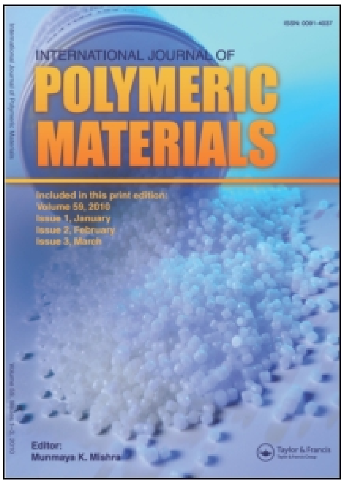

International Journal of Polymeric Materials
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713647664

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Ahmed A. Hossam-eldin[a]
[a] Electrical Engineering Department, Faculty of Engineering, University of Alexandria, Alexandria, Egypt

To cite this Article Hossam-eldin, Ahmed A.(1984) 'Electric Strength of Polymers Under Vacuum at Cryogenic Temperatures', International Journal of Polymeric Materials, 10: 4, 293 — 302

To link to this Article: DOI: 10.1080/00914038408078647

URL: http://dx.doi.org/10.1080/00914038408078647

Intern. J. Polymeric Mater., 1984, Vol. 10, pp. 293–302
0091-4037/84/1004-0293 $18.50/0

Printed in the United Kingdom

Electric Strength of Polymers Under Vacuum at Cryogenic Temperatures

AHMED A. HOSSAM-ELDIN

Electrical Engineering Department, Faculty of Engineering, University of Alexandria, Alexandria, Egypt

(Received December 1, 1983)

The electric strength of solid polymers under high vacuum is investigated at a temperature ranging from 293°K down to that of liquid helium (5°K) under power frequency alternating- and direct-voltages. The electric strength of polymers was found to be very dependent on the pre-breakdown partial discharges when measured in cryogenic medium whether gas or liquid. When helium was used as coolant, discharges may extend very far from the electrodes and thus exerted high electric stresses on large areas of the sample under test. These discharges may produce flash-over and serious troubles. It may also lead to localised breakdown of polymers which may give apparent reduction in dielectric strength.

A large increase in the electric strength of polymers was observed when used at cryogenic temperatures under vacuum; the increase was very significant for polyethylene and polyimide specially under direct voltages.

The results showed promising properties and it is concluded that the high vacuum will offer the solution to many insulation problems at liquid helium temperatures in cryogenic and superconducting equipment.

INTRODUCTION

In recent years there is a growing interest in the use of cryo-equipment and superconducting machines.[1,2] High vacuum is an essential feature of any cryogenic machine and the added advantage of the thermal insulation afforded by an evacuated space makes the use of a vacuum environment for high voltage insulation an attractive economic proposition. This would make it very important to know the behaviour of polymers under vacuum at cryogenic temperatures.

It was reported that the electric strength and dielectric losses of non-polar materials will be approximately constant below a certain temperature, but that of polar materials will increase with reduced temperature.[3,4]

The purpose of the present studies was to measure the electric strength of polymers in different immersion medium in order to choose the proper coolant with the main goal of increasing the service stresses in actual insulation. To explain the relatively low properties in helium as medium detailed investigations, as liquid and gas, were carried out.

EXPERIMENTAL METHODS

Tests were performed on samples made of layers of the polymer which were supplied in sheet form of 50 microns thickness. The materials tested were chosen to have special interest in research as polar and non-polar materials and also those found on application in industry like:

i) High density polyethylene (PE) as non-polar material,
ii) Polytetrafluoroethylene (PTFE-Teflon) as non-polar,
iii) Tetrafluoroethylene-hexafluoropropylene copolymer (FEP-Teflon), which is slightly polar, and
iv) Polyimide (Kapton) as polar material.

The specimens were mounted between flat plane electrodes made of manganese bronze with mirror-like surfaces. A predetermined pressure was applied to the specimen due to the upper electrode weight to ensure intimate electrode/dielectric contact. At room temperature the test cell was immersed in dry silicon fluid Type MS 200/20CS, Dimethicone 20. In experiments made at cryogenic temperatures the specimens were directly plunged into the cooling medium. For vacuum, a cylindrical vessel was evacuated down to 10^{-7} torr and immersed in a cryostat containing the liquid helium which, by conduction, ensure cooling the specimen and electrodes to the required temperature. The temperature of the specimen was measured by two thermocouples, provided with leads and Northrup 8686 mV potentiometer, placed at two different sites fixed in ducts on the low voltage electrode. Necessary precautions were taken to eliminate any external discharge interference and the test cell showed to be discharge-free up to the maximum possible applied voltage.[5]

During testing the voltage was increased in steps of 1 kV per minute until breakdown occurs. To avoid scattering in results each test was carried out ten times and the mean value was recorded. Partial discharge activity was measured adopting the earlier used technique.[6]

The electric strength of the different immersion mediums, namely liquid nitrogen (77°K), liquid helium (5°K) and vacuum at 293°K was measured. The electric strength of cryogenic gases at different temperatures against gap spacing was also studied. Due to the lack of sophisticated equipment it was difficult to measure the electric strength of vacuum at cryogenic temperatures.

RESULTS AND DISCUSSIONS

Electric strength of ambient mediums

Figure 1 shows the variation of electric strength of liquid nitrogen, liquid helium under atmospheric pressures and vacuum at room temperature. The results indicate a high electric strength of vacuum as the gap length increases. Although it was difficult to measure its electric strength at cryotemperatures, it is believed that the value is very high. The largest discharge magnitude measured at cryotemperatures was insignificant.

Measurement of resistivity of these different mediums was difficult to be performed at this stage of studies and to the best of my knowledge no solid data has been published. But the tentative measurements reported indicate that it may be very high and greater than 10^{18} Ωm. Liquid helium has higher resistivity than that of most liquids but lower breakdown strength.[7] This may be attributed to the relatively large discharge magnitudes recorded in it.

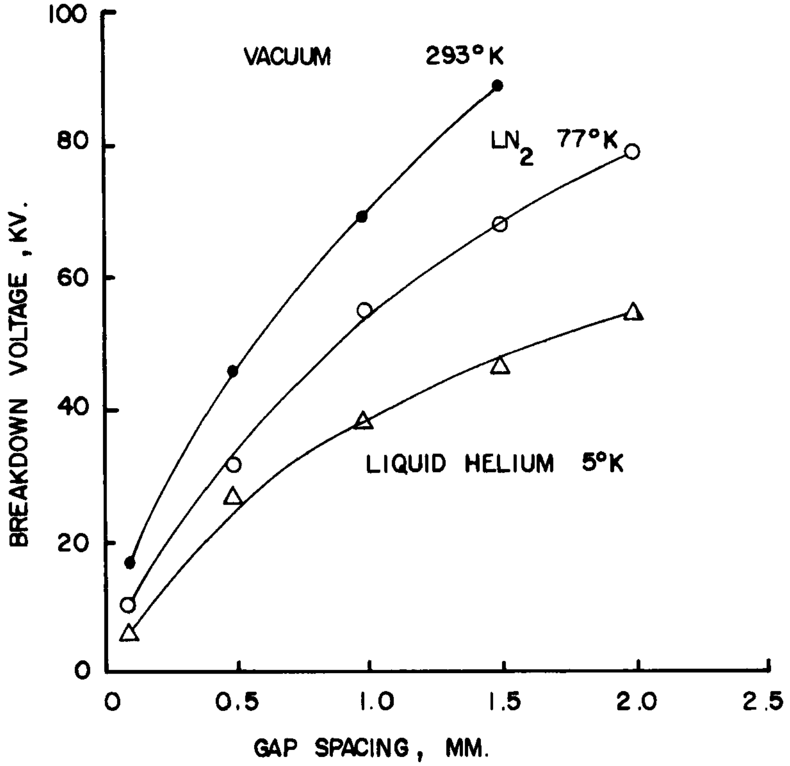

FIGURE 1 Breakdown strength of different immersion mediums with gap spacing.

Electric strength of cryogenic gases

Variation of the breakdown voltage of gaseous helium at different temperatures against gap length is given in Figure 2. The results showed slight scattering and when purifying helium it did not lead to less scattered values. This may be due to ionisation within cavitation bubbles originating in violent movements of the liquid around the highly stressed areas. These results show that this gas obeys Paschen's law and agrees with Swift results.[8]

Electric strength of polymers in different environments

a) *Silicon fluid and liquid nitrogen.* Table I gives the results obtained at 293°K with silicon fluid compared with that having liquid

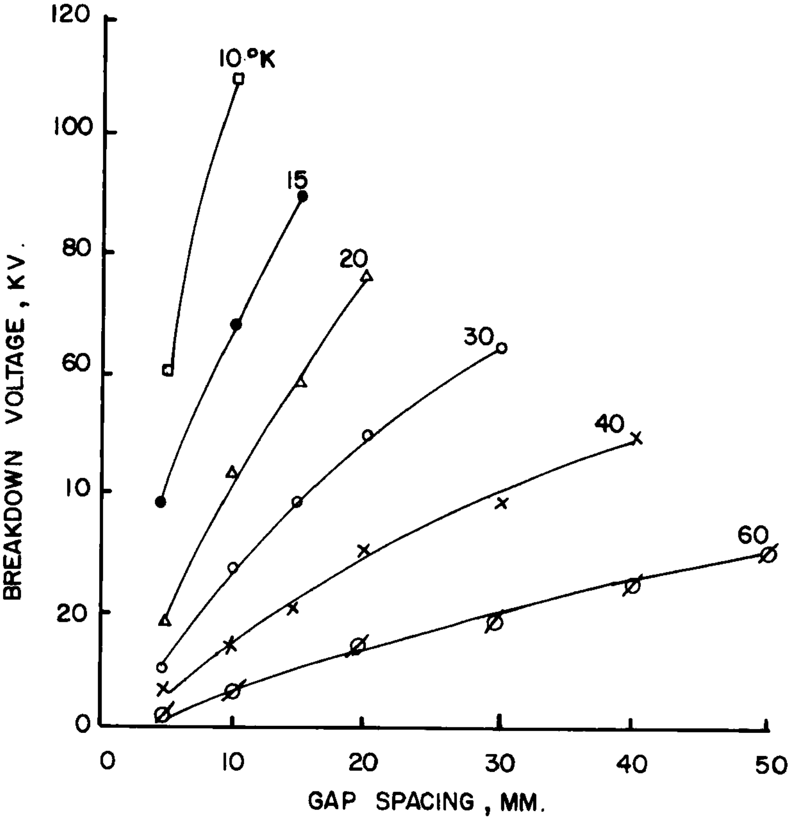

FIGURE 2 Variation of ac breakdown of gaseous helium with gap spacing.

TABLE I

Mean a.c. electric strength of polymers under silicon fluid and liquid nitrogen

Immersion medium / Materials tested	Mean a.c. electric strength MV/m (r.m.s.)		
	Silicon fluid (293°K), E_1	Liquid nitrogen (77°K), E_2	E_2/E_1
PE	181	401	2.21
PTFE	202	294	1.46
FEP	131	209	1.59
Polyimide	209	371	1.77

TABLE II

Mean d.c. electric strength of polymers under silicon fluid and liquid nitrogen

Immersion medium / Materials tested	Mean d.c. electric strength MV/m: Silicon fluid (293°K), E_3	Mean d.c. electric strength MV/m: Liquid nitrogen (77°K), E_4	E_4/E_3
PE	230	580	2.52
PTFE	273	430	1.58
FEP	187	310	1.66
Polyimide	292	540	1.85

nitrogen as immersion mediums under a-c voltages. The high electric strength with liquid nitrogen may be due to the small discharges detected at cryotemperatures.

The largest discharge magnitude, which contributes to the breakdown of samples, in silicon fluid was around 50 pC. The corresponding value with liquid nitrogen was less than 10 pC and the repetition rate was greatly reduced.

Measurements under d.c. voltages may be seen in Table II under the same test conditions. The higher values observed under d-c conditions may be attributed to the drastically reduced discharge activities and low dielectric losses[6] at low temperature. Since breakdowns generally occurred at places in contact with ambient medium it is believed that they are due to partial discharges and not only directly due to the applied field. This would indicate how partial discharges are so serious to solid polymers immersed in liquid dielectrics of high resistivities.

TABLE III

Mean a.c. electric strength of polymers under liquid helium and vacuum

Immersion medium / Material tested	Mean a.c. electric strength MV/m (r.m.s.): Liquid helium (5°K), E_5	Mean a.c. electric strength MV/m (r.m.s.): Vacuum (5°K), E_6	E_6/E_5
PE	233	440	4.9
PTFE	189	350	1.85
FEP	230	468	1.67
Polyimide	300	630	2.1

b) *High vacuum and liquid helium.* The measured results obtained with specimens under vacuum at 5°K and that in liquid helium are given in Table III, under power-frequency a-c voltages.

The breakdown under liquid helium is lower than that under vacuum at 5°K. With liquid helium partial discharges of relatively high magnitudes (70 pC) were observed, while the corresponding values with vacuum were very insignificant (Figure 3). The high electric strength in vacuum environment may be due to the very negligible discharge activity and the very low loss factor.

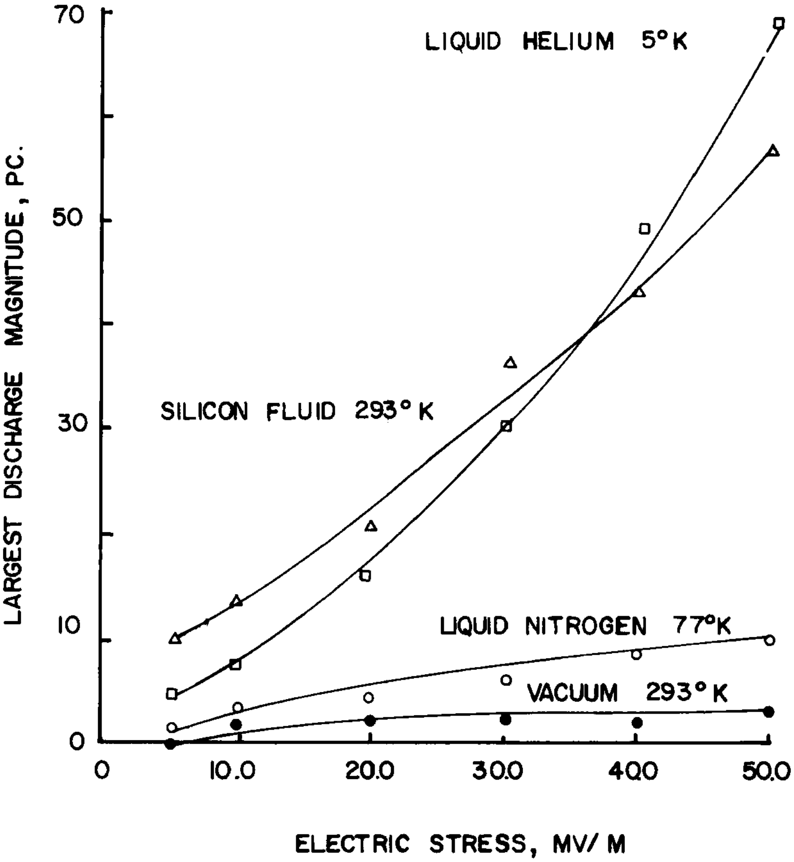

FIGURE 3 Variation of largest discharge against electric stress.

TABLE IV

Mean d.c. electric strength of polymers under liquid helium and vacuum

Medium	Mean d.c. electric strength MV/m		
Material	Liquid helium (5°K), E_7	Vacuum (5°K), E_8	E_8/E_7
PE	294	535	1.82
PTFE	255	510	2.00
FEP	400	720	1.80
Polyimide	420	882	2.10

The measurements under d-c voltages are as shown in Table IV may support the above conclusions which indicate great improvements for vacuum. Very negligible discharge activity was detected under vacuum.

The above results may be due to the prebreakdown discharges existing in liquid helium which may extend very far from the

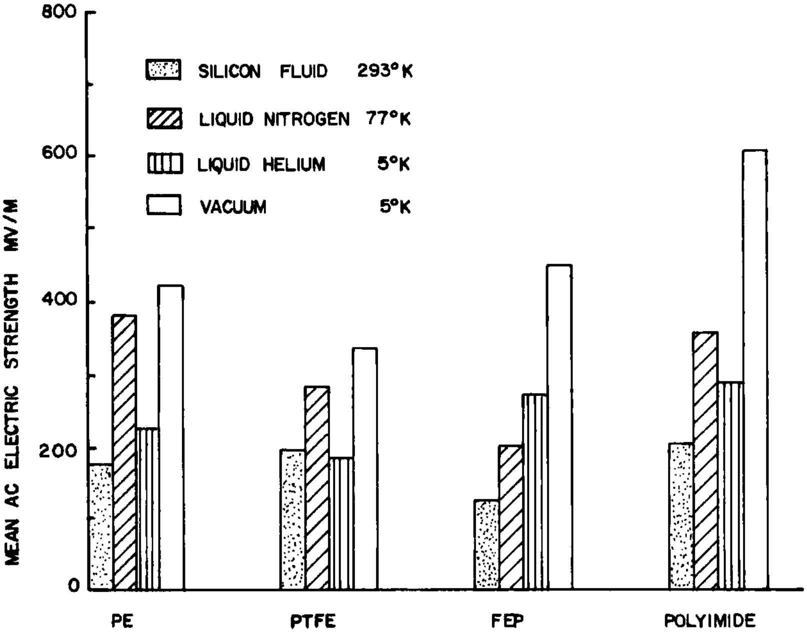

FIGURE 4 Compared ac electric strength of polymers in different immersion mediums.

electrodes and exert high stresses on large areas of the tested specimen and thus lead to very rapid degradation of solid dielectric especially polymers which have a low erosion resistance.[9] In addition these discharges may be creating localised high fields which might be applied to the specimen and therefore allow breakdown to occur at relatively lower voltages.

The compared results are shown in Figures 4 and 5. These results are in good agreement with values reported as intrinsic electric strength.[10]

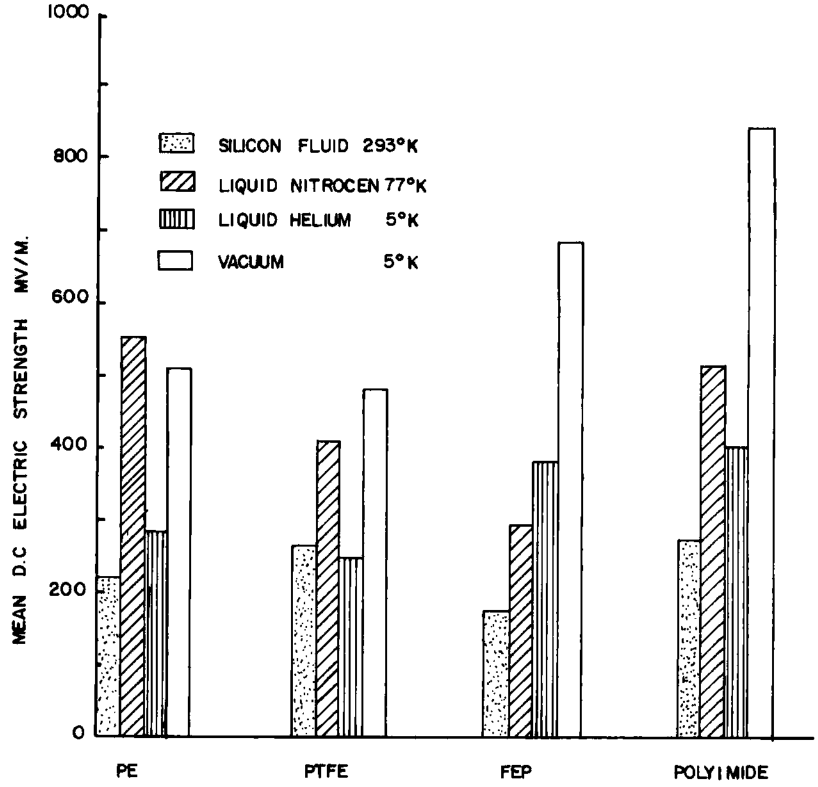

FIGURE 5 Compared dc electric strength of polymers in different immersion mediums.

CONCLUSIONS

For economical utilization of solid polymers in high voltage cryogenic equipment many important data concerning the behaviour of these materials in different environments at cryotemperatures is needed.

A large increase in the electric strength of polymers at cryotemperatures was obtained when used under high vacuum. It was concluded that high vacuum, added to the high thermal insulation, is a good immersion medium for solid polymers, it eliminates many insulation problems that may occur at low temperatures if other mediums were used.

The pre-breakdown partial discharges play very important roles in the mechanism of degradation of solid dielectrics when immersed in high resistivity liquids. Liquid nitrogen results ensure that it is much more economical to use cryoresistive machines rather than superconducting ones.

Acknowledgements

The author would like to acknowledge Plessey Co. Ltd. and I.C.I. of G. Britain for supplying the materials tested. He wishes to thank Mr. K. N. Mathes of G.E., U.S.A. for encouragement and valuable suggestions. Mr. D. W. Heron for helping on experimental work.

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