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VACUUM INSULATOR STUDIES
FOR THE DIELECTRIC WALL ACCELERATOR

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Abstract

   As part of our ongoing development of the Dielectric Wall Accelerator, we are studying the performance of multilayer high-gradient insulators. These vacuum insulating structures are composed of thin, alternating layers of metal and dielectric, and have been shown to withstand higher gradients than conventional vacuum insulator materials. This paper describes these structures and presents some of our recent results.

INTRODUCTION

   Surface flashover of insulators in vacuum is generally the limiting factor in the design of high voltage vacuum devices [1]. The most widely-accepted theory of surface flashover holds that an avalanche of secondary electrons occurs along the insulator surface, desorbing gas through which the breakdown occurs [1-4]. A number of techniques, such as angled insulators or applied magnetic fields, can increase the voltage at which flashover occurs by making it more difficult for the secondary electrons to return to the insulator surface [1]. However, these techniques are not useful in all applications. One example is the Dielectric Wall Accelerator (DWA), now under development at Lawrence Livermore [5]. Insulators in the DWA will be subjected to voltage reversals, which prevents optimized use of angled insulators since they have a preferred polarity, and the strong magnetic fields needed for magnetic flashover inhibition are not desirable as they would complicate beam transport. In support of the DWA project, we are currently studying multilayer high-gradient insulators (HGIs). HGIs are vacuum insulating structures composed of alternating layers of metal and dielectric (Fig. 1) which have been shown in previous tests to have higher flashover voltages than conventional (un-angled) insulators by a factor from 1.5 to 4 [6,7], an improvement which is comparable to that obtained by use of angled insulators [1].

   In this paper we will discuss our testing procedure and the effects of conditioning and sample geometry on HGI strength.

TESTING AND CONDITIONING

   The HGIs tested in these experiments consisted of thin Rexolite and stainless steel layers, hot pressed and machined to the final 2.54 cm diameter. Testing is

conducted using a dedicated high voltage test stand [7]. In this test stand, the samples are held between stainless steel electrodes in a vacuum chamber pumped to 2×10^{-7} Torr. A negative voltage pulse from a 16-stage Marx generator is applied to the upper electrode. This pulse has a rise time of 10 ns, a FWHM pulse length of 100 ns, and a peak voltage adjustable from 60 kV to 290 kV.
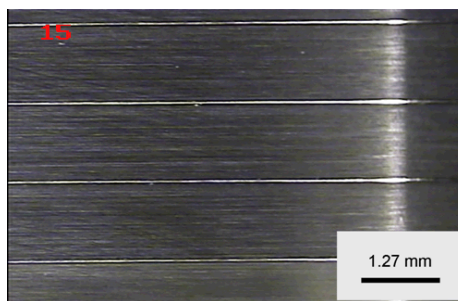

Figure 1: Photograph of HGI surface (R213). The thin horizontal lines are stainless steel layers, while the remainder of the structure is Rexolite.

   Testing is normally accomplished by applying one pulse per minute to the sample, and increasing the Marx charging voltage by 500 V after every fifth shot until a flashover occurs ($n = 5$). The Marx charging voltage is then reduced by 500 V and the process repeats. The test is concluded when a total of three flashovers have occurred at any charging voltage level ($m = 3$). Insulator strengths quoted here represent the highest voltage or gradient held without flashover during testing. As an insulator's ultimate strength is approached, the percentage of successful shots drops precipitously, and so the highest voltage held without flashover in these tests is only slightly higher than the 50% success voltage.

   The choice of test procedure, and in particular n and m, will affect the test results. Changing the number of shots taken at each voltage level (n) may be expected to affect the measurement by changing the amount of conditioning applied to the sample during the test. To investigate this, insulators R168, R169, and R170 were tested using the standard procedure, except that they were subjected to one, five, and ten shots, respectively, at each voltage level before proceeding to the next voltage level. The resulting conditioning of R169 and R170 increased the voltage at which the first flashover was observed, but it did not have a significant effect on the peak voltage sustained (Fig. 2).

Following the testing, the samples remained under vacuum for over 24 hours, and were tested again using $n = 1$. For each sample, the first flashover occurred at a voltage which was higher than the first flashover in the previous test, but lower than the peak voltage held during the previous test. This indicates that the flashovers occurring in the initial testing had a net conditioning effect, and that most of that conditioning was retained permanently, presumably due to physical changes in the insulator surface or removal of contaminants. The additional temporary conditioning which occurred during the initial tests was probably due to desorption of gas from the insulator surface, which was readsorbed over time from the imperfect vacuum used for the test. This combination of permanent and temporary conditioning has been observed previously, notably in vacuum arc studies [8].

Sample R169 showed inferior performance compared to R168 and R170. This is believed due to a mechanical deformation of the structure observed in microphotographs taken before testing. Images taken after testing show that the main regions of damage corresponded to the location of minimum spacing between adjacent metal layers. Results for these insulators are summarized in Fig. 2 along with those for R173 [7], which was frequently removed from vacuum during testing and therefore did not receive the same conditioning benefits.
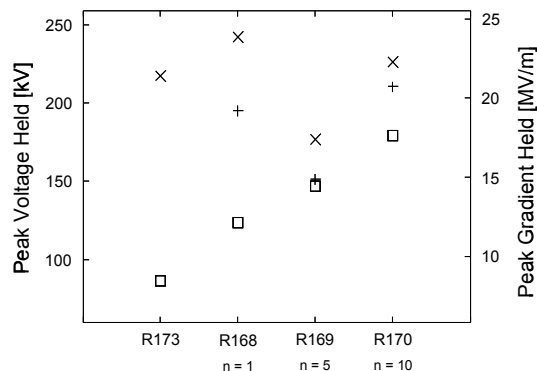
Figure 2: Observed HGI performance as a function of conditioning procedure. Highest voltage achieved before the first flashover (□), highest voltage achieved (X), and highest voltage achieved before the first flashover on the second day (+) are shown.

It was also important to establish whether the reported value of insulator strength would increase significantly by requiring a higher number of flashovers to occur at a given voltage level before the test was concluded (m). To investigate this, three HGIs with different layer thicknesses were tested until a total of five flashovers were observed at any voltage level. The highest peak voltage sustained by the insulator before the first, second, third, fourth, and fifth flashovers at any voltage level are plotted in Fig. 3. This figure shows that continuing the

tests beyond $m = 3$ did not significantly improve the reported strength in any of the three samples.
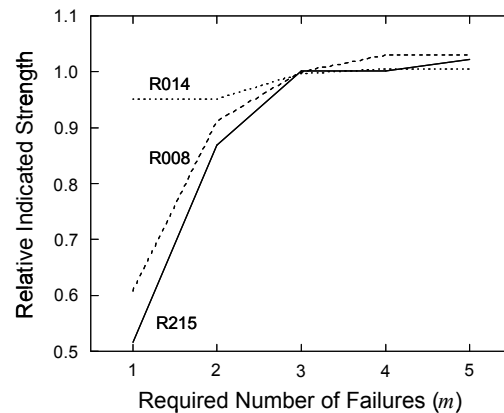
Figure 3: Observed HGI performance as a function of testing procedure. The plotted sample strength is relative to values from Tables 2 and 3.

Finally, tests were also carried out using samples R207-R212 to determine if conditioning could be achieved by applying a series of extra pulses at the lowest voltage achievable in the test stand before beginning the standard test procedure, and to investigate the effect of changing the Marx configuration. These tests yielded inconsistent results, and no dependence on conditioning procedure could be discerned. These results are shown in Table 1.

Table 1: HGI Samples with 5.48 mm length.

HGI	Rexolite [mm]	Insulator/ Metal Ratio	Length [mm]	Strength [MV/m]
R207	1.3	100	5.48	31.7
R208	1.3	100	5.48	16.7 [1]
R209	1.3	100	5.48	12.3 [2]
R210	1.3	100	5.48	12.3
R211	1.3	100	5.48	28.9 [3]
R212	1.3	100	5.48	21.0 [3]

[1] 50 preliminary conditioning shots at lowest voltage
[2] 10 preliminary conditioning shots at lowest voltage
[3] Marx in 11-stage configuration

DEPENDENCE ON SAMPLE GEOMETRY

A key concern of these tests was to search for ways to increase the strength of HGIs by changing the thickness of the metal and insulator layers, and so a variety of sample geometries were tested. Table 2 shows results of tests using HGIs with lengths of approximately 11 mm, and several values of insulator layer thickness; the metal layer thickness for all of these samples was 0.013 mm.

In addition, we tested four samples with metal layers that were slightly thicker than the insulator layers, as shown in Table 3. This geometry was suggested by Leopold, et al., who attempted to explain the improved performace of HGIs in terms of electron deflection away from the HGI-vacuum interface [9]. This effect relies on

the curvature of equipotential lines near the HGI surface, and requires relatively thick metal layers. In addition, the effect is sensitive to the choice of metal or dielectric for the initial layer, with an initial metal layer being preferred. The four samples listed in Table 3 were initially fabricated with dielectric end layers, but two were modified by removal of the end layers. In our tests, the thick-metal HGIs performed more poorly than the thin-metal HGIs. The discrepancy between our experimental results and the experimental and theoretical results of Leopold is not entirely unexpected, since the structure period used in our samples was significantly less than that used in Leopold's work, which is believed to result in significantly less deflection of electrons away from the HGI surface.

Table 2: HGI Samples with ~11 mm length.

HGI	Rexolite [mm]	Insulator/ Metal Ratio	Length [mm]	Strength [MV/m]
R008	0.26	20	12.31	21.4
R009	0.26	20	12.31	23.5
R010 [7]	0.26	20	12.31	>22.3 [1]
R168	0.51	40	10.15	23.8 [2]
R169	0.51	40	10.15	17.6 [2,3]
R170	0.51	40	10.15	22.3 [2]
R173 [7]	0.51	40	10.15	21.4 [2]
R213	1.3	100	10.67	>26.5 [1]
R214	1.3	100	10.67	20.3
R215	1.3	100	10.67	26.1

[1]Exceeded voltage capability of test stand
[2]Conditioning test shown in Fig. 2
[3]Damaged in manufacturing

Table 3: HGI Samples with thick metal layers.

HGI	Rexolite [mm]	Insulator/ Metal Ratio	Length [mm]	Strength [MV/m]
R011 [1]	0.26	0.833	12.36	10.5
R012 [1]	0.26	0.833	12.36	11.2
R013 [2]	0.26	0.833	11.51	14.1
R014 [2]	0.26	0.833	11.43	10.9

[1]Dielectric end layers
[2]Metal end layers

Fig. 4 shows the results from Tables 2 and 3 plotted as a function of the ratio of insulator and metal layer thicknesses (I/M). The best results for each value of I/M fall approximately on the curve

$$E = 2.5\ln(I/M) + 15 \ \ [MV/m]. \qquad (1)$$

At this time, we have no theoretical explanation for this observation. As $I/M \rightarrow \infty$, the structure will no longer be an HGI, and therefore we expect the strength in this limit to return to the strength of bare Rexolite, previously measured as 17.4 MV/m in our test stand.
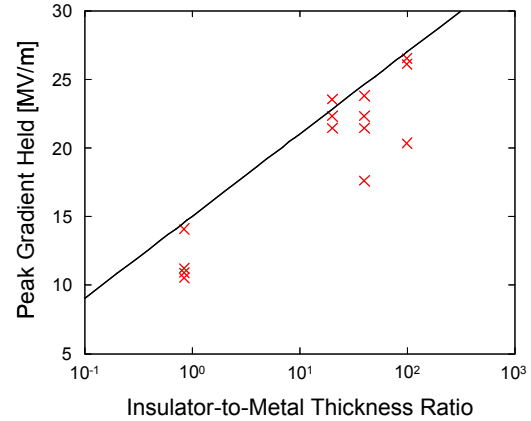

Figure 4: Observed performance of ~ 11 mm tall HGIs as a function of I/M, from Tables 2 and 3.

CONCLUSION

In this paper, we discussed results from our recent testing of HGIs. We found that proper high-voltage conditioning of the insulators could delay the onset of flashovers during testing, but did not seem to affect their ultimate strength. The observed conditioning consisted of both a permanent and temporary part. The voltage-holding capability of HGI configurations tested increased as I/M was made larger. However, we expect that this result will not hold for very large values of I/M, and that it also depends on the HGI period and length.

ACKNOWLEDGEMENTS

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