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VACUUM INSULATOR FAILURE MEASUREMENTS AND IMPROVEMENT*

G. E. VOGTLIN, J. E. VERNAZZA
LAWRENCE LIVERMORE NATIONAL LABORATORY
UNIVERSITY OF CALIFORNIA
LIVERMORE, CA 94550

ABSTRACT

Cones, cylinders, and insulators have been tested with a 3 nanosecond full width halfmax pulse. These insulators were made of epoxy, acrylic, lexan, and nylon. The tests were conducted with cone insulators at +45 degrees, -45 degrees, and 0 degree. Additionally, tests were conducted with a plug in the anode that reduces the anode stress, and anodized cathodes. Best results were obtained with both an anodized cathode and an anode plug where failure was through the solid dielectric at 600 kV/cm. Results of this testing will be presented.

Explosive emission was also evaluated with the same apparatus. All tests were conducted without conditioning. Currents could be detected down to 10 milliamps. Data for brass, copper, stainless, aluminum will be presented. The onset of explosive emission could be detected. The lowest onset was for brass at less than 200 kV/cm. The best was a carbon loaded epoxy emission. Currents have been detected that follow a Fowler-Nordheim like function of voltage.

INTRODUCTION

Vacuum insulator failure is often the primary limitation in pulse power systems design. This is particularly true in devices that operate at high peak power density. The combination of low impedance (small gaps) and high voltages results in severe design limits. A primary objective of this work was to determine the stress limits for insulators subject to a 3 nanosecond voltage pulse. Various configurations and materials have been tested.

The initiating factor in insulator failure is particle emission. This emission can originate at the anode, cathode or insulator surface. Particles can be electrons from Fowler-Nordheim emission and/or electrons and ions from explosive emission. Insulator surface failure on a nanosecond basis is due to charge accumulation that allows grazing incidence of electrons traveling along the surface. This grazing incidence allows an avalanche to occur. The determination of electrode and insulator emission and its suppression should lead to higher insulator stress.

All measurements presented are first shot data. No electrical conditioning was conducted. The specimens were cleaned with isopropyl alcohol and kimwipes and dusted with a gas duster before evaluation at pressure below 5 x 10^{-5} Torr.

BACKGROUND

Measurement of vacuum insulator breakdown for cones at various angles was initiated by Ian Smith.[1] He has shown that with a 30 ns pulse and common insulator material that 200 kV/cm or greater could be held with a cone angle of 45°. Glock and Linke [2] demonstrated that breakdown was time dependent with a 6 nanosecond rise time resulting in 300 kV/cm breakdown with a 45° positive angle. Other rise times tested were 30 ns with a 200 kV/cm breakdown, and 300 ns with a 120 kV/cm breakdown.

Anode-initiated breakdown mechanisms were investigated by R. A. Anderson.[3] Evidence for anode or insulator surface insulator flashover were trees initiating near the anode. Cathode initiated surface breakdown was recently reviewed by Arnold, Thompson, Sudarshan, and Douglas.[4] This initiation requires an enhancement point in the cathode triple point.

Vogtlin, Hofer, and Wilson [5] showed that with a 3 nanosecond pulse, anode, surface, and cathode initiated breakdown could occur. This initiator was a small piece of velvet placed on the respective surfaces. Tracking occurred only on anode or surface initiated breakdown. A plug was used in the anode side of the cone to reduce the anode stress. This plug, with an anodized aluminum cathode, did not experience surface breakdown. Failure was through the solid dielectric at 630 kV/cm stress in the vacuum gap.

Dust or particulates can initiate breakdown. Velvet on a cathode surface is an optimum dust concentration for plasma formation. Scarpetti [6] found velvet plasma formation below 100 kV/cm with a 30 nanosecond wide pulse. We have seen velvet plasma formation at 20 kV/cm peak with a 100 ns, 10-90, rise and a 3.5 μs e-fold fall time. The mechanism is probably an avalanche of electrons on the dust particle surface. Glock and Linke [2] concluded that a streamer could reach saturation density within a fraction of a millimeter on an insulator surface.

EXPERIMENTAL PARAMETERS

The 3-ns pulse used was constructed by Scarpetti and described in Ref. [6]. The electrode and insulator arrangement is shown in Figure 1.

Specimens were cleaned with isopropyl alcohol and dusted with a micro duster before sealing and pumpdown. In all cases a single shot was fired with each specimen. Cathodes were either refinished or were not reused. Anodes were not always refinished or replaced. The surface smoothness of the insulators did not seem to be a factor; however, all specimens included in the data were polished with a light abrasive. The surface condition can influence breakdown with longer pulses. A particular problem is with microscopic chips stuck at one end in their machining groove. These chips can only be seen by blowing on the specimen in the dark while illuminated by flash light. They appear to be as long as 0.5 cm.

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14. ABSTRACT
Cones, cylinders, and insulators have been tested with a 3 nanosecond full width halfmax pulse. These insulators were made of epoxy, acrylic, lexan, and nylon. The tests were conducted with cone insulators at +45 degrees, -45 degrees, and 0 degree. Additionally, tests were conducted with a plug in the anode that reduces the anode stress, and anodized cathodes. Best results were obtained with both an anodized cathode and an anode plug where failure was through the solid dielectric at 600 kV/cm. Results of this testing will be presented.

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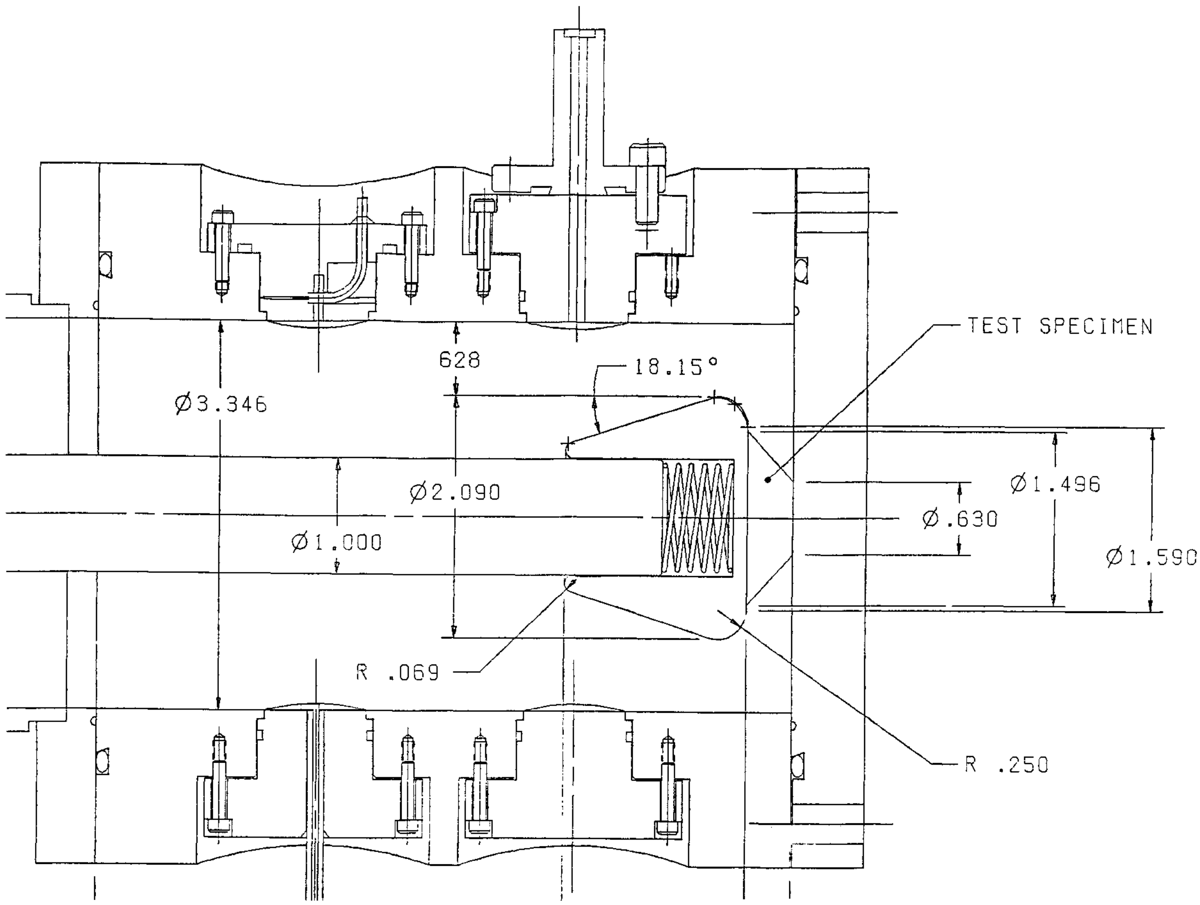

Fig. 1. TEST SETUP

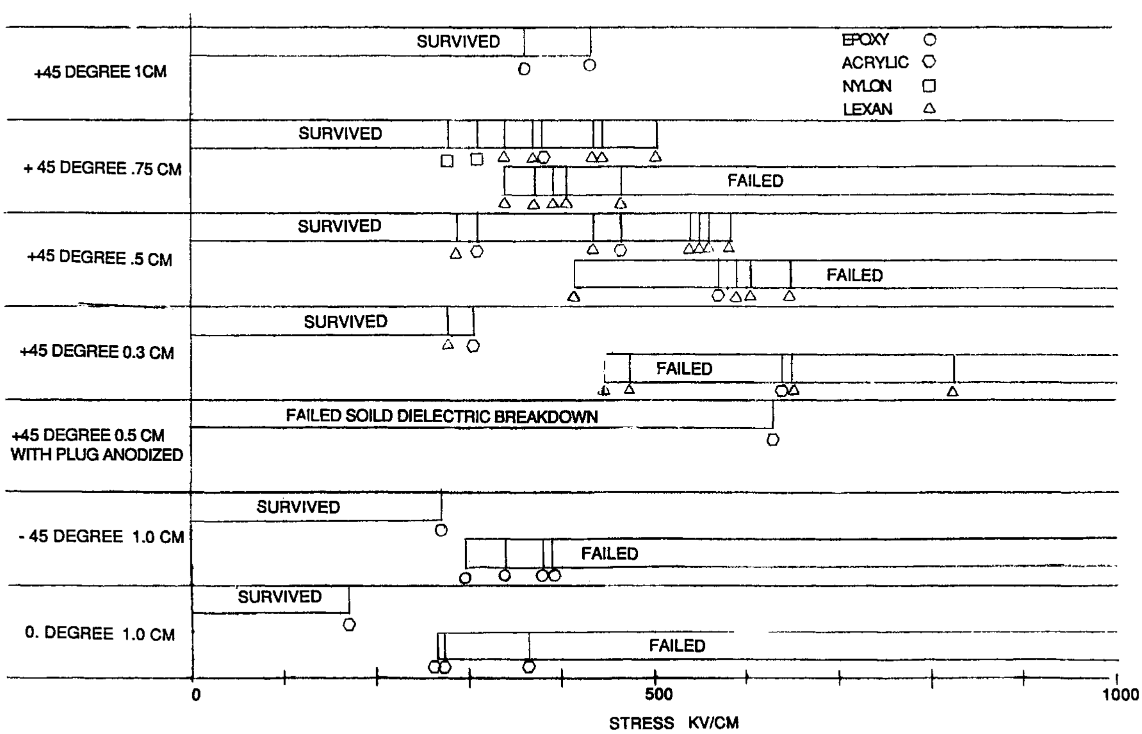

Fig. 2. INSULATOR FAILURE-SURVIVAL CHART

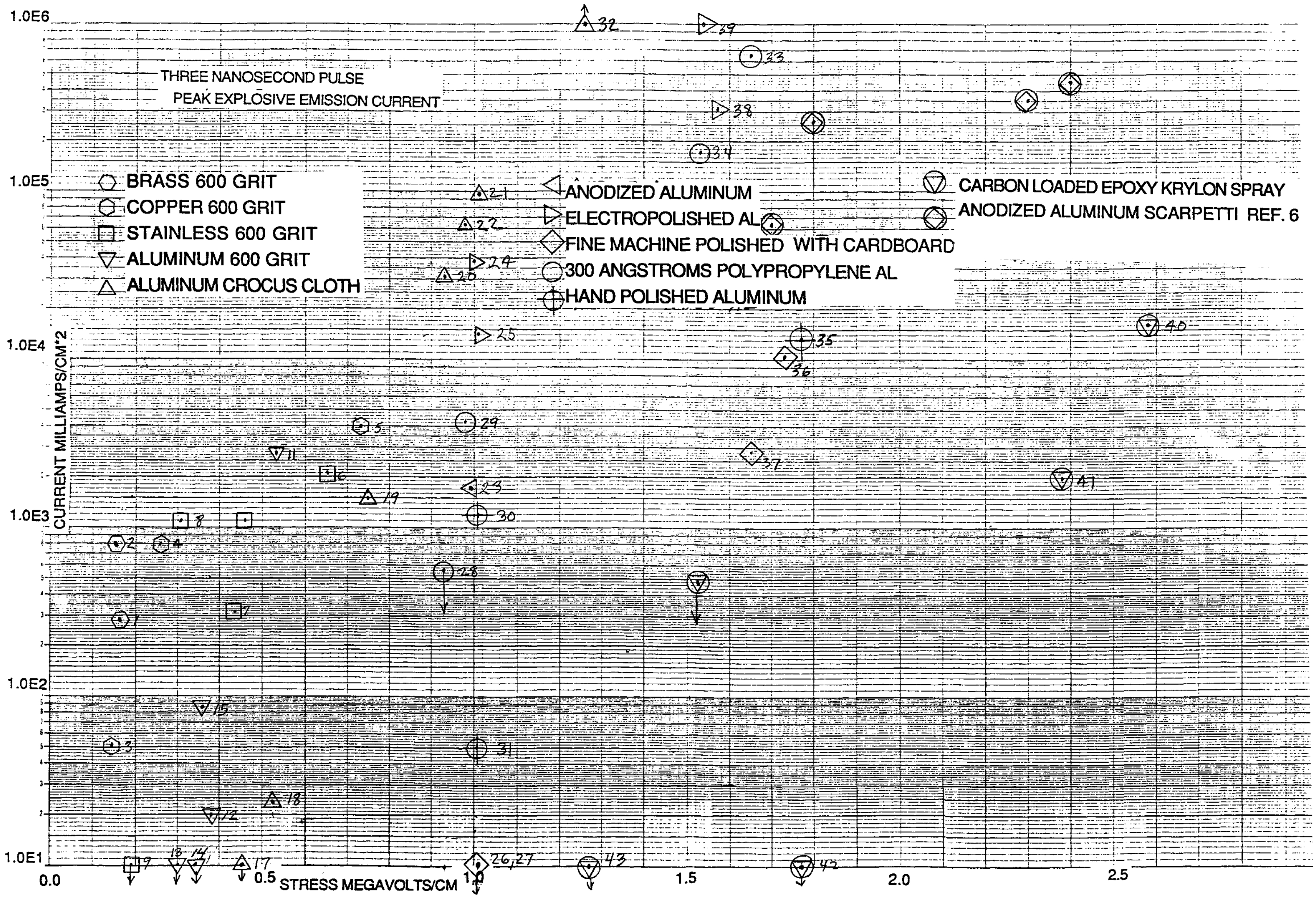

Fig. 3. PEAK EXPLOSIVE EMISSION CURRENT VS STRESS

INSULATOR EXPERIMENTAL RESULTS

Specimens tested either held the 3 nanosecond pulse or failed during the pulse. Figure 2 shows results of this testing. The first bar on the top shows 3 specimens 1 cm high and a +45° angle. They survived 360 kV/cm and 430 kV/cm. No specimens failed since this was close to the voltage limit of the pulser. The second bar is for +45° 0.75 cm specimens, 7 specimens survived and 5 specimens failed. The highest survival was 505 kV/cm with a Lexan specimen and the lowest failure was 310 kV/cm with a nylon specimen. Data is presented for an angle of +45° with .5 cm and .3 gaps. Other angles are -45° and 0° with 1 cm specimen. The highest level was achieved with a 0.5 cm acrylic specimen with an anode plug to relieve the anode stress and an anodized aluminum cathode surface. The failure was at 620kV/cm. This failure, however, was through the solid dielectric from the plug to the cathode. A description of this specimen in given in Ref. [5].

ELECTRON EMISSION EXPERIMENTAL RESULTS

Field emission was measured with the same apparatus as described in Reference [5]. Figure 3 (current vs stress) shows the results for various metal surfaces. The surfaces tested from 100kV to 800 kV/cm were finished with 600 grit or crocus cloth. Brass with a 600 grit finish gave a peak current of 800 milliamps with a peak stress of 180 V/cm. If we assume an emission per point of 100 ma, then there would be 10 emission points. This is in an area of .785 cm^{-2} or 12 points/cm^2.

It would seem unlikely that an emission point would fall on the cathode triple point; however, the probability always exists even if there is only a single emission point. The plasma expansion from an explosive emission point is on the order of 2.5 cm/µs. This would imply a hemisphere of plasma 1.5 millimeters in diameter at 3 ns. Later at 1 microsecond, this hemisphere would be 5 cm in diameter. The longer the pulse, the more likely that plasma will reach the cathode triple point. The higher the stress without measurable emission, the better the performance of the cathode surface. Other surfaces such as crocus cloth finished aluminum reached 460 kV/cm with less than 10 ma of current.

Figure 3 from 800 kV to 1.8 meV/cm shows materials such as anodized aluminum and electron polished stainless steel. One specimen held 1mV/cm without meaurable current. This specimen was fine machined stainless steel, polished on a lathe with a piece of cardboard. The next best was an aluminum specimen coated with 300 angstroms of polypropylene, which emitted 50 ma at 1 mV/cm.

Another surface tested was aluminum coated with a carbon filled epoxy. The epoxy coating was approximately 0.1 millimeters thick with a surface resistivity of 200-800 KΩ per square. This surface was polished with paper and sprayed with krylon spray, matte finish. Figure 3 shows this surface did not have any measurable emission at 1.7 megavolts/cm. It emitted 3 amps at 2.3 megavolts/cm. This current probably represents no more than two explosive emission points.

The 3 nanosecond pulser into a high impedance load produces a second pulse, 12 ns later, with the same shape but about 70% in amplitude. The current for the second pulse is much greater than the current from the first pulse. We attribute this effect to explosive emission and resultant plasma expansion. An approximate formula for the current is $I = 1 \times 10^{-9} (t)^2 V^{3/2}/d^2$. Where t is in nanoseconds, V in volts, and d the gap in centimeters. The ratio of first to second peak would be approximately 20. Many measurements are close to this ratio.

Fowler Nordheim currents would decrease dramatically on the second pulse. Stress above 1.5 mV/cm with no explosive emission resulted in currents of tens of milliamps for the first current peak and approximately half that amount for the second peak. These current peaks were repeatable and varied in amplitude with voltage. A typical test would be 420 kV peak voltage, Gap 0.254 cm, first current peak 20 milliamps, and second current peak 16 milliamps. These currents and the current relationship to voltage would indicate Fowler-Nordheim like currents.

CONCLUSIONS

The 3 nanosecond pulse testing of insulators was similar to previous work with longer pulses. It was found that a positive 45° angle cone held the highest stress. Failure of these cones was associated in most cases with surface tracking which we believe to be indicative of anode induced breakdown. The introduction of an anode plug to reduce the anode stress caused failures that were a higher level and did not involve tracking. We believe these are cathode induced. The use of an anodized cathode and a plug relieved anode resulted in the highest stress before failure, 630 kV/cm, and failed due to solid dielectric breakdown.

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