MASTER MASTER

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PARTIAL DISCHARGE PERFORMANCE OF LAPPED PLASTIC INSULATION FOR SUPERCONDUCTING POWER TRANSMISSION CABLES AND THE DIELECTRIC STRENGTH OF SUPERCRITICAL HELIUM GAS[†]

A. J. Pearmain[††], M. Kosaki[†††] and R. A. Thomas
Brookhaven National Laboratory[*]
Associated Universities, Inc.
Upton, New York 11973

1. Introduction

Brookhaven National Laboratory (BNL) has been working on a project to develop a superconducting power transmission cable since 1972. A flexible ac cable with Nb_3Sn superconductor force-cooled by supercritical helium, was the design selected[1]. Any dielectric used in a superconducting cable must have a very low dissipation factor so that the heat load to the refrigeration system is minimized. Differential contraction during cooling makes it impossible to use extruded dielectric, so a lapped, multilayer plastic tape construction was selected, with supercritical helium gas filling the butt spaces between tapes. Evaluation of many different tapes[2] has shown biaxially oriented laminated polypropylene tape to be a promising dielectric.

A series of tests at BNL[3] on short samples of insulation wound in a cable-type configuration has enabled improvements to be made in screen design and winding techniques. The stress at which discharge inception occurs should be determined by the electric strength of the helium gas in the butt gaps. Several workers have measured the electric strength of cold helium gas between plane metal electrodes over a range of densities[4,5,6], and measurements of the partial discharge inception stress for single artificial butt gaps have also been made[7,8]. In this

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[††] On leave of absence from Department of Electrical and Electronic Engineering, University College, Dublin, Ireland.

[†††] On leave of absence from Department of Electrical Engineering, Nagoya University, Nagoya, Japan.

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paper we describe some partial discharge results from short sample tests. These are not in complete agreement with the results of previous workers, so we have constructed an apparatus with variable electrode spacing to study the effect of electrode material, spacing and area on the breakdown strength of supercritical helium.

2. Short Sample Partial Discharge Tests

The cryostat used for these tests is an improved version of the BNL cryogenic high-voltage test facility that has been described elsewhere[9]. The pressure vessel now has an internal diameter of 102 mm, enabling a stainless steel mandrel of 51 mm diameter to be used as the center conductor for the co-axial geometry samples. The sample construction is shown in Figure 1. Tapes of 22 mm width are wound helically on the mandrel. The sample has stress relief cones at each end, with 508 mm of sample between these cones. Great care is taken to avoid registration of the butt gaps.

The 60 kV test transformer and high-voltage feedthrough system are discharge free up to 20 kV. A Biddle discharge detector is used and the threshold sensitivity is 0.2 pC. The temperature of the sample is measured four-terminally by three carbon resistors taped to the two ends and the center of the sample. The highest of the measured temperatures is used to calculate the gas density because discharges should start at the lowest voltage in the lowest density region. A temperature difference up to 2 K can occur along the sample. A heater controlled by a feedback system maintains the temperature constant at 7 K for densities above 125 Kg/m^3 and at 8 K for lower densities. The pressure is varied in the range 0.16 MPa to 1.84 MPa to obtain helium densities from 15 Kg/m^3 to 150 Kg/m^3. Pressure measurement is by a transducer at the warm end of the pressure line.

The results are reproducible when the same thickness of tape is used to wind the samples. Figure 2 shows a plot of the discharge inception stress against gas density for two samples. One sample consists of five layers of 66 μm polypropylene tape. The tape is a laminate of two layers of oriented polypropylene bonded with polyurethane. Intercalated screen tapes of 51μ m thick Kapton aluminized on one face are placed adjacent to the mandrel (aluminum in contact with the mandrel) and adjacent to the outer electrode (aluminum in contact with the outer electrode). These screen tapes are an attempt to prevent any helium-metal interfaces being present in the electric field. The other sample is similar, but the five layers are of a 100μ m thick three layer oriented polypropylene laminate, bonded with polyurethane. In this case the intercalated screens are 100 μ m thick Valeron, aluminized on one face.

3. Variable - Gap Electrode Tests

The cryostat and 60 Hz electrical system is the same as that used for the short-sample tests. The variable-gap electrode system is shown in Figure 3. The gap between the electrodes is adjustable from 25 μ m to 254 μ m and electrodes of different materials and area can be used. A 50 M Ω series resistor is used to limit the damage to the electrode surface during gas breakdown. The Biddle discharge detector is used to detect breakdown. Each result is the mean of five readings. Two four-terminal resistors at the ground electrode position are used to measure the gas temperature.

Figure 4 shows a plot of the breakdown voltage against gas density times gap length for a pair of Bruce profile brass electrodes with 15.2 mm diameter flat portion.

Further experiments are continuing with this apparatus.

4. Discussion

Figure 2 shows that for a helium density of 110 Kg/m^3 (the minimum helium density in the BNL cable design) the partial discharge inception stress is 15 MV/m for 100 μ m thick tape and 18 MV/m for 66 μ m thick tape. Unfortunately the 100 μ m thick tape appears essential for a real cable to bend successfully at room temperature.

Figure 5 shows a Paschen's law plot comparing the results of Meats[7] for butt gaps and for bare metal electrodes with the results of Figure 4 and the voltage calculated to appear across the butt gap for the partial discharge inception stresses for the short sample tests.

The two results of the short sample tests are a reasonable fit to a single curve when plotted in this form. However, for density-gap products greater than 6 Kg/m^3 x mm the values are 20% to 35% below the mid-dielectric void values of Meats, and nearer to his metal electrode results.

Figure 4 shows the BNL helium breakdown voltages for brass electrodes at varying spacings to be a reasonable fit to a single curve when plotted against gas density times electrode spacing. However, the voltages obtained are distinctly higher than those obtained by Meats.

A reduction in the breakdown strength of the gas with increasing electrode area could explain some of the discrepancy between the results. The effect of electrode area on the 60 Hz breakdown strength of SF_6 has been investigated by Nitta et al[10] in SF_6. They found a 29% to 35% reduction in breakdown strength (depending on the gas pressure and electrode roughness) when the electrode area was increased from 8×10^{-3} m^2 to 0.2 m^2. The BNL short-sample results represent a butt gap area of 3×10^{-3} m^2, while the Meats mid-dielectric void has an area of only 1×10^{-6} m^2. However, our results are very similar to the results of Schwenterly et al[8] for partial discharge inception in a single 8×10^{-7} m^2 mid-dielectric void.

The relative areas for the bare metal electrode experiments are 1.82×10^{-4} m^2 for the BNL results and 1.96×10^{-3} m^2 for the Meats experiment.

Pachen's law is known not to be obeyed[5] for the gas density range used in these experiments, so true comparison can only be made between experiments that used identical electrode spacings, but all the experiments compared here used electrode spacings of comparable magnitude.

Meats[5] considered that breakdown of supercritical helium was initiated by field emission from metal electrode surfaces. He considered[7] that this explained the higher breakdown voltage for mid-dielectric voids. In our short samples the aluminum layer on the screen tapes does not go to the tape edge so that field emission from a metal surface into the gas is minimized. However, a thin film of helium is always present between the tapes and a computer field plot has shown a field enhancement at the aluminum edge of a factor greater than three. Some field emission into the gas is possible and this may be a reason why the short sample results are nearer to the metal electrode results of Meats.

The effect of electrode area and of insulating coatings on electrode surfaces on the breakdown strength of supercritical helium for the butt gap depths found in a lapped cable dielectric is important for superconducting cable design. Further experiments on these effects are in progress.

6. Conclusions

A short sample of lapped cable dielectric using 100 μm thick tapes has a partial discharge inception stress of 15 MV/m for a helium density of 110 Kg/m^3. Results for 66 μm and 100 μm tapes fit a single curve for a Paschen plot.

Short-sample tests give butt gap breakdown voltages 20% to 30% lower than the mid-dielectric void results of Meats, and much nearer to his metal electrode results.

7. References

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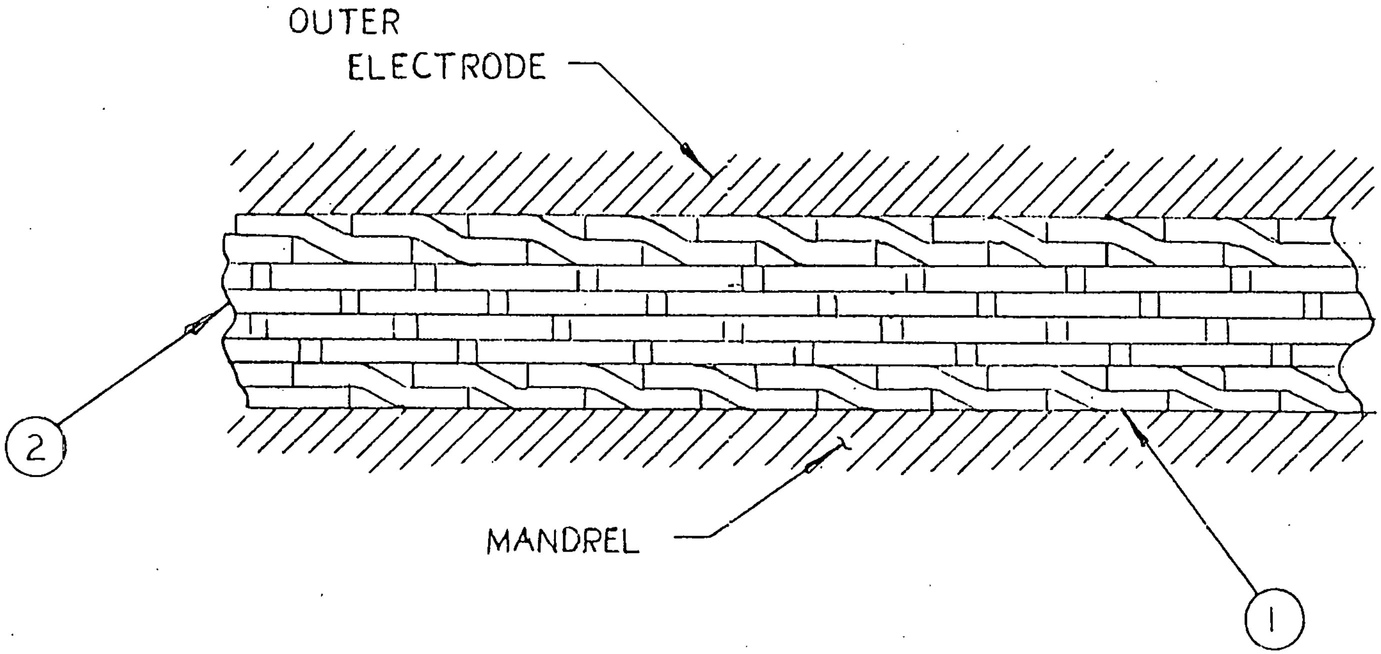
Figure Captions

1. Short sample construction.
2. Average rms stress in the insulation at partial discharge inception vs helium density for short samples.
3. Variable electrode spacing apparatus.
4. 60 Hz breakdown voltage vs product of gas density and electrode spacing for brass electrodes and helium gas.
5. A comparison of butt gap voltage for partial discharge inception and helium gas breakdown voltage.



1. INTERCALATED SCREENS
   (ALUMINUM ON POLYESTER)
2. DIELECTRIC TAPE

figure 1

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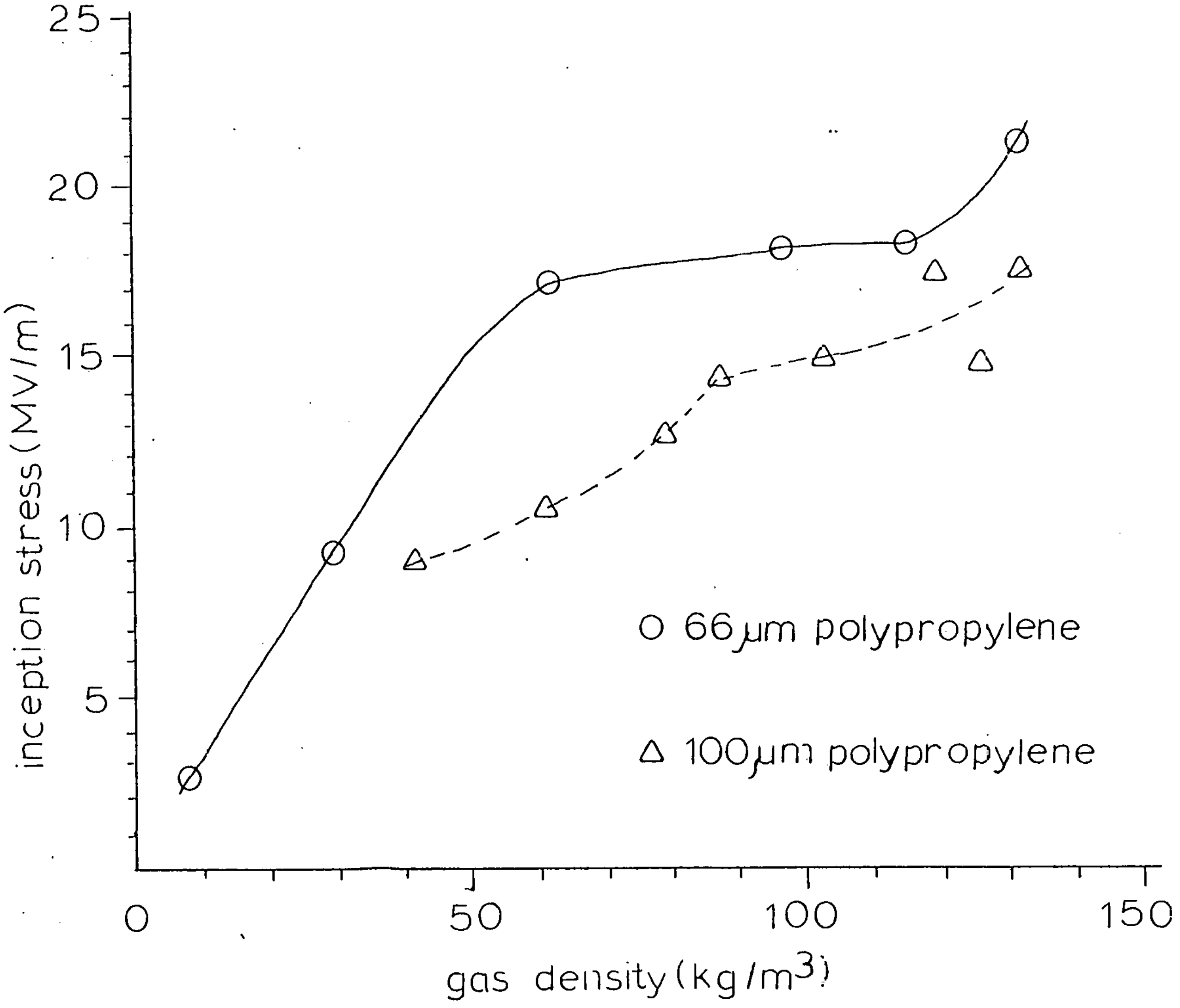
25
20
15
10
5
inception stress (MV/m)
0
50
100
150
gas density (kg/m^3)
○ 66 µm polypropylene
△ 100 µm polypropylene

figure 2

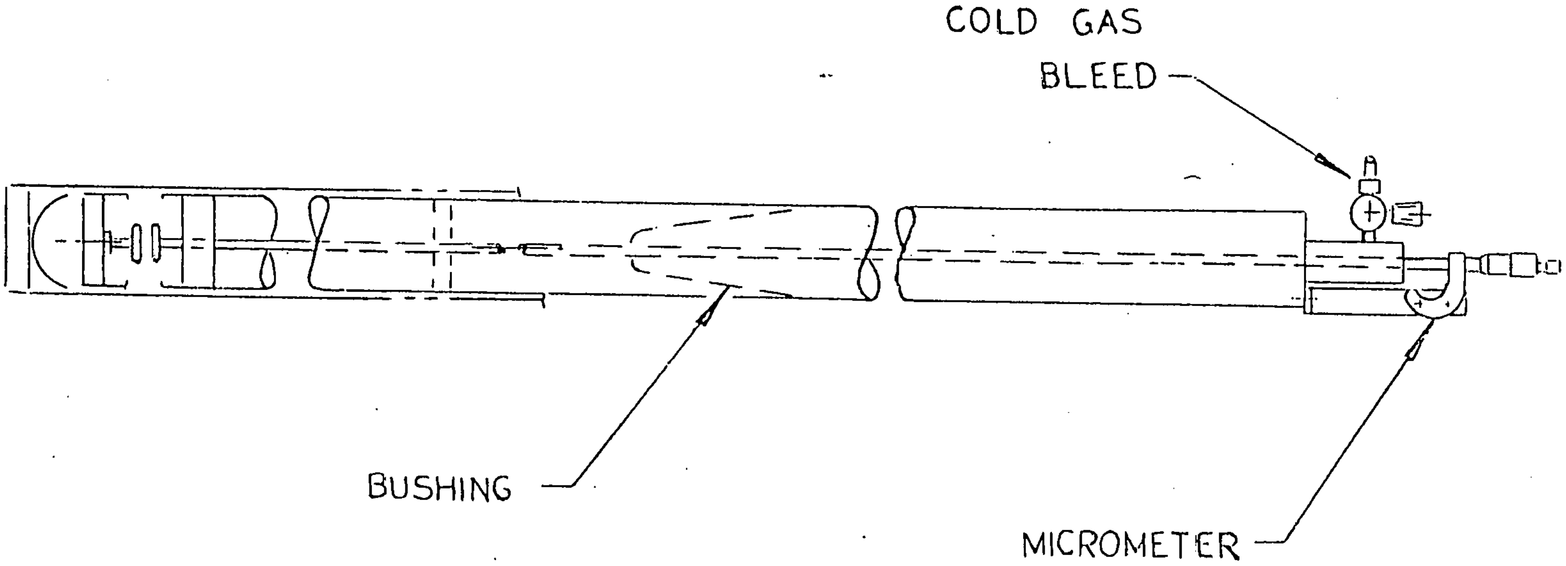

figure 3

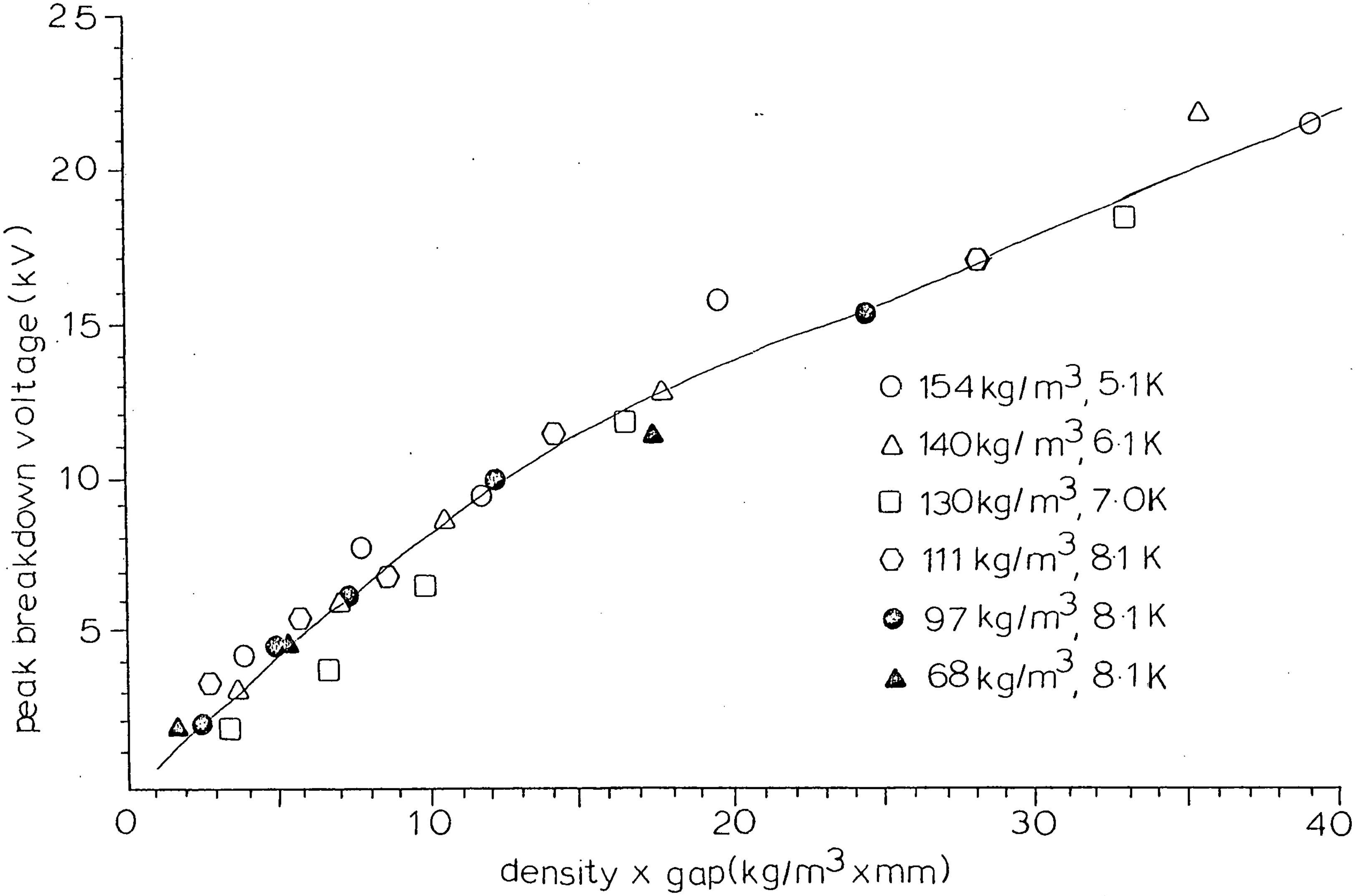
25
20
15
10
5
0
10
20
30
40
peak breakdown voltage (kV)
density x gap(kg/m3 x mm)
○ 154 kg/m3, 5·1K
△ 140 kg/m3, 6·1K
□ 130 kg/m3, 7·0K
⬡ 111 kg/m3, 8·1 K
● 97 kg/m3, 8·1 K
▲ 68 kg/m3, 8·1 K

figure 4

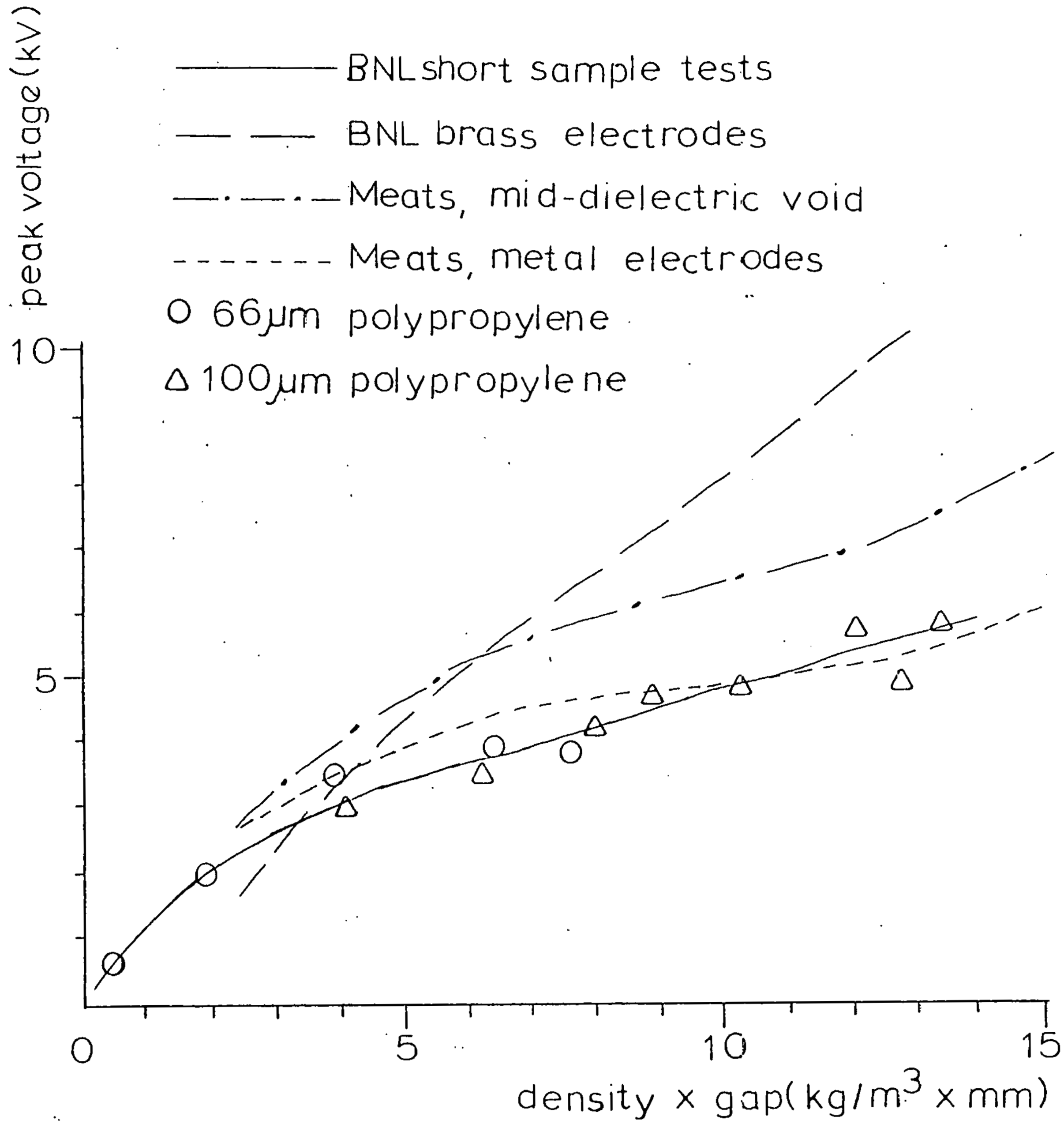
BNLshort sample tests
BNL brass electrodes
Meats, mid-dielectric void
Meats, metal electrodes
O 66μm polypropylene
Δ 100μm polypropylene
peak voltage (kV)
10
5
0
5
10
15
density x gap(kg/m3 x mm)

figure 5