

DIELECTRIC STRENGTH OF LIQUID HELIUM
IN MILLIMETER GAPS*

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I. INTRODUCTION

In a previous paper¹ a program underway at Oak Ridge National Laboratory to investigate the high voltage electrical properties of fluids and solids for cryogenic systems was described. As the first result of these investigations we report here on measurements of the breakdown strength of liquid helium boiling at atmospheric pressure, under voltages up to ± 130 kV dc and in gaps of up to 2.5 mm. Preliminary results with ac voltage have also been obtained.

Previous breakdown measurements with dc or ac voltage in liquid helium have yielded widely differing results. For helium boiling at 4.2 K, dielectric strengths ranging from 160 kV/cm to 400 kV/cm have been observed in gaps of between one and twelve mm.²⁻⁶ For non-boiling helium, values from 360 kV/cm⁷ to 530 kV/cm⁸ have been obtained at gaps close to 1 mm. As with other types of insulation, the dielectric strength has been found to increase as the electrode gap is decreased. Breakdown fields greater than 1 MV/cm have been observed in 100- μ gaps.⁹

A few general trends can be extracted from examination of the above data. Usually the higher breakdown voltages at a given gap have been observed with smaller electrodes (e.g., 10-mm diameter spheres), indicating that electrode area is of importance. However, if the electrode radius

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of curvature approaches the gap, the breakdown voltages decrease due to the resulting field inhomogeneities. Experiments with strongly inhomogeneous fields such as those of point-plane electrodes have in addition indicated strong polarity effects.^{3,7,10} Lower breakdown voltages are observed when the point is negative, probably because of enhanced field emission at the cathode. Boiling decreases the observed dielectric strengths, presumably as a result of discharges initiated in vapor bubbles. Contamination by dielectric particles or frozen gases has not been found to play a significant role, although a drastic decrease in breakdown strength has been noted when the liquid is contaminated with frozen oil vapor.⁸ No dependence on electrode material has been found, although heavy pitting or oxidation of the electrode surface has been shown to degrade the measured dielectric strengths.^{6,8}

II. Apparatus and Experimental Procedure

The cryostat used for the experiments employs a special bushing with vacuum electrical insulation, and has been described elsewhere.¹ Figure 1 is a more detailed view of the lower end of the bushing. A perforated copper shield S promotes temperature equilibrium. A liquid helium level detector L, and a carbon resistor thermometer R_T are shown.

In all of our measurements to date we have used stainless steel sphere-plane electrodes as shown in Fig. 1. The spherical electrode has a diameter of 38 mm. The electrodes are polished with 1200 grit white aluminum oxide lapping compound. They are carefully cleaned with trichloroethylene followed by alcohol before installation in the dewar.

Before each test period the cryostat is flushed several times with purified gaseous helium and the apparatus is cooled to liquid nitrogen temperature. Liquid helium is then transferred while maintaining a slight

over-pressure in the dewar to prevent atmospheric contamination. No effort is made to purify the helium as it is received from the supplier. Usually helium is transferred until the level is at least 300 mm above the insulating disc C. The heat leak is about 350 milliwatts and the level drops to C by the end of a day's run (6-8 hours). As long as the liquid level remains at least 50 mm above C, very little boiling occurs between the electrodes.

High voltages are provided by 130 kV, 50 ma dc and 80 kV, 70 ma ac power supplies. Both supplies are provided with motor drives for various constant ramp rates and automatic arc detection circuits which shut off the voltage at breakdown. A 1 M Ω resistor in series with each high voltage supply limits the breakdown arc current, to minimize pitting of the electrodes.

After filling the dewar with liquid helium and before making breakdown measurements, it is necessary to condition the vacuum bushing electrically with a gap setting of about 6 mm. This is accomplished by running the voltage up in small steps, waiting at each step until glow activity inside the bushing dies away. Usually 70 kV can be applied immediately after transferring helium, once the initial conditioning run has been completed.

We have found that it is necessary to wait about 20 seconds after each breakdown before switching on the power supply for ramping the voltage up for the following breakdown. This holding period permits any disturbance in the helium or debris from the previous breakdown to clear away.

III. Results

For the purposes of organization, the data are grouped into experimental runs during which the cryostat was continuously at helium temperature. During each run, measurements were taken at several gaps to ensure that consistent results could be obtained under relatively constant conditions

of heat leak, electrode pitting, and helium purity. Usually thirty breakdown voltages were taken at each gap setting, although at certain gaps, 120 to 200 breakdowns were recorded for more extensive statistical analysis. The average breakdown voltages measured at the same gap setting in different runs nearly always agreed to well within experimental scatter. For the data with positive polarity, four different dc voltage ramp rates were used, ranging from less than 0.1 kV/sec to 10 kV/sec. Since no significant deviations were found with variation of the ramp rate, all subsequent data were taken at 2.0 kV/sec.

In Fig. 2 the upper set of points gives the average breakdown fields for both positive and negative high voltage electrode polarity as a function of electrode separation in mm (see Figure Captions for symbols). Each point represents an average of at least 60 values from 2 or more runs. The circled points are averages containing runs with 100 or more values. The percentage standard deviation σ/\bar{E}_b was found to be independent of the gap, and averaged $21 \pm 1\%$ for the positive and $19 \pm 1\%$ for the negative data. The lower set of points gives the minimum breakdown fields observed for the same data sets. These are important in the design of electrical utility equipment, which must operate reliably for long periods without faults. The minimum values for the large and small data sets are very consistent, even though the large data sets probe the distribution at the 0.5% to 1% level, while the small sets only probe the 3% level. One explanation for this surprising result might be that the distribution function of observed values goes to zero at some non-zero minimum voltage. Although theoretically very few statistical distributions have this property, it seems physically reasonable to suppose that a threshold voltage might exist at each gap below which all possible breakdown processes are energetically unfavorable.

The average breakdown fields, and to a lesser extent, the minimum fields, increase considerably as the gap falls below 1 mm. Above 1.5 mm, the average and minimum fields appear to saturate at about 400 kV/cm and 200 kV/cm, respectively. The average data can be fitted closely with the function

$$\bar{E}_{br} = A + Bd^{-1/2},$$

originally proposed by Ritz¹¹ and Holzer¹² for breakdown in air. When d is in mm, for positive polarity $A^+ = 21.3$ and $B^+ = 29.8$, while for the negative data $A^- = 24.9$ and $B^- = 17.9$. So far, no physical interpretation has been proposed for these constants. However, the fact that no drastic falloff of the breakdown field occurs at larger gaps is encouraging for the design of cryogenic EHV equipment.

The positive points are systematically somewhat higher than the negative ones. Similar behavior has been observed by Meyerhoff.⁶ This phenomenon cannot be explained adequately by field inhomogeneity or variation in electrode pitting. Furthermore, measurements made on the same day at three different gaps with both polarities again showed systematically lower voltages for negative polarity, although the experimental conditions were kept as constant as possible. Further work will be necessary to clarify this point.

Peak breakdown fields for two preliminary data sets with ac voltage are also shown in Fig. 2. These are considerably lower than the dc points. Probably this was due to a low helium level when the ac data were taken, which allowed the region of boiling near the liquid surface to reach the electrode gap. Further measurements with ac under better conditions are planned for the near future.

For purposes of comparison, the measurements of several other workers are plotted in Fig. 2. The data of Meyerhoff and Meats were taken in boiling helium with much larger electrodes (25 cm sphere-plane and 60 mm uniform field electrodes, respectively). Meats has suggested that these values are lower than ours due to the combined effects of boiling and electrode area.¹³ The measurements of Burnier *et al.*⁴ were also taken in boiling helium with 62.5 mm diameter spherical electrodes, and are about 15% higher than those of Meyerhoff and Meats. Gerhold has reported measurements in non-boiling helium at 1 atm.⁸ His results for spherical electrodes of 25 mm radius and gaps up to 0.5 mm are also shown in Fig. 2. Our results appear to be a reasonable extrapolation of those of Gerhold. Evidently the small amount of boiling produced by the residual heat leak into our apparatus does not affect the average breakdown values.

Considerable effort has been devoted to statistical analysis of the large data sets containing 100 to 200 breakdowns at a single gap, in order to determine the form of the distribution function. Well-known graphical techniques were used, in which the experimental values are plotted against a special non-linear cumulative probability scale. This scale is arranged to give a straight line plot if the data fit the distribution function corresponding to the scale. The best fit has been found to occur when the logarithms of the breakdown voltages are distributed according to the Gumbel extreme value function

$$p(x) = -k \left(\frac{\mu_0}{x} \right)^{k-1} \exp \left[\left(- \frac{\mu_0}{x} \right)^k \right],$$

where $x = \log V$, μ_0 is the mode or most likely value, and $1/k$, the Gumbel slope, is a measure of the dispersion. In Fig. 3, the probability plots

for this function at several gap spacings for both positive and negative polarity are given. The linearity of the plots is evident, except for the following peculiarity. Each data set exhibits a main slope up to a cumulative probability of 90-92% which is more or less independent of gap. The lowest 8-10% of the measured voltages have a slightly different slope which appears to decrease slightly for larger gaps. For the positive data at small gaps, a discontinuity appears at the break in slope, corresponding to a region where the distribution function is close to zero. Similar discontinuities were observed by Gerhold¹⁰ when the liquid was contaminated by frozen oil vapor. These characteristics indicate that two separate processes, e.g. bubbles and particles, are or may be responsible for breakdown.¹⁴ It should be pointed out that the distributions are strongly skewed toward lower breakdown voltages. This fact is of great importance in practical high voltage insulation design, since the design voltage required for a given breakdown probability is then lower than the voltage which would be chosen if a Gaussian distribution with the same standard deviation is assumed.

IV. Conclusion

In agreement with several other authors, we feel that our investigations indicate that liquid helium is a well-behaved dielectric, meriting considerable optimism for future practical use in large cryogenic systems. For instance, an encouraging result of our tests is that in the range of our experiments the standard deviation was very consistently 20% of the mean breakdown voltage at each gap. Nevertheless, we do not think that extrapolation of our results with respect to voltage by even one order of magnitude could be done with confidence. Still more uncertain is the extrapolation by many orders of magnitude to relate the electrode surface areas used in our experiments to

the very large conductor surfaces encountered in practical systems such as cryogenic power cables. Further investigations are mandatory to determine the scaling laws applicable for higher voltages and larger electrode areas. Finally, up to the present our measurements have been carried out in liquid helium in nearly homogeneous electric fields, whereas for practical applications more complex electric fields as well as the effects of solid dielectrics must be taken into account. Future investigations will be directed by these considerations.

Acknowledgement

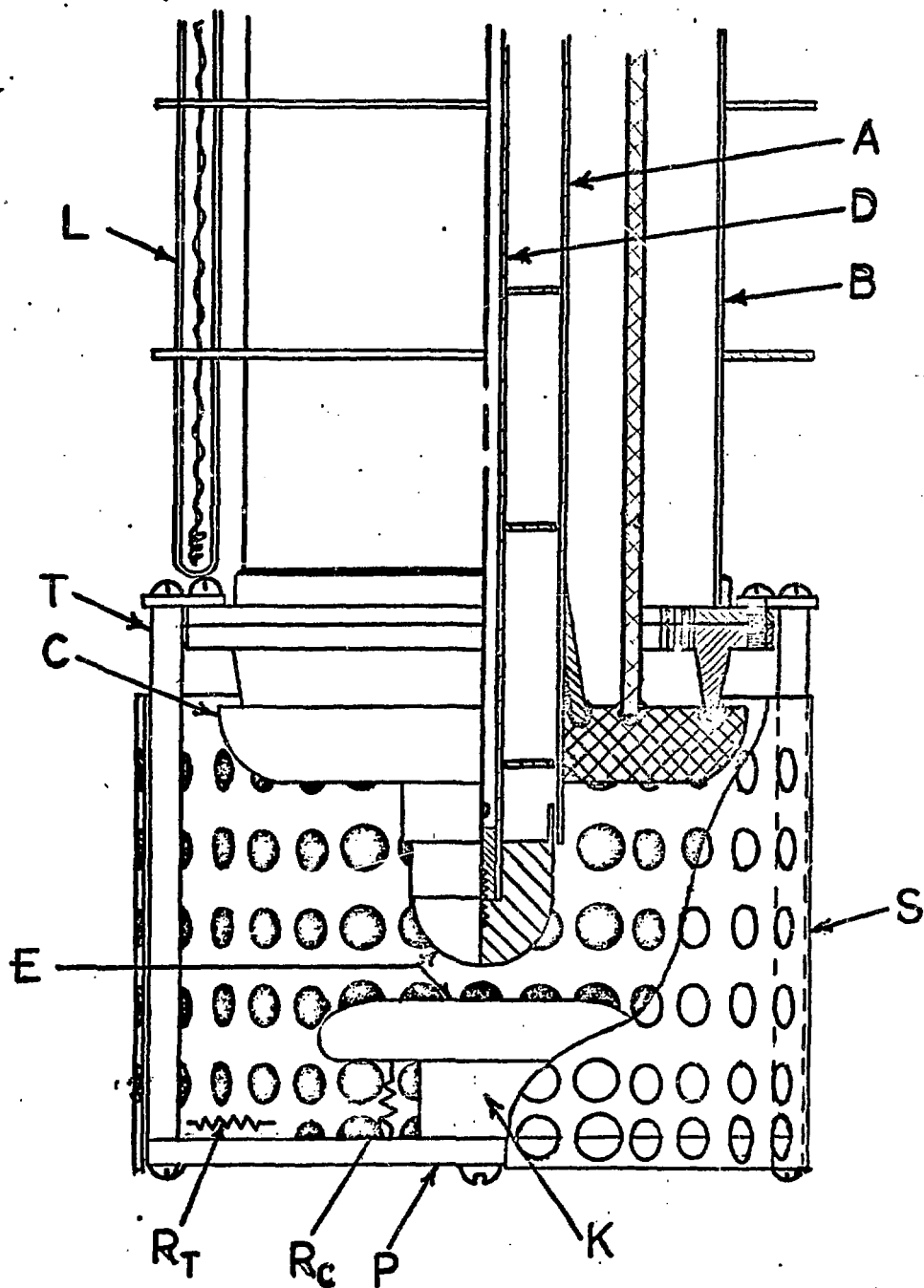
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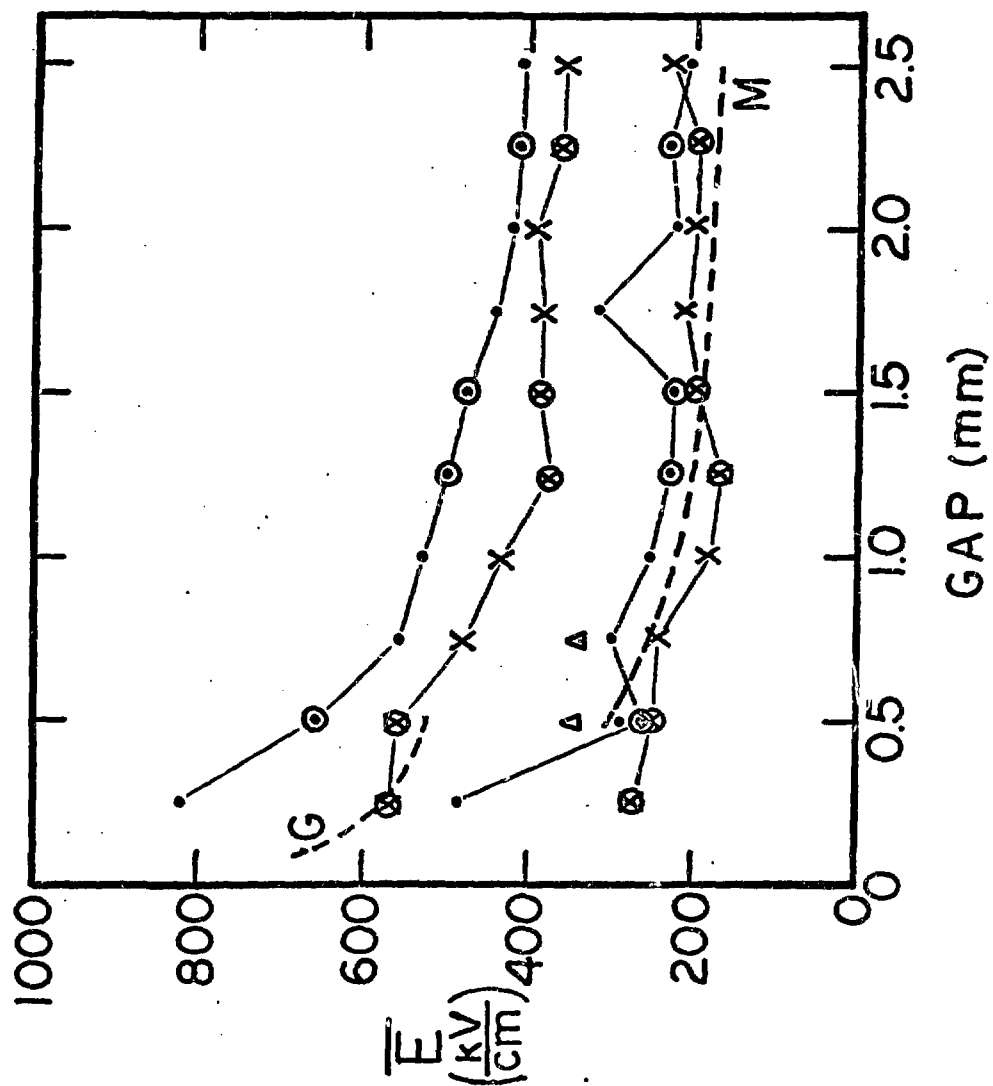
References

1. W. F. Gauster, R. H. Kernohan, H. M. Long, and S. W. Schwenterly, *Proc. 1973 Conference on Electrical Insulation and Dielectric Phenomena*, Quebec, Canada, Paper E-9.
2. K. N. Mathes, *IEEE Transactions EI-2*, 24 (1967).
3. B. Fallou, J. Galand, J. Boho and A. Dubois, *Proc. IIF Conference on Low Temperature and Electric Power*, London, 1969, 201; Low Temperatures and Electric Power (Pergamon Press, Oxford, 1970), 377.
4. P. H. Burnier, J. L. Moreau, and J. P. Lehmann, *Adv. Cryog. Eng.* 15, 76 (1970).
5. R. J. Meats, *Proc. IEE* 119, 760 (1972).
6. R. W. Meyerhoff, *IEEE Conference Record, 1974 Underground Transmission and Distribution Conference*, Dallas, Texas, p. 567.
7. C. Blank and M. H. Edwards, *Phys. Rev.* 119, 50 (1960).
8. J. Gerhold, *Cryogenics* 12, 370 (1972).
9. J. M. Goldschvartz and B. S. Blaisse, *Ref. 3*, p. 367 (1970).
10. J. Gerhold, *Thesis, Technical University Graz*, 1972 (unpublished).
11. H. Ritz, *Arch. Elektrotech.* 26, 219 (1932).
12. W. Holzer, *Arch. Elektrotech.* 26, 865 (1932).
13. R. J. Meats, *Private communication*.
14. W. Weibull, *Jour. Appl. Mech.* 18, 293 (1951).

Figure Captions

- Fig. 1. Lower end of vacuum bushing. E - electrodes; L - helium level detector; R_T - resistance thermometer; S - copper thermal shield.
- Fig. 2. Breakdown electric fields vs gap in slowly boiling liquid helium. Upper and lower dots - mean and minimum values respectively, for positive sphere. Upper and lower crosses - mean and minimum fields for negative sphere. Triangles - ac data. Dotted lines: M - data of Meats (see Ref. 5) and Meyerhoff (see Ref. 6) for boiling liquid helium; G - data of Gerhold (see Ref. 8) for non-boiling liquid helium. All data were taken at $T = 4.2$ K, $P = 1$ atm.
- Fig. 3. Linearized log extreme value cumulative probability plots for several large data sets. Dots - positive sphere; open circles - negative sphere.





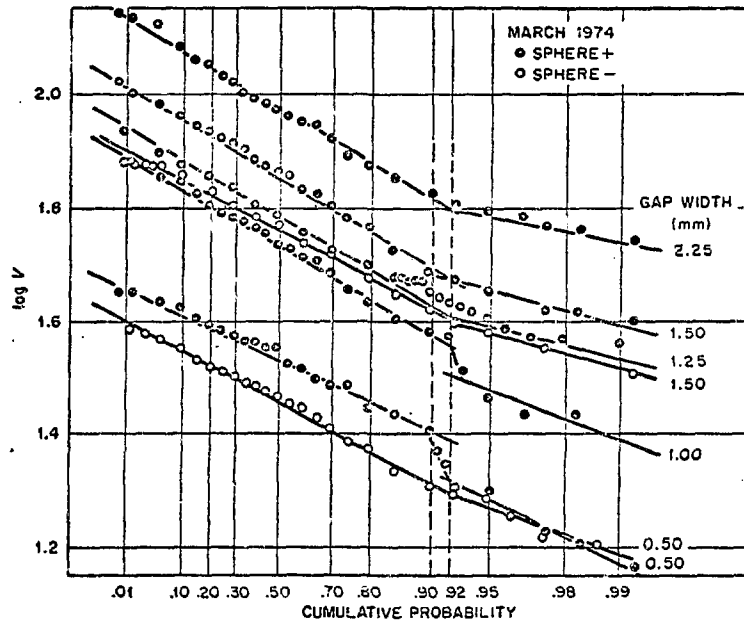


Fig 3.