prevent a transient voltage pulse from affecting downstream components. Though widely used, the physical mechanisms for surface breakdown in surge arresters are not well understood. Electrical discharge experiments are being conducted to help develop predictive computational models of the fundamental processes of surface breakdown in the vicinity of high-permittivity material interfaces. Discharge path imaging and electrical data are presented. Results are compared to electrostatic calculations using an ionization coefficient-based approach and Townsend-breakdown criteria for non-uniform fields and the observed breakdown path. It is shown that rutile reduced the breakdown voltage of an electrode gap by ~50% even when the visible discharge path did not interact directly with the sample.

I. INTRODUCTION

Sensitive electrical systems may be subject to strong transient currents from lightning strikes, switching feedback, or shorting due to component failure. Surge arresters of many forms rely on dielectric surface flashover to safely redirect these electrical spikes to ground. It was observed that the presence of a high-dielectric material between two electrodes significantly reduces the breakdown threshold of the gap and the standard deviation of breakdown levels [1]. However, the physical mechanisms involved with this process are not well characterized. Recent work has quantified the effects of certain gas compositions, electrode geometries, and humidity on the surface flashover phenomenon of low-dielectric-constant materials [2][3].

This paper presents experimental and modeling results of surface flashover using a sintered TiO_2 material known as rutile. Rutile is a unique semi-conducting material with strong absorption in the ultraviolet and dielectric constant near 100 depending on the manufacturing process. The experiments presented here utilize the highly non-uniform electric field produced by a cone to plane electrode geometry with an intervening rutile cylinder resting on the planar electrode.

II. NUMERICAL APPROACH

The simulations described here used the Eiger code [4], which solves for electromagnetic or electrostatic fields using boundary element methods. In this case Eiger solves for the electrostatic field for a particular configuration of electrodes at different potentials. The electric field solution is calculated for a voltage difference of 1 volt between the electrodes. The electric field is linear in the voltage differences and can be evaluated for other voltage differences through simple scaling. To find the breakdown voltage, we vary the electrode voltage through scaling and integrate the primary ionization coefficient (α) along a field line until the Townsend breakdown threshold [5] is exceeded just as the integration path touches the anode. This threshold is dependent on the secondary electron emission coefficient (γ). For the model used here, α depends on the magnitude of the electric field, the type of gas through which the breakdown occurs, and the gas pressure. Values for parameters appearing in the functions for α and γ are derived from fits to experimental data for different gases [6]. This approach has been applied to a number of test cases (including the pin and ground plane electrode configuration) and compared to both analytical results and experimental data with good agreement [6].

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III. EXPERIMENTAL SETUP

The experimental setup used for this work is shown schematically in Figure 1. The pulsed electrical driver of this system was a surge test generator (HiLo PG 24-2500) with a surge current rise/fall time of 8/20μs and +25kV maximum operating voltage. The voltage pulses were transmitted through a high-voltage coaxial transmission cable to the test fixture (not shown). The test fixture was designed to support the current and voltage probes while allowing fine x-y-z translation of the electrodes. The ground of the transmission cable was separated and connected to six return-current cables arranged coaxially and attached to the cathode of the system. The center conductor of the transmission cable passed through a calibrated Pearson current loop (CVT) to measure current delivered to the electrode gap. A Tektronix high-voltage probe was also fielded between the conductors of the transmission cable at the test fixture. The Al anode used was conical with 82° full angle and a 0.5mm radius tip. The Al ground plane, upon which the rutile samples rested during experiments, was 50mm in diameter.

The voltage delivered to the test stand was gradually increased over several attempts to ensure breakdown occurred near the peak of voltage pulse. This minimized the effect of the time rate of voltage increase in order to better compare with the Eiger electrostatic simulations.

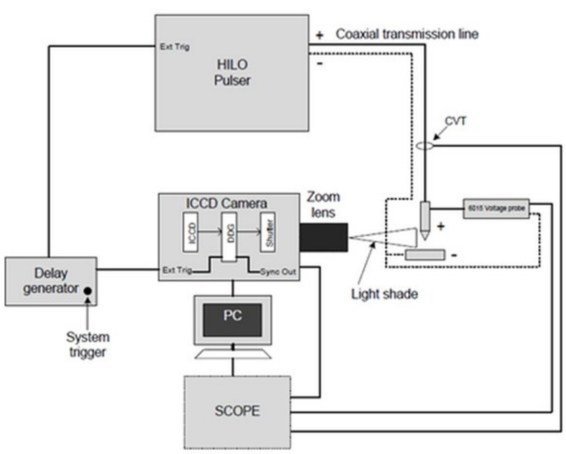

Figure 1. Experimental setup for generating and imaging electrical discharge.

A. Rutile Samples

The rutile samples were prepared by spray coating a TiO_2 powder with a solution of polyvinyl alcohol (binder), polyethylene glycol (plasticizer), and oleic acid (lubricant). The powder mixture was then air dried, deagglomerated using a mortar and pestle and then passed through a sieve. This powder was uniaxially dry pressed at 3000psi into 5cm diameter x 2 cm thick discs and then cold isostatically pressed at 30000psi. The discs were then oven dried at 270C and slow sintered for two hours at 1350C (static air and ambient pressure). The sintered discs were then machined into 1cm diameter 1cm long cylinders. The samples were then thermally annealed in flowing air at 1000C for 6 hours.

Thermally annealing these samples allows oxygen molecules to fill vacancies within the TiO_2 crystalline structure that would otherwise act as electron traps [7]. This process also acts to heal subsurface damage caused during the sample machining and ensures optimal surface uniformity. Rutile produced using this procedure has a dielectric constant of approximately 100. A new sample was used for each experiment and the electrode was positioned over the midpoint of the cylinder axis.

B. Imaging diagnostics

Imaging dielectric surface breakdown requires nanosecond gating and high signal gain to capture transient behavior. A fast-gated intensified charged coupled device (ICCD) with cathode sensitivity above 10% between 300nm and 750nm and an image size of 25mm x 25mm (1024x1024 pixels) was used for these experiments (Andor iStar 334T). All images shown were produced by combining a reference image (50ms exposure, external lighting) with an experimental image (10ns exposure, self-illuminated).

Image formation was achieved using an f/2.8-4 macro zoom lens (Nikon AF Zoom-Nikkor 24-85mm) at close range or an f/5-6.3 ultra-telephoto lens (Tamron SP AF200-500mm A08) fielded farther from the discharge. Spatial image resolution was 50-100μm. The high-voltage system and the imaging system were triggered externally from a delay generator.

III. RESULTS AND DISCUSSION

This series of experiments explores the effect of a 1cm diameter, 1cm long rutile cylinder on the breakdown voltage of a 10.5mm electrode gap at various positions. The electrodes remained in a fixed coaxial position while the sample was translated between d = 0mm (directly below the electrode) and d = 14mm.

The results taken during a discharge where the sample was directly below the anode at d = 0mm are shown in Figure 2. The voltage delivered by the pulse generator rose to 13.5kV prior to breakdown (solid line). As the voltage dropped, the current increased (dashed line). This time is taken as the experimental t = 0s. The black square indicates the timing of the ICCD image 3.5μs after current start.

The ICCD image, shown in Figure 2 Frame b), shows the discharge path across the right side of the cylinder. The plasma channel carried 6kA at the time of this image and appears as a 4mm wide emission zone that terminates to ground through an air path, leaving the lower surface of the sample undamaged.

The electrostatic simulation of the experimental geometry, shown in Figure 3, shows the effect of the rutile sample on the electric field structure. The arrows indicate the direction of the field lines, while the shading indicates field strength. The field structure is highly nonuniform with strong field enhancement near the anode indicated by the lighter shading (all images use the same scale). The field lines enter the sample at a near orthogonal angle due to the high dielectric constant of rutile.

Comparing the experimentally observed discharge path with the simulated electric field produced, it is clear that the discharge path does not correlate with the electric field lines, but instead traverses the field lines as the arc tracks the surface of the sample. This produced an unrealistic calculated voltage breakdown due to the extremely low

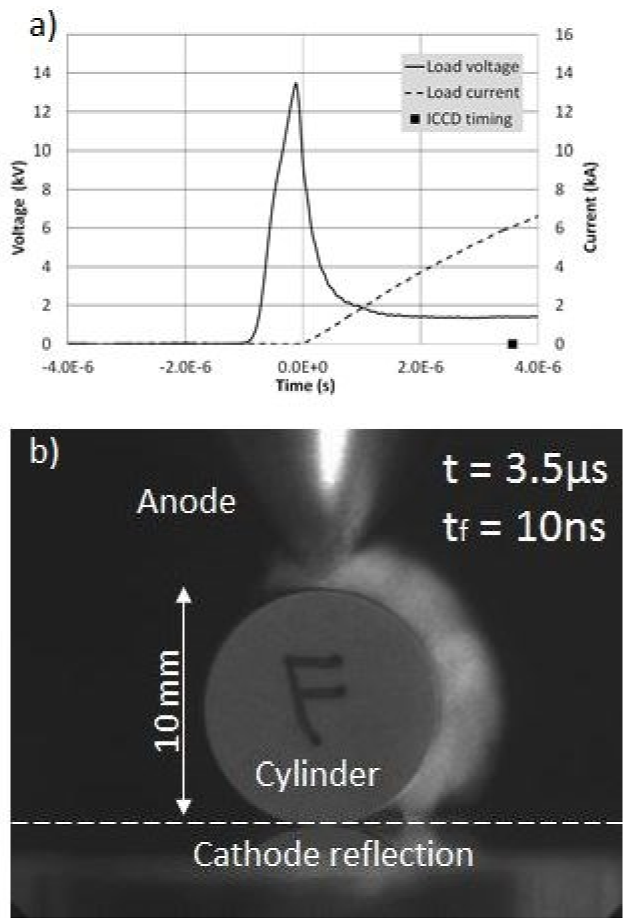

Figure 2. Results from rutile sample displaced 0mm and experimental time taken from the start of current: a) Voltage and current measurements with ICCD synchronization; b) ICCD image with labeled features. T is timing relative to current start, t_f is frame time. The electrode is 0.5mm above the rutile sample. Breakdown voltage was 13.5 kV.

tangential component of the electric field at the surface and the high concentration of field between the cone tip and the rutile cylinder surface: 65kV.

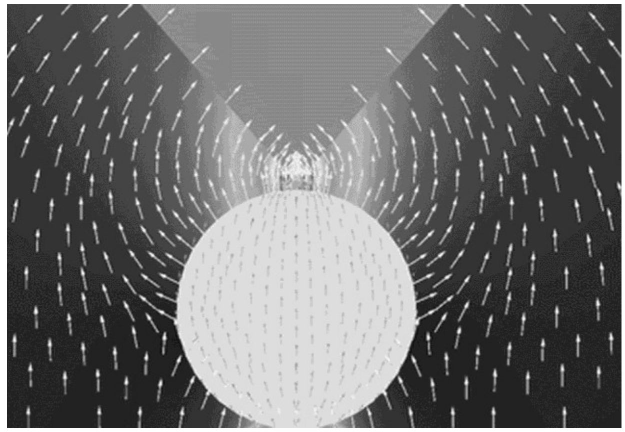

Figure 3. Eiger electric field simulation of the experimental geometry shown in Figure 2. Higher field strengths are indicated in air by lighter shading.

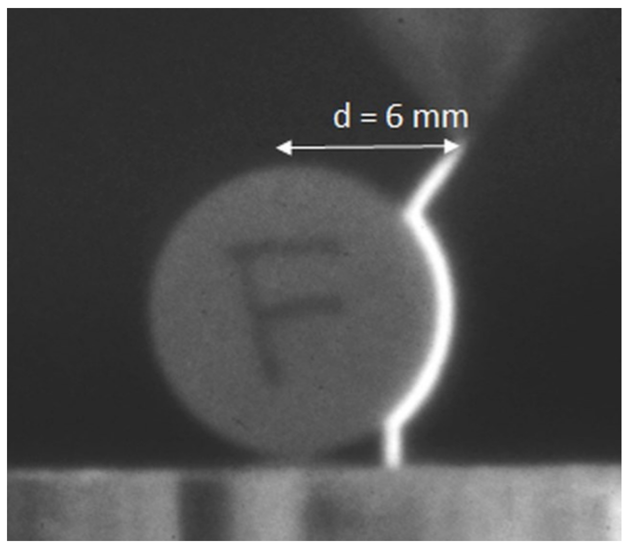

Figure 4. ICCD of discharge path rutile sample displaced 6mm from axis. The lower part of the image is the edge of the cathode. Breakdown voltage was 12.5kV.

The image from a d = 6mm experiment is shown in Figure 4 with the complementary simulation shown in Figure 5. Three distinct breakdown regions became clear as the sample was displaced farther from axis: air breakdown from the sample to the anode, surface breakdown along the rutile sample, and air breakdown from the ground plane to the sample. The discharge threshold of this configuration was 12.5kV.

Comparing the experimentally observed discharge path to the simulated electric field shows that the air breakdown occurred along field lines and there was reduced field enhancement near the anode due to the

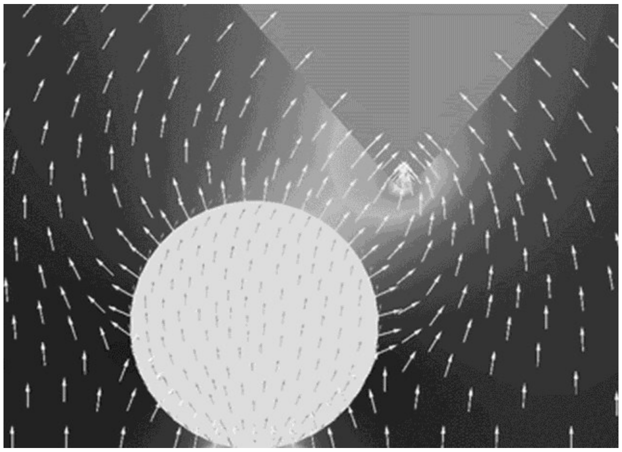

Figure 5. Electric field simulation of the experimental geometry shown in Figure 4. Higher field strengths are indicated in air by lighter shading.

increased distance to the sample. The near-normal field lines at the surface again produced an unrealistic breakdown prediction: 86kV.

The discharge attached to the rutile sample for all positions until d = 14mm. The experimental image is shown in Figure 6 with complementary simulation in Figure 7. The plasma channel formed along the electric field line directly between the ground plane and the anode. The breakdown voltage for this shot was not recorded due to a technical failure. However, the maximum voltage delivered was 19kV. The simulated breakdown of this configuration was 14kV.

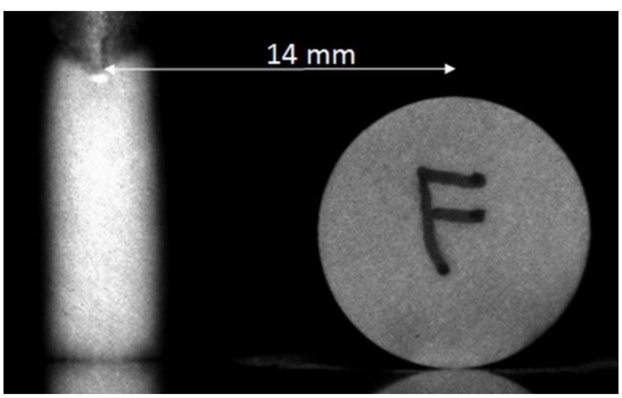

Figure 6. ICCD of discharge path rutile sample displaced 14mm from axis. The lower part of the image is the edge of the cathode. Breakdown voltage was 19kV.

The voltage breakdown values of all displacements tested are shown in Figure 8. The error bar estimate of ±1.5kV was established through a five-shot series at d = 0mm. The range of measured breakdown voltages was 11kV to 19kV between d = 0mm and d = 14mm. In comparison, the empty gap breakdown for this geometry was experimentally determined to be 34kV (17kV for 5.25mm

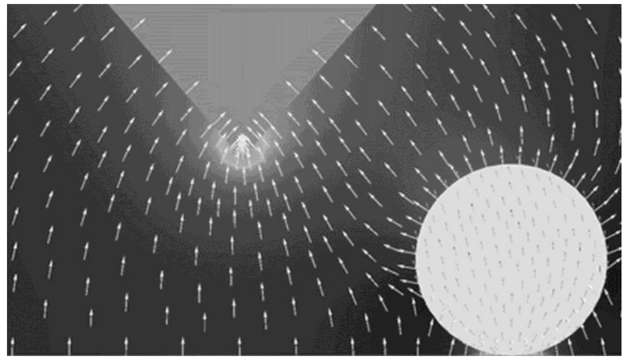

Figure 7. Electric field simulation of the experimental geometry shown in Figure 6. Higher field strengths are indicated in air by lighter shading.

gap due to maximum voltage limitations). Therefore, the presence of the intervening rutile dielectric reduced the breakdown threshold of this electrode configuration by 67% to 44%. Remarkably, this breakdown reduction persisted as the sample was displaced 14mm and the discharge formed directly between the electrodes. The physical mechanism for this observation is not understood, but it is hypothesized that the rutile sample is acting as an electron source aiding the formative avalanche that leads to discharge.

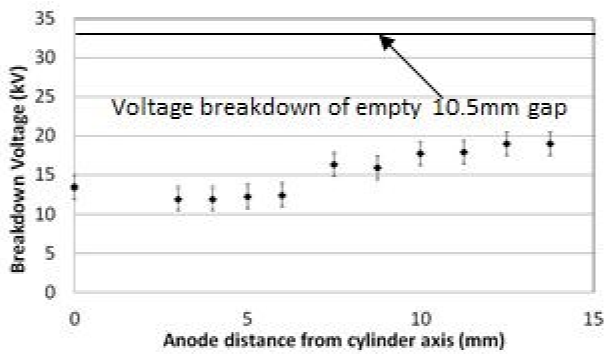

Figure 8. Graph showing the change in breakdown voltage as sample displacement increases. Experimentally measured breakdown threshold of empty 10.5mm gap is indicated.

Future work is planned that will utilize smaller rutile samples in order to reduce operating voltages. Also, a negative polarity shot series would enhance field emission from the conical electrode. Alternate materials may also be used to separately investigate the effects of high permittivity versus the rutile sample acting as a source/sink of electrons. Framing camera images will offer insight into the formation and evolution of the breakdown arc. Quantum efficiency measurements of rutile along with spectroscopy measurements during breakdown will quantify the ability of rutile to act as a source/sing of electrons during the breakdown process.

IV. SUMMARY

A fast gated imaging system and electrical diagnostics were utilized during a series of electrical discharge experiments to gain insight into the gap breakdown in the presence of a high-dielectric rutile cylinder with a 10mm diameter. The breakdown plasma channel was attracted to the sample where the cylinder axis was within 14mm of the electrical axis. At a sample displacement of 14mm, the discharge formed directly between electrodes. Remarkably, the breakdown range for these shots only varied from 11kV to 19kV, whereas the breakdown threshold of the empty electrodes was found to be 34kV. These results indicate that the rutile sample reduced the hold off voltage of the electrodes by 44% - 67% without altering the discharge path or directly interacting with the arc.

Eiger was used to perform numerical simulations of the experimental geometry considering the dielectric properties of the rutile sample, and the gas composition of the air. As expected, breakdown in the presence of a rutile surface involved more phenomena than the simple effects of the high permittivity on the electrostatic field. Images of the formation of the breakdown arc along with other follow on experiments investigating the properties of rutile as a source/sink of electrons will allow us to develop more advanced transient models for breakdown.

VI. REFERENCES

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