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FIRST WALL INSULATOR MATERIALS

AUTHOR(S): James M. Bunch and Frank W. Clinard, Jr.

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DIELECTRIC BREAKDOWN OF POTENTIAL RTPR FIRST WALL INSULATOR MATERIALS*

by

James M. Bunch and Frank W. Clinard, Jr.

University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544

Abstract

Dielectric strength of Al_2O_3 and a number of other refractory insulators was evaluated using both dc and pulsed voltages, at temperatures up to 1073 K. Results were compared with those for alkali halides. The dielectric breakdown behavior of the low porosity insulators was qualitatively similar to that of alkali halides, indicating that the breakdown mechanisms are also similar. Pulsed voltage breakdown strength was found to be considerably greater than dc strength for low porosity materials, an observation of considerable engineering importance for the RTPR design. It appears that porosity has a deleterious effect on dielectric strength, both by reducing dc values and by suppressing the enhancement predicted to accompany pulsed voltage application at high temperature.

Introduction

The pulsed theta pinch fusion reactor requires an electrically insulating coating on the first wall to prevent breakdown through the plasma by the large pulsed emf's associated with the fast-rising implosion magnetic field. (Insulation is also required elsewhere in the reactor, but the first wall appears to be the most difficult requirement.) In the ANL/LASL Reference Theta-Pinch Reactor design,¹ with a first wall insulator thickness as determined by heat transfer requirements, the required dielectric strength radially is about 10 kV/mm. This is within the range of published values for commercial ceramics and glasses under dc voltages at room temperature, but it is not clear how relevant these values are under pulsed voltages, at the proposed reactor operating temperature (~ 1100 K), and in the expected reactor environment. Thus dielectric breakdown is being investigated as part of the LASL first-wall materials program.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

The first part of the breakdown study has been aimed at learning how to measure the breakdown strength of small samples of well characterized materials at high temperature with pulsed voltages, but under conditions otherwise not typical of the expected reactor environment. One of our goals is to categorize the breakdown mechanism where possible by fitting the data to existing theoretical models. Then when the measurement techniques are developed and well understood, we will investigate breakdown under conditions which simulate more closely the expected reactor environment, including especially the radiation field. Also, we will test larger samples resembling prototype reactor first wall sections.

Previous Work

Most previous investigations² of high temperature pulsed voltage dielectric breakdown in inorganic insulators have been confined to studies of alkali halides and a few glasses; the following discussion is based mostly on the conclusions from these studies, since some of them will presumably apply to our materials also.

Several regimes of breakdown may be delineated, theoretically and experimentally. It is useful to distinguish these in terms of the time interval required for breakdown to occur after the field is applied. If breakdown occurs after a time lag long compared to some characteristic interval (typically 10^{-6} sec) it is usually assumed to have occurred as a result of a thermal instability mechanism arising from Joule heat produced in the bulk of the sample by the applied field. This "thermal" breakdown can be further categorized, depending on whether the time-to-breakdown is sufficiently short that thermal diffusion in the sample can be neglected. If so, the breakdown is called "impulse thermal". Simple theories have been developed² for impulse thermal breakdown, relating time-to-breakdown to sample resistivity, temperature, and applied field strength. At a given temperature, the time is expected to decrease with increasing field strength, and this is observed experimentally; however, as will be discussed later, other effects sometimes have to be invoked to obtain detailed agreement between theory and experiment.

For long times, one expects the field to approach asymptotically a value, which can be called the dc thermal breakdown field, below which breakdown will never occur. Theoretically, this field should decrease with increasing temperature, and this is in fact generally observed experimentally. The dc breakdown strength is dependent on sample geometry, and on electrode material and configuration, since these influence conduction of heat away from the sample.

For larger fields, the time-to-breakdown decreases until a time interval characteristic of the interaction of free electrons with the lattice is approached. Then breakdown presumably occurs by an instability mechanism which involves creating large numbers of free electrons with energies high compared with lattice thermal energies. Theories² of electronic, or "intrinsic" breakdown have met with modest success in describing some of the general features of the experiments with alkali halides. In particular, electronic breakdown strength should not be expected theoretically to vary strongly with temperature above room temperature.

Note that, theoretically, "breakdown" is defined as the onset of instability; it is not necessarily synonymous with physical destruction of the sample, and in fact at the higher temperatures we have observed that it is possible for a sample to survive repeated "breakdown" if the power supply current is limited.

Present Results

Figure 1 shows some of our breakdown data for dense, high purity polycrystalline Al_2O_3 . The samples, which consisted of flat plates 25 mm square, were placed on a nickel pedestal which served as the negative electrode. Contact on the upper side was made through a spherical nickel electrode held against the sample by gravity. In some cases, contact was to bare samples, otherwise to evaporated chromium or chromium-gold contact spots a few thousand Å thick. Samples and contacts were placed in a tube furnace which was within a tank filled with N_2 at 2.4×10^6 Pa (350 psi); the N_2 is used as insulating medium, intended to suppress corona and surface flashover.

The dc breakdown measurements were made by applying a slowly increasing dc voltage to the sample through a 1 megohm series resistor and a meter for measuring sample current. Breakdown was defined to occur at the voltage where the slope of the I-V curve increased sharply, and/or where the current became unstable with time. The pulse measurements were made by charging a 0.25 μF capacitor to the desired test voltage, then connecting it to the sample through a triggered switch tube in series with a 5000 ohm current limiting resistor. Rise time was about 10^{-6} sec, and decay time about 1 sec. Breakdown after some time interval was observed as a sharp drop in voltage, on an oscilloscope connected to a voltage divider across the sample.

For the Al_2O_3 samples, the time to breakdown varied so rapidly with applied voltage (faster than expected on the basis of simple impulse-thermal theory) that a breakdown field could be defined nearly independent of delay time. In Fig. 1 the pulse breakdown strength so defined is nearly independent of temperature, and is considerably larger than the dc value at the higher temperatures. This behavior is generally in agreement with theory, and with experiments on alkali halides. In spite of the presence of high pressure N_2 , pulse breakdown often was accompanied by surface flashover, as evidenced by a track on the sample after testing. We feel for two reasons that the flashover is initiated by incipient breakdown in the sample: first, its occurrence depends on the field in the sample, unlike surface-initiated flashover; second, flashover does not always occur, and when it does not, breakdown is clearly through the sample, at essentially the same field that causes flashover in similar samples.

Some effort has been devoted to determining the extent to which the measured dielectric strength has been reduced from the "intrinsic" value because of the non-uniform field obtained with the spherical contact on bare samples. Evaporated chromium or chromium-gold contacts with diffuse edges were applied, in an effort to obtain a more uniform field in the sample. The results (for pulse measurements) are indicated by the shaded area in Fig. 1; increases in breakdown strength of as much as 100% were obtained.

Figure 2 shows examples of the variation of time-to-breakdown with applied voltage for a commercial porcelain enamel examined at 873K, and for the same Al_2O_3 as discussed above at 973K, both with contacts to bare samples. The relation between time-to-breakdown and applied field for the enamel is in qualitative agreement with that observed by Watson and Heyes³ for NaCl. They found that the details including times much shorter than predicted theoretically could be explained only by assuming that the thermal breakdown mechanism is modified by the presence of a time dependent polarization space charge in the sample. We have not yet measured the other sample parameters needed to attempt fitting our data quantitatively to this model. In the theory of Watson and Heyes, the asymptotic value of breakdown strength for long times is a function of the test pulse time decay constant; only for infinitely long pulses in this value synonymous with the dc breakdown strength defined earlier. Presumably, the lack of long breakdown times for our Al_2O_3 samples can be explained in this context; if the power supply produced longer pulses, the data should fall on a curve of the same shape as for the enamel sample.

We have also tested a number of samples of other materials known to contain some porosity (Table I). Although the data are too sparse to permit detailed conclusions, the following seems evident; for porous materials, there is usually little or no enhancement of breakdown strength with pulsed voltages, perhaps because breakdown is initiated in the gas in the pores on a time scale short compared to bulk thermal breakdown; and the breakdown strength for a porous material is lower than that for the same material near theoretical density. This behavior is consistent with the theoretical predictions and experimental observations of Gerson and Marshall.⁴

Conclusions

We find the dielectric breakdown behavior of the low porosity refractory electrical insulators tested to be qualitatively similar to that of alkali halides. The latter are reasonably well described by a body of theory, and although we do not yet have enough data to permit a quantitative comparison, it appears that this theory is applicable to refractory insulators.

We have shown that pulsed voltage breakdown strength is considerably greater than that for dc voltage for low porosity materials, an observation of considerable engineering importance for the reactor design.

It appears that porosity has a deleterious effect on dielectric strength, both by reducing dc values and by suppressing the enhancement predicted to accompany pulsed voltage application at high temperature.

Acknowledgments

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References

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TABLE I

Dielectric Strength of Insulator/Metal and Insulator Samples

Insulator*	Temperature, K	Dielectric Strength, kV/mm**		Density, % of Theoretical
		DC	Pulsed	
Plasma-Sprayed Insulator on Metal Substrate***				
Al ₂ O ₃	300	28	30	85
	873	11	9	
Al ₂ O ₃ (different gun)	300	--	32	82
	873	--	20	
Y ₂ O ₃	300	25	32	--
	873	~ 7	21	
Insulator				
AlN (hot-pressed)	300	5	5	77
	873	12	13	
Si ₃ N ₄ (hot-pressed)	300	20	25	54
	873	12	16	
Si ₂ ON ₄ (hot-pressed)	873	~ 2	10	96
Y ₂ O ₃ -10% ThO ₂ (hot-pressed)	300	22	25	92
	873	13	15	
Y ₂ O ₃ (slip-cast and sintered)	300	24	29	94
	873	~ 5	10	

* Insulator thickness 0.3-0.5 mm.

** Spherical upper electrode.

*** Metal substrates were austenitic stainless steel, Inconel, or Nb-1% Zr, ~ 1 mm thick; no effect of substrate composition on dielectric strength was observed.

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Fig. 1

DC and Pulsed Dielectric
Strength of Al_2O_3

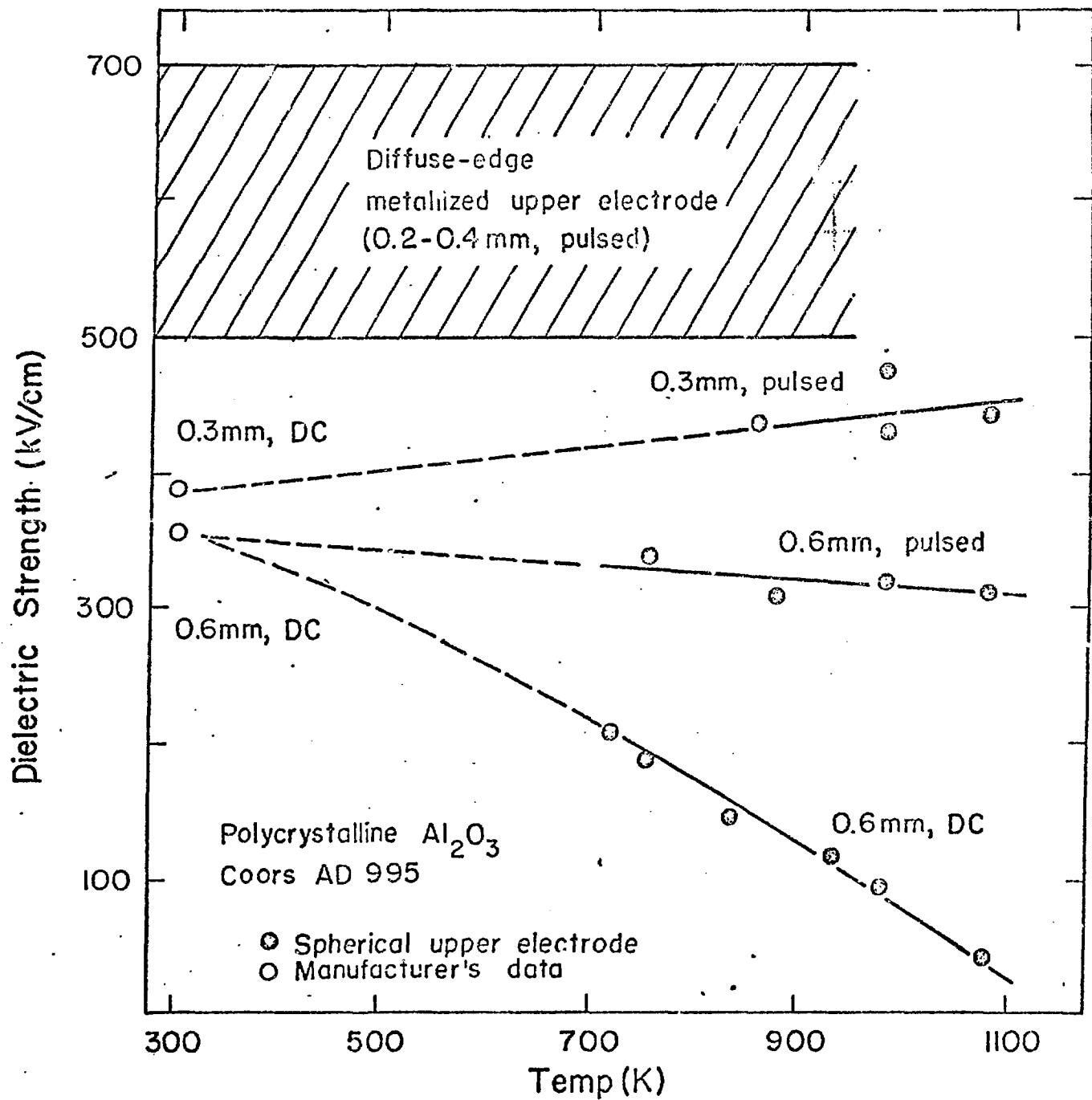
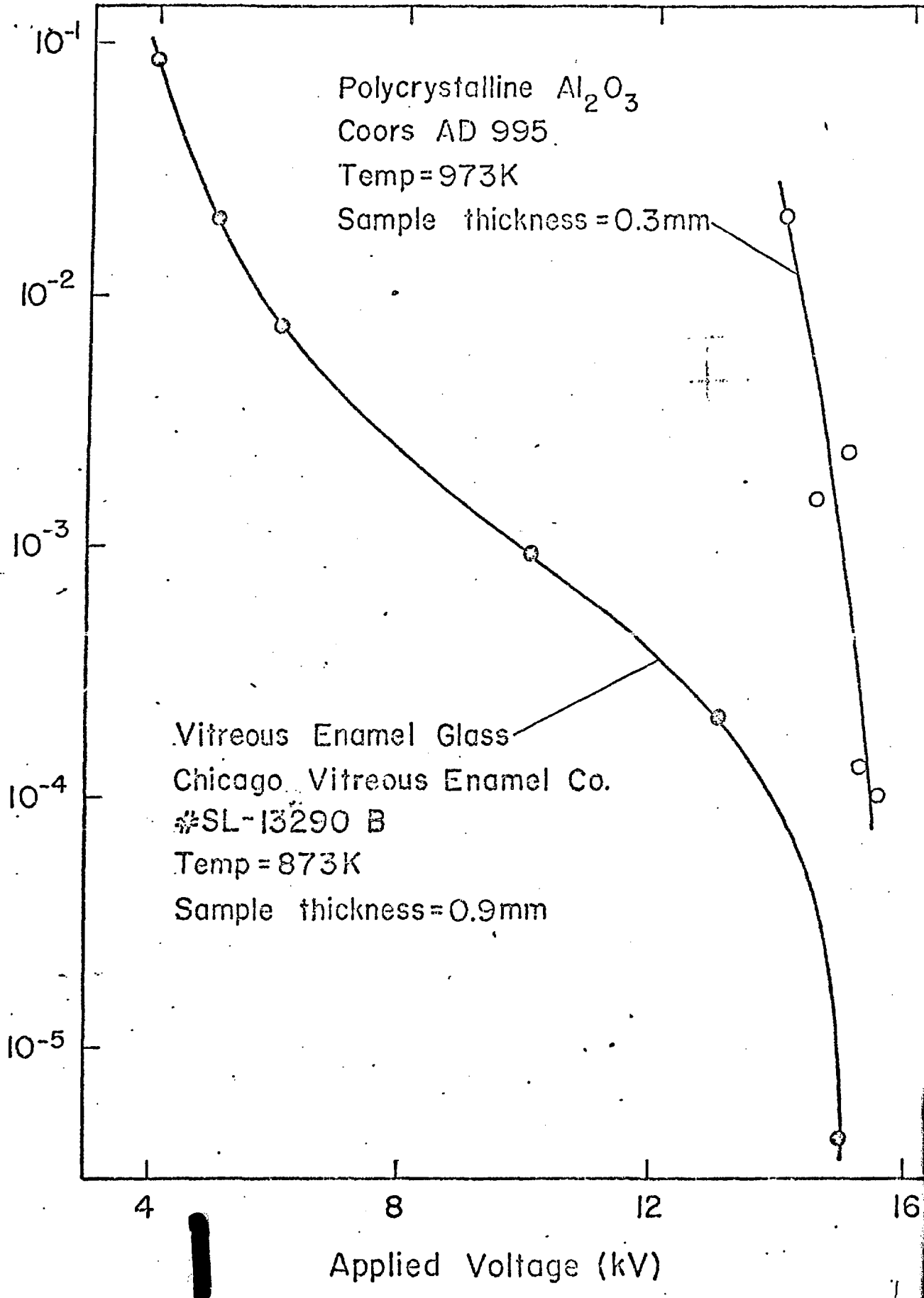


Fig. 2

Time to Breakdown as a Function
of Applied Voltage for Al_2O_3 and
a Vitreous Enamel Glass

Time to Breakdown (s)



Applied Voltage (kV)

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Polycrystalline Al_2O_3
Coors AD 995
Temp = 973K
Sample thickness = 0.3mm

Vitreous Enamel Glass
Chicago Vitreous Enamel Co.
#SL-13290 B
Temp = 873K
Sample thickness = 0.9mm

4

8

12

16

Applied Voltage (kV)

2

148 AEC 01121A

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