Multilayer High Gradient Insulator Technology

S. E. Sampayan, P. A. Vitello
Lawrence Livermore National Laboratory, Livermore, CA

M. L. Krogh and J. M. Elizondo
Allied Signal, FM& T Kansas City, MO

ABSTRACT

We are investigating a novel insulator concept that involves the use of alternating layers of conductors and insulators with periods on the order of <1 mm. These structures perform many times better ($\sim$1.5 to >4× higher breakdown electric field strength) than conventional insulators in long pulse, short pulse, and alternating polarity applications. A previously defined scaling law of $d^{-0.5}$, where d is the insulator length, appears to apply to these new structures when the scaling parameter d is replaced by the layer period d_1. This observation implies that each layer within the structure behaves independently in the breakdown process. We present our ongoing studies investigating the degradation of the breakdown electric field strength resulting from surface roughness, the effect of gas pressure, and the performance of the insulator structure under bi-polar stress. Further, we present our initial work on scaling and modeling studies.

1 INTRODUCTION

Several techniques have been implemented in the past to increase the threshold electric field strength E_{bd} at which breakdown or flashover of an insulator surface, bridging two metallic electrodes in vacuum, occurs. Among these techniques are the application of a 200 nm Cu_2O coating to the insulator surface [1], a Mn/Ti doping into an alumina substrate [2], spark discharge treatment of an insulator surface [3], tailoring of the electric field in the vicinity of the dielectric metal interface [4], and study of the effects of surface roughness on the insulator performance [5]. Many of these techniques have been shown to increase the breakdown threshold E_{bd} by factors ranging from 1.2 to $\sim$2.0. In this paper, we present a technique which shows that a more substantial increase in E_{bd} can be realized by fabricating the insulator from multiple thin alternating layers of metal or metal coatings and the dielectric.

This high gradient insulator technology was originally conceived by Gray in the early 1980's [6] and follows from experimental observations that the threshold electric field strength for surface flashover increases with deceased insulator length [7, 8]. The concept laid dormant until the mid-to-late 1980's, when this technology was pursued and successfully showed substantial increases in the breakdown threshold over conventional, single substrate insulators [9]. In more recent work, we pursued verification of the technology and showed an increase of 1.5 to 4.0× that over conventional insulator technology [10]. In later studies, we explored the properties of these structures in the context of switching applications, investigating their behavior under high fluence photon bombardment [11], and their microwave properties in bridged induction accelerator vacuum gaps [12].

2 EXPERIMENTS AND DISCUSSION

Small sample testing was performed in a turbo-molecular pumped, stainless steel chamber in the 10^{-6} to 10^{-5} Pa range. HV was developed with a 10 J 'mini-Marx'. The Marx generator developed a pulsed voltage of $\sim$1 to 10 μs (base-to-base) and amplitude $\leqslant$250 kV across the sample. Diagnostics consisted of an electric field sensor and a current viewing resistor. Failure of the insulator was determined by a rapid increase in Marx current and a sudden collapse in the voltage across the sample.

A set of samples was fabricated by interleaving layers of 0.25 mm fused silica. The interleaved metallic layers were formed by depositing gold on each planar insulator surface by a sputtering technique and then bonding the stacked layers by heating while applying pressure. As a final step in the process, the outside diameter of the structure was machined flush, *i.e.* the conductive layers do not extend beyond the insulator surface. Bond strength between the gold layer and substrate using this technique was measured to exceed 6.9×10^7 N/m^{-2}. To perform the breakdown experiments, the structure was slightly compressed between highly polished bare aluminum electrodes which establish the electric field for the tests.

1070–9878/0/ $3.00 © 2000 IEEE

To obtain a particular data set, the insulators were subjected to several low voltage conditioning pulses. The voltage was then increased a small amount incrementally until breakdown occurred. Voltage was then reduced for several shots and then incrementally increased again until a constant value was achieved. In these experiments, however, we generally observed that these insulators did not condition. Once a breakdown occurred at a particular field, reducing the voltage slightly and increasing it again did not cause an increase in breakdown field. To produce a given data set we would apply 150 to 200 shots to a given structure and would attempt to determine if any damage to the structure occurred which significantly altered the breakdown characteristics. At these applied energies, we generally did not observe any degradation. These data were then reduced to reliability plots by determining the total number of successful shots over the total number of applied shots. In these data we define the electric field as the applied voltage divided by the total insulator length. We define reliability at a given electric field as the total number of successful shots over the total number of shots.

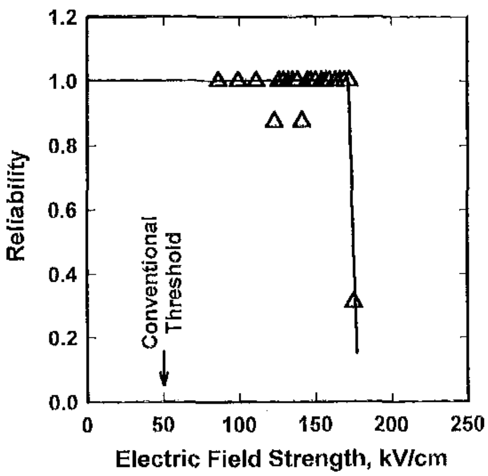

Figure 1. Pulsed surface breakdown reliability: ground fused silica high gradient insulator.

Using this method, we observed flashover of these small samples at ~175 kV/cm for these fused silica substrates (Figure 1). The effect of pulse width from 1 to 10 μs on this breakdown threshold was well within the statistical range of our data.

The previous trend in E_{bd} for conventional insulator technology is tabulated (Table 1) and plotted (Figure 2) for straight wall, cylindrical insulators ($\theta = 0°$, see Figure 2 for nomenclature) as a function of the temporal width of the applied electric field t_p. Although there is a high degree of scatter in the previous data, we attempt to determine a global trend for comparison purposes by performing a standard fourth order regression fit $f(t_p)$ (dotted line), with coefficients a_0 through a_4 as tabulated in Table 2. Shown also is the trend for the more classical slopes ranging from $t_p^{\ 1/6}$ and $t_p^{-1/3}$ scaling. From this Figure, such classic trends are only applicable in a narrow region of this parameter space particularly in the region of 1 μs and above where there is little dependence on the breakdown threshold as a function of pulse width. Noting the trend in these past data and comparison of the regression fit

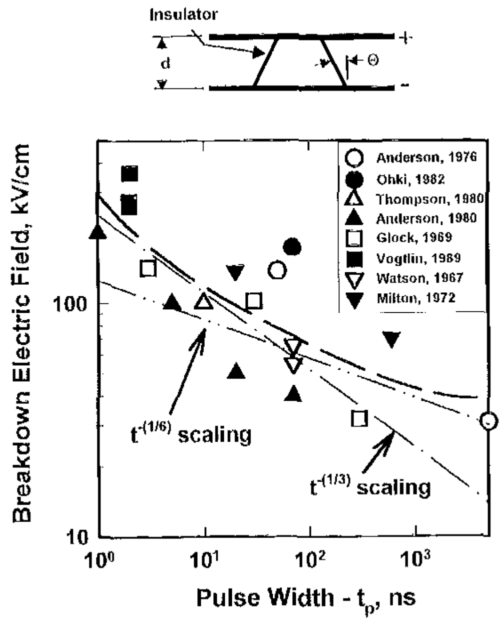

Figure 2. Previous pulsed surface breakdown electric field strength data E_{bd} as a function of pulse width t_p for single substrate, straight wall insulators ($\theta = 0°$). Slopes are shown for classical $t_p^{-1/6}$ and $t_p^{-1/3}$ scaling. Dash line indicates regression fit (Table 2).

Table 1. Summary of breakdown thresholds of conventional insulators. All data is for straight wall insulators, $\Theta = 0$.

d mm	V_{bd} kV	E_{bd} kV/cm	t_p ns	Material	Ref.
13	175	138	20	PMMA	Milton, 1972 [7]
	90	71	600		
13	40	31	5000	PMMA	Anderson, 1976[13]
	175	138	50		
9.5	165	173	70	Polycarbonate	Ohki, 1982 [14]
		100	10	PMMA	Thompson, 1980 [15]
		200	1	PMMA	Anderson, 1980 [16]
		100	5		
		50	20		
		40	70		
		142	3	PMMA	Glock, 1969 [17]
		102	30		
		32	300		
10		260	2	PMMA	Vogtlin, 1989 [18]
		275	2		
		365	2		
		66	70	Polycarbonate	Watson, 1967 [19]
		55	70	Epoxy	

to the data in Figure 1 shows a net increase in insulator performance of >3.5.

We are also studying various effects that can adversely affect these new structures. For instance, to ensure concentricity, a finish grinding operation was performed on the outside diameter. This process is a time consuming second operation and an alternate fabrication means was pursued. To simplify fabrication, we attempted an ultrasonic machining process. Although it was possible to fabricate the part in a single operation, the surface was left slightly rougher. Comparison of the breakdown characteristics of these samples showed significantly

Table 2. Coefficients of regression fit for Figure 2. $f(t_p) = \sum a_k \log(k(t_p))^k$.

Coef.	Value
a_0	2.471
a_1	0.5518
a_2	0.2115
a_3	-0.06609
a_4	0.008635

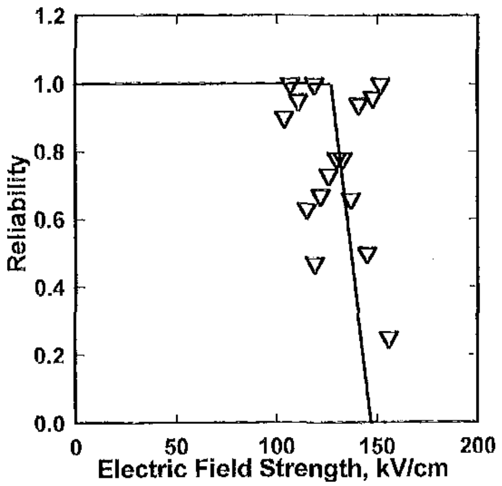

Figure 3. Pulsed surface breakdown reliability: roughened fused silica high gradient insulator.

more scatter and on average a slightly decreased breakdown threshold of ~25% (Figure 3).

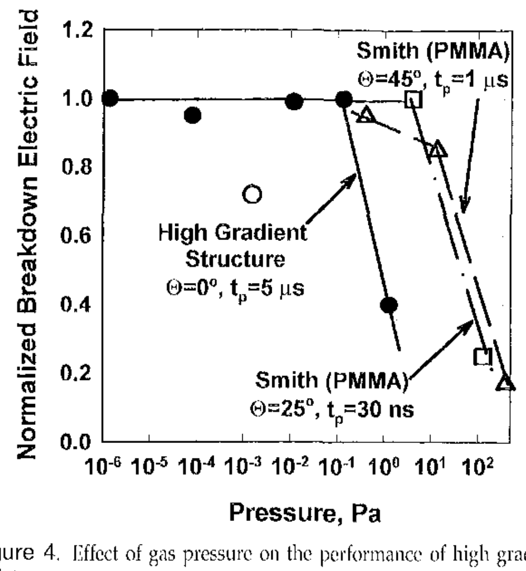

Figure 4. Effect of gas pressure on the performance of high gradient insulators.

The structures also were subjected to increased pressures to determine susceptibility to breakdown (Figure 4). In these data, using the previously described procedure, a fixed reliability was established at the various pressures. All data was then normalized to a mean breakdown electric field strength. Susceptibility to breakdown stays relatively constant up until the $\sim 10^{-1}$ Pa, at which point, the field at which breakdown occurs decreases rapidly. Also shown are data from previous work by Smith [20]. From this comparison, it appears that these new structures exhibit a threshold breakdown electric field strength at lower pressures.

Table 3. Summary of high gradient insulator test sample performance.

d_l mm	d mm	E_{bd} kV/cm	t_p ns	Material	Symbol Fig.5
0.13	10	350	100	polycarbonate	◇
0.13	10	190	1300	fused silica	☆
0.76	25	200	30	polyimide	○
		120	70		
		100	100		
1.17	10	92	1300	polycarbonate	△
1.52	22	200	30	polyimide	□
		110	56		
		70	110		
2.54	50	200	20	polyimide	▽

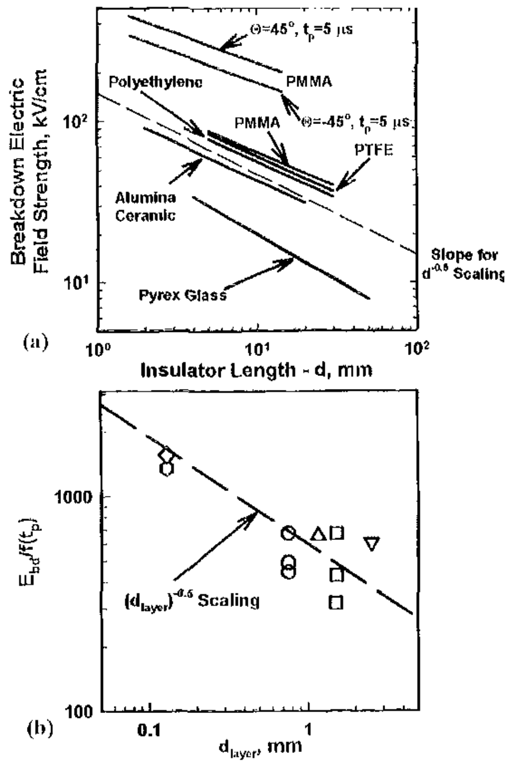

Figure 5. Insulator length scaling effects on the surface breakdown electric field strength. Scaling parameter is overall length for conventional insulators and insulator period for multilayer high gradient insulator. (a) Past data from conventional insulators. 5 μs PMMA pulsed data for $\theta = \pm 45°$ is from [7], remaining data is from [8]. Scaling approaches $d^{-0.5}$. (b) Scaling comparison to individual layer thickness for the high gradient multilayer insulator and comparison to $d_l^{-0.5}$ scaling.

We also performed similar testing on a large group of varied samples. The results are summarized with the previous sample in Table 3. These data were then compared to classical insulator length scaling (Figure 5).

Shown in Figure 5(a) are the results from previous researchers [7, 8]. polymethylmethacrylate (PMMA), $\theta = 45°$ (both negative and positive angles) insulators are results from a pulsed test where $t_p = 5$ μs [7].

A trend of $d^{-0.5}$ was inferred by these researchers from these data and was shown to be consistent with a model based on an electron stimulated desorption mechanism; ionization then develops in the emitted gases leading to flashover of the surface [8].

Shown in Figure 5(b) are data from our test normalized for pulse width by $f(t_p)$ (as defined in Table 2). Also shown is a similar scaling except that the overall insulator length d is now replaced by the high gradient insulator layer thickness (*i.e.*, the layer period), d_l (dash line). Comparison of this later slope appears to show a similar global trend and independence from the overall length d.

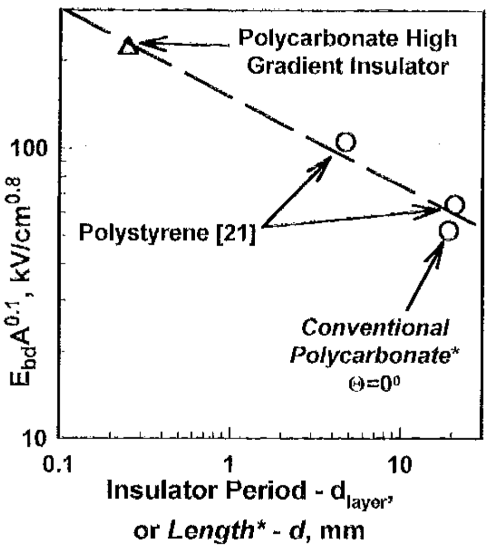

Figure 6. The effect of period length scaling under bi-polar stress.

A similar effect is observed when the high gradient insulator structures are subjected to an oscillating field. In this experiment, the Marx generator was allowed to undergo free oscillation with an inductive load. Period of the oscillation was ~500 ns. In this test, a high gradient insulator was compared directly to a similar conventional insulator structure. The results are shown in Figure 6. On this plot are also shown tests from a similar experiment [21]. A standard area scaling of $A^{0.1}$ was used to normalize the data for difference in scale size. Again, a general trend shows that a strong dependence on layer period, not overall length, is shown.

This observation perhaps indicates that in the breakdown process, these high gradient insulator structures exhibit a similar breakdown mechanism as conventional insulators except on the layer period scale (*i.e.* over length d_l), and exhibit only weak coupling to the adjoining layers on the macro-scale (*i.e.* over length d).

3 MODELING

Voltage breakdown for insulators surrounded by vacuum is believed to take place along the insulator surface and not within the insulator or exterior to the insulator in the vacuum. Breakdown occurs on the time scale of nanoseconds, making this a difficult process to study experimentally. The basic physical processes involved are poorly understood. Present theories of surface breakdown are mainly descriptive, and are not suited for the purpose of designing insulators. Due to the computationally intensive nature of a self-consistent model of surface breakdown, few attempts have been made to model the complete process.

The two most widely accepted published models for surface breakdown focus on the initial process occurring either just below or just above the insulator surface [19, 22]. These models focus respectively on solid state physics phenomena, and the propagation and emission of electrons through the vacuum just exterior to the insulator surface. Both models lead to surface heating, and evaporation of gas from the insulator. This evaporated gas is the medium where ultimately the voltage breakdown occurs along very localized 'streamer' channels. Pressures in the evaporated gas close to the insulator surface where the discharge forms can reach a significant fraction of atmospheric pressure. The surface breakdown is likely to be closely related to high-pressure voltage breakdown processes [23].

We have compared processes involved in surface breakdown with other well understood breakdown phenomena at high pressure. Our conclusion is that an accurate theoretical model of surface breakdown must also include the long time scale evolution of the streamer discharge though the evaporated gas. Further, the tip of a propagating streamer is known to produce intense high-energy radiation emission that we believe can lead to photoconduction in the insulator. Because conduction in the insulator strongly modifies the voltage that drives the streamer discharge, accurate coupling of the streamer to the insulator also must be included. Thus, our modeling approach is that the surface breakdown couples competing processes inside and external to the dielectric surface, and that a detailed, self-consistent model must be built to study this process accurately.

Our baseline code is INDUCT95 [24]. This code is a plasma discharge code that has been applied to plasma reactors, flat panel plasma display discharges, streamer discharges and other problems involving complex systems. It solves the standard time dependent fluid equations of the form

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot n_i \vec{v}_i + \sum_{j=1}^{N_c} R_{ij} \quad (1)$$

and

$$\frac{\partial n_i \vec{v}_i}{\partial t} = -\nabla \cdot (n_i \vec{v}_i \cdot \vec{v}_i) + \frac{q_i n_i \vec{E}}{m_i} - \frac{1}{m_i}\nabla n_i k T_i - \sum_{j=1}^{N_N} n_i \vec{v}_i v_{ij} \quad (2)$$

for the ions, where R_i is the source term for the changes in the ion densities. And for the electrons

$$\frac{\partial n_e}{\partial t} = -\nabla \cdot \Gamma_e + \sum_{j=1}^{N_c} R_{ej} \quad (3)$$

with the energy balance equation

$$\frac{\partial W_e}{\partial t} = -\nabla \cdot \vec{Q} - e\Gamma_e \cdot \vec{E} - P_{in} \quad (4)$$

where Γ_e is the electron flux and P_{in} is the energy loss rate due to inelastic collisions.

Preliminary examples of two geometries and results are shown in Figures 7 and 8. This simulation was performed with the updated

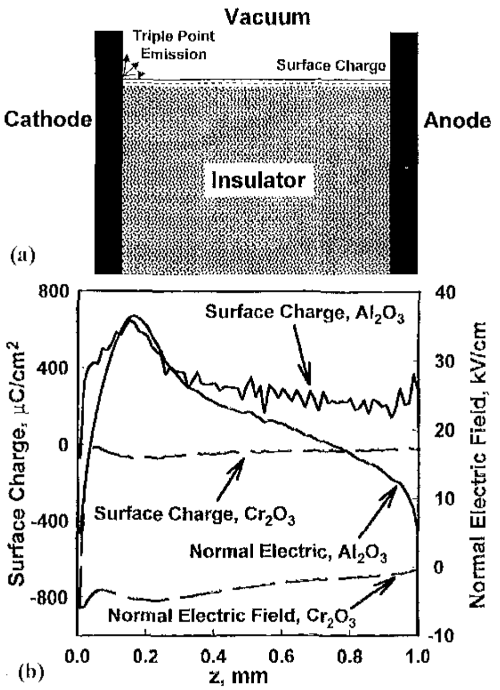

Figure 7. INDUCT modeling for two secondary emission coefficients and a straight wall insulator ($\theta = 0°$). (a) Input geometry and (b) result.

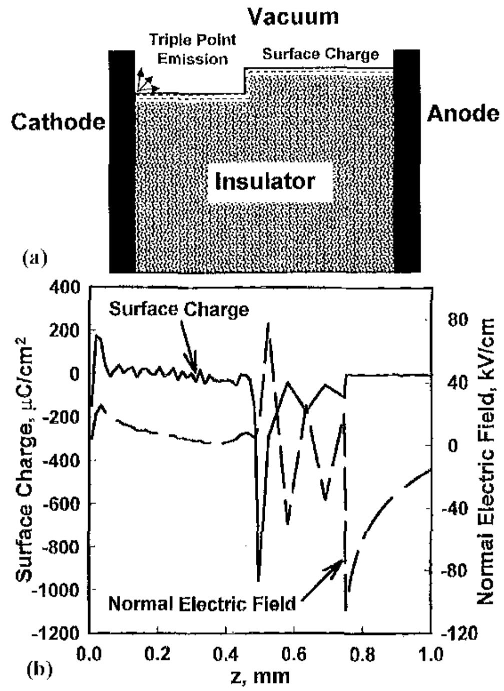

Figure 8. INDUCT modeling for a straight wall insulator with an outward step discontinuity at $z = 0.5$ mm. (a) Input geometry and (b) result.

version of INDUCT95/HYBRID and uses a Monte-Carlo treatment of electrons and a fluid treatment of ions to follow the discharge development. Several geometry configurations and surface materials were investigated. The standard configuration studied had an electrode separation of 1 mm with an applied voltage of 50 kV/cm. An insulator with a permittivity, $\varepsilon_r = 15$ was placed between the electrodes. The dielectric was considered to either have a flat surface (Figure 7) or a step discontinuity (Figure 8) halfway between the electrodes. Electrons were launched with random initial direction from the cathode triple point until they either struck the insulator or the anode. Upon striking the insulator, electrons generated secondary electrons.

The secondary emission yield is a strong function of incident electron energy. Secondary yield profiles were modeled for Al_2O_3 and Cr_2O_3. The secondary yield for Al_2O_3 has a maximum of 2.42 while the Cr_2O_3 peaked at 0.98. A yield higher than unity implies that the electron impact can lead to a positive surface charge on the insulator as more than one electron will be emitted. Simulation results showed strong positive surface charging for Al_2O_3 and weak negative surface charging for Cr_2O_3 for the flat dielectric case (Figure 7). Regions of positive surface charge on the insulator attract electrons emitted from the triple point and electrons emitted by secondary emission. This attraction leads to enhanced scattering onto the insulator surface which results in avalanche. For Cr_2O_3, the negative surface charge repelled electrons from the triple point, reducing scattering and no avalanche was obtained. As would be expected, the insulator geometry was found to influence surface charging strongly. A step dielectric geometry was also modeled for Al_2O_3. Strong negative surface charging developed along the step due to high-energy electron impact (the secondary emission yield drops below unity at high energy). This negative charge repelled electrons upward away from the insulator surface, inhibiting the avalanche growth for this geometry.

4 SUMMARY

We are continuing development of a new high gradient insulator technology. The insulator consists of finely spaced metal electrodes or metalized coatings interleaved with the insulator substrate. We observed factors of 1.5 to >4 improvement in the vacuum surface flashover threshold E_{bd}, over conventional straight wall ($\theta = 0°$) insulators. We have also tested the susceptibility of these insulators to breakdown under various conditions: surface roughness resulting from different fabrication techniques and the effect of gas pressure. There is preliminary evidence that suggests each layer obeys a classical electron desorption scaling rule of $E_{bd} \propto d^{-0.5}$ except that the scaling parameter is layer thickness and not overall length. Further, we are developing the necessary design tools to model and further scale the behavior of the high gradient insulator. From our study of present models, we conclude that an accurate theoretical model of surface breakdown must also treat photo-ionization during the long time scale evolution of the streamer discharge through the evaporated gas. That is, the tip of a propagating streamer is known to produce intense high-energy radiation emission that we believe can lead to photoconduction in the insulator. As conduction in the insulator will strongly modify the voltage, which drives the streamer discharge, accurate coupling of the streamer to the insulator was included. We showed initial calculations that were performed.

ACKNOWLEDGMENT

Work performed under the auspices of the US Dept. of Energy by LLNL under contract W-7405-ENG-48.

REFERENCES

[1] J. D. Cross and T. S. Sudarshan, "The Effect of Cuprous Oxide Coatings on Surface Flashover of Dielectric Spacers in Vacuum", IEEE Trans. Elec. Insul., Vol. 9, pp. 146–150, 1974.

[2] H. C. Miller and E. J. Furno, "Improving the Voltage Holdoff of Alumina Insulators by Mn/Ti Treatments", in VIII International Symposium on Discharges and Electrical Insulation in Vacuum (Sandia Laboratories, 1978), pp. D6.1–D6.8

[3] L. L. Hatfield, G. R. Leiker, M. Kristiansen, C. Colmenares, W. W. Hofer, and M. S. DiCapua, "A Treatment which Improves Surface Withstand Voltage in Vacuum", IEEE Trans. Elec. Insul., Vol. 23 (1), pp. 57-61, 1988.

[4] H. C. Miller, "Surface Flashover of Insulators", G. E. Aerospace Report (GEPP-TIS-1064-UC-13), August 31, 1988.

[5] R. G. Bommakanti and T. S. Sudarshan, "Correlation of Alumina Surface Finish with Pulsed Surface Flashover Performance", in Digest of Techinical Papers, 7th IEEE Pulsed Power Conference (IEEE, New York, NY, 1989), pp. 828–831.

[6] Private communication, Eoin Gray

[7] O. Milton, "Pulsed Flashover of Insulators in Vacuum", IEEE Trans. Electr. Insul., Vol. 7, 1972, pp. 9-15, 1972.

[8] A. S. Pillai and R. Hackam, "Surface Flashover of Solid Dielectric in Vacuum", J. Appl. Phys., Vol. 53 (4), pp. 2983–2987, 1982.

[9] J. Elizondo and A. Rodriguez, "Novel High Voltage Vacuum Surface Flashover Insulator Technology", in Proceedings of 1992 15th International Symposium on Discharges and Electrical Insulation in Vacuum (Vde-Verlag Gmbh, Berlin, 1992), pp. 198–202.

[10] S. Sampayan, G. Caporaso, B. Carder, Y. Chen, C. Holmes, E. Lauer, D. Trimble, J. Elizondo, M. Krogh, B. Rosenblum, C. Eichenberger, and J. Fockler, "High Gradient Insulator Technology for the Dielectric Wall Accelerator", in Proceedings of the 1995 Particle Accelerator Conference (IEEE, New York, NY, 1995), pp. 1269–1271.

[11] S. Sampayan, G. Caporaso, B. Carder, M. Norton, D. Trimble, and J. Elizondo, "Optically Induced Surface Flashover Switching for the Dielectric Wall Accelerator", in Proceedings of the 1995 Particle Accelerator Conference (IEEE, New York, NY, 1995), pp. 2123–2125.

[12] T. Houck, G. Caporaso, C. Shang, S. Sampayan, N. Molau, and M. Krogh, " Measured and Theoretical Characterization of Stacked, High Gradient Insulator Material", in Proceedings of the 1997 Particle Accelerator Conference (IEEE, New York, NY, 1998), pp. 2627–2629.

[13] R. A. Anderson, "Study of Surface Flashover of Conical Insulators Using 3 ns Risetime Pulses", in VII International Symposium on Discharges and Electrical Insulation in Vacuum (Novosibirsk, 1976), pp. 252–256.

[14] Y. Ohki, "Surface Flashover along a Polycarbonate Plate in Vacuum under a Non-Uniform Electric Field", in Xth International Symposium on Discharges and Electrical Insulation in Vacuum (Columbia, SC, 1982), pp. 322–326.

[15] J. E. Thompson, J. Lin, K. Mikkelson, and M. Kristiansen, "Investigations of Fast Insulator Surface Flashover in Vacuum", IEEE Trans. Plasma Sci., Vol. 8, pp. 191–197, 1980.

[16] R. A. Anderson and J. P. Brainard, "Mechanism of Pulsed Surface Flashover Involving Electron-Stimulated Desorption", J. Appl Phys., Vol. 51 (3), pp. 1414–1421, 1980.

[17] W. R. Glock and S. Linke, *Pulsed HV Flashover of Vacuum Dielectric Interfaces*, Cornell University Report, Laboratory of Plasma Studies (LPS 24), August 1969 and in W. R. Glock, MS thesis, Cornell University, 1969.

[18] G. E. Vogtlin and J. E. Vernazza, "Vacuum Insulator Failure Measurements and Improvement", in Digest of Techinical Papers, 7th IEEE Pulsed Power Conference (IEEE, New York, NY, 1989), pp. 808–811.

[19] A. Watson, "Pulsed Flashover in Vacuum",J. Appl. Phys. Vol. 38, pp. 2019–2023, 1967.

[20] I. D. Smith, "Pulsed Breakdown of Insulator Surfaces in Poor Vacuum", unpublished AWRE report, Aldermaston, United Kingdom and in I. D. Smith, Proceedings of the International Symposium on Insulation and HV in Vacuum, (Cambridge, USA, 1964), pp. 261-280.

[21] R. A. Anderson and W. K. Tucker, "Vacuum Surface Flashover from Bi-Polar stress", J. Appl. Phys, Vol. 58, pp. 3346–3349, 1985.

[22] G. Blaise, "Space-Charge Physics and the Breakdown Process", J. Appl. Phys., Vol. 77, pp. 2916, 1995.

[23] E. W. Gray, "Vacuum Surface Flashover: a High-Pressure Phenomenon", J. Appl. Phys., Vol. 58, pp. 132–141, 1985.

[24] P. A. Vitello, R. A. Stewart, D. B. Graves, E. F. Jaeger, and L. A. Berry, " INDUCT94: a Two-Dimensional Fluid Model of High Density Inductively Plasma Sourses", Lawrence Livermore National Laboratory Report (UCRL-MA120465), March 24, 1995.

This paper is based on a presentation given at the 18th International Symposium on Discharges and Electrical Insulation in Vacuum, Eindhoven, The Netherlands, 17–21 August 1998.

Manuscript was received on 15 November 1998, in final form 4 May 1999.