As a basic study of insulation techniques at low temperatures which are necessary for the future development of the electrical power transmission by cryogenic cables, breakdown voltages of gaseous nitrogen and air have been measured by sphere-to-sphere gaps over the temperature range 293 K to 93 K.

When the 50 Hz ac and dc voltages were applied, Paschen's law proved to be valid down to a temperature of 93 K. However, for the impulse waveforms the 50% breakdown voltages became higher at low temperatures because of the decrease in electron emission from the surface of the negative electrode.

Breakdown voltages of gaseous N_2 and air from normal to cryogenic temperatures

H. Fujita, T. Kouno, Y. Noguchi, and S. Ueguri

To make use of superconductivity and low resistivity at cryogenic temperatures, it is necessary to know the dielectric behaviour of insulating materials at very low temperatures. Recently, much work has been done on the dielectric strength of both liquid and gaseous helium[1] and liquid nitrogen.[2, 3] Furthermore, trial superconducting cables are being attempted in various places.[4] However, investigations concerning the breakdown voltages of gases, the temperature of which varies continuously from normal to cryogenic temperatures, are few.[5] It is also interesting to examine whether Paschen's law is valid over the wide range of low temperatures or not.

Therefore measurements of the breakdown voltages of gaseous nitrogen and air were carried out at 93-293 K keeping the gas density constant (10^5 Nm^{-2} at 293 K). For a sphere-to-sphere gap, the dc and 50 Hz ac breakdown voltages obey Paschen's law, ie it does not change at any temperature if the gas density is fixed. When the impulse waveforms are applied, the 50% breakdown voltage increases at the low temperatures, because electron emission from the cathode surface is suppressed.

Apparatus

In order to change the temperature from 293 K to 93 K and also to keep it constant at any desired value during a test run, a special cryostat was constructed. Fig. 1 shows the structure of this cryostat which consists of outer and inner vessels thermally isolated by a vacuum (about 13.3 x 10^{-4} Nm^{-2}). The bottom of each vessel was fixed with bolts, so that it could be opened if necessary. Both the copper pipe and the heating wire were wound around the outer wall of the inner vessel. Each vessel had two crystal windows, one for observation and the other for illumination of uv light.

Fig. 2 shows the schematic diagram of the thermal control system. The temperature of the gas was measured with six copper-constantan thermo-couples set in the inner vessel and, according to the measured temperature relative to the setting value, either cooling or heating was effected. Liquid nitrogen flowed in the above mentioned copper pipe and evaporated to cool the inner vessel. Finally it was blown out through an electromagnetic valve which was opened and shut by the thermal regulator. In time everything in the vessel attained the same temperature. Furthermore the temperature of the testing gas was determined from its pressure to ensure that it was at the desired temperature.

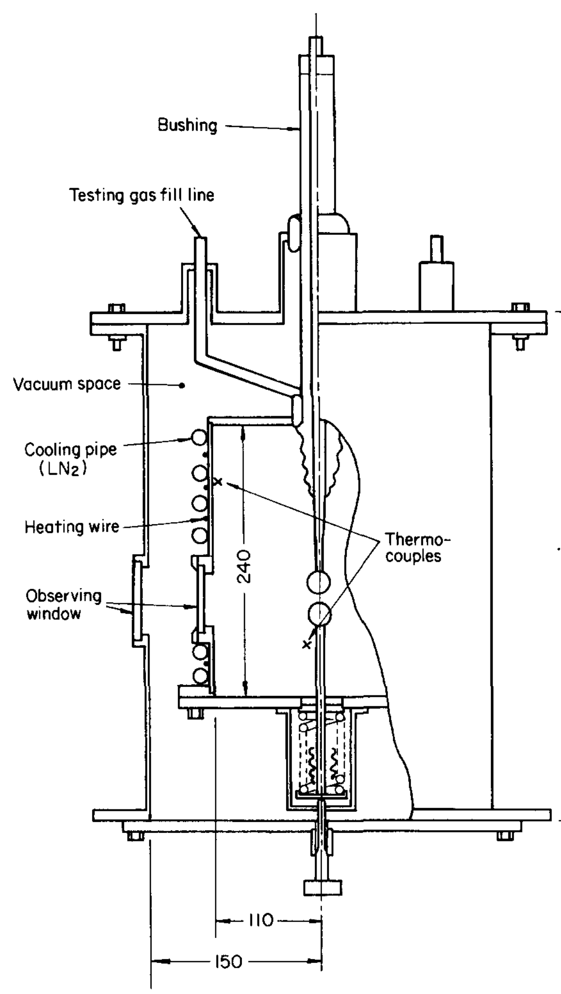

Fig. 1 Structure of cryostat

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Before starting an experiment, the inner chamber was exhausted to 13.3×10^{-1} Nm^{-2} (10^{-2} Torr) and a research grade gas of high purity (for example, N_2 : 99.999%) was filled slowly through a liquid nitrogen trap. Then the chamber was sealed and the gas density kept constant (10^5 Nm^{-2} at 293 K) at various temperatures.

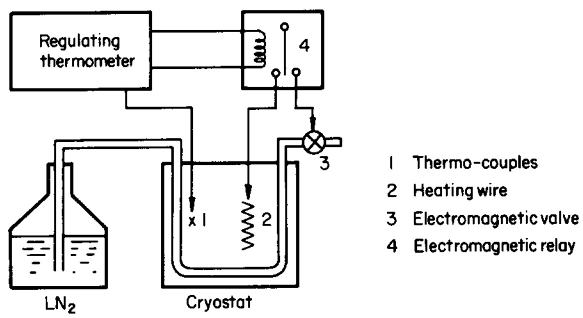

Fig. 2 Thermal control system

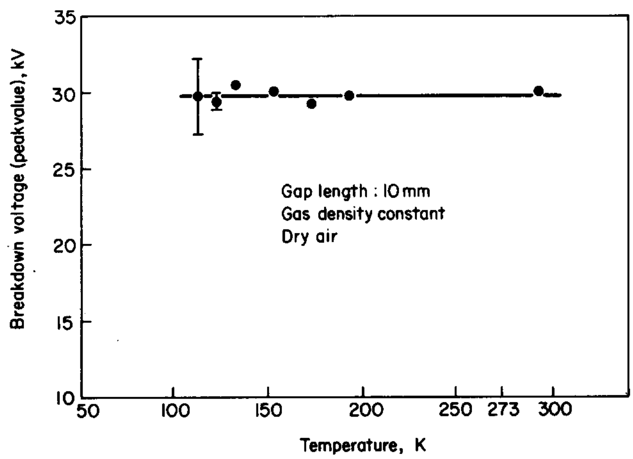

Fig. 3 50 Hz ac breakdown voltages vs gap length in air

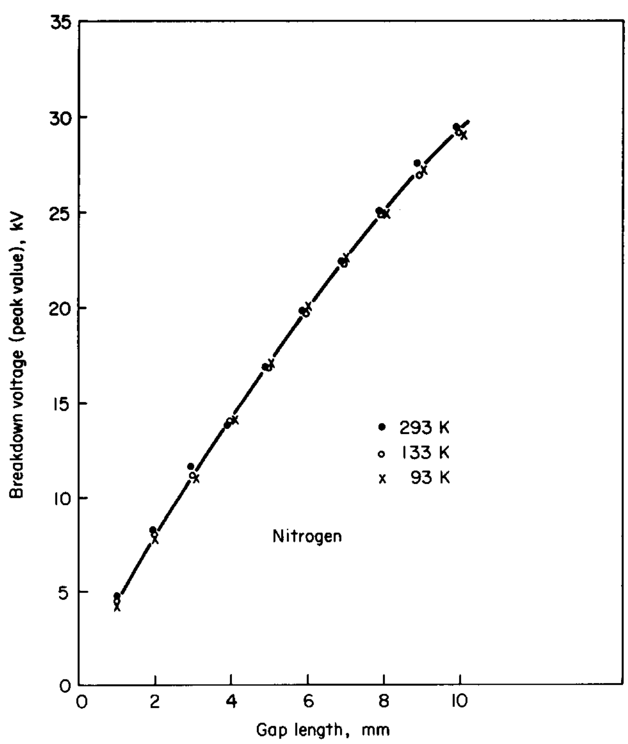

Fig. 4 50 Hz ac breakdown voltages vs gap length in nitrogen

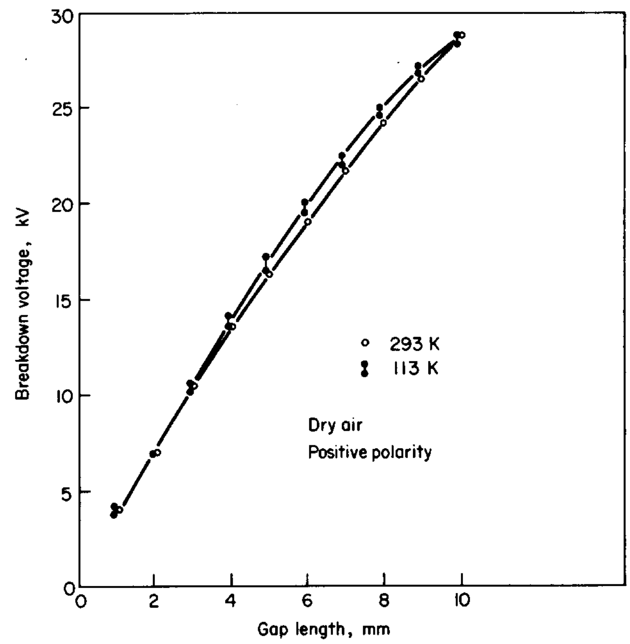

Fig. 5 dc breakdown voltages vs gap length in air

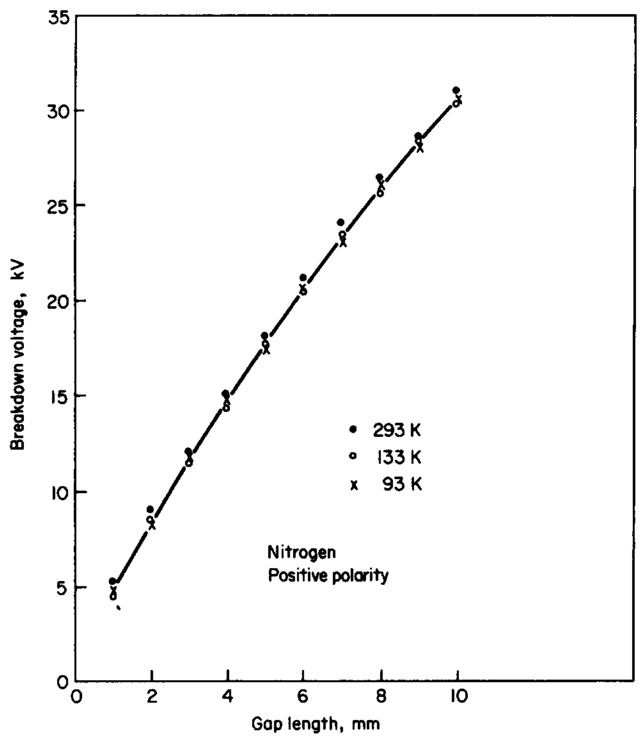

Fig. 6 dc breakdown voltages vs gap length in nitrogen

Highly polished copper spheres of 20 mm diameter were used as electrodes. The gap length was measured by a telescope via the windows of the cryostat. The diverter circuit saved the electrodes from being damaged.

Results and discussion

All experiments were performed under the following conditions.

1. The sphere electrodes were illuminated by uv light to lessen the dispersion of breakdown voltages.

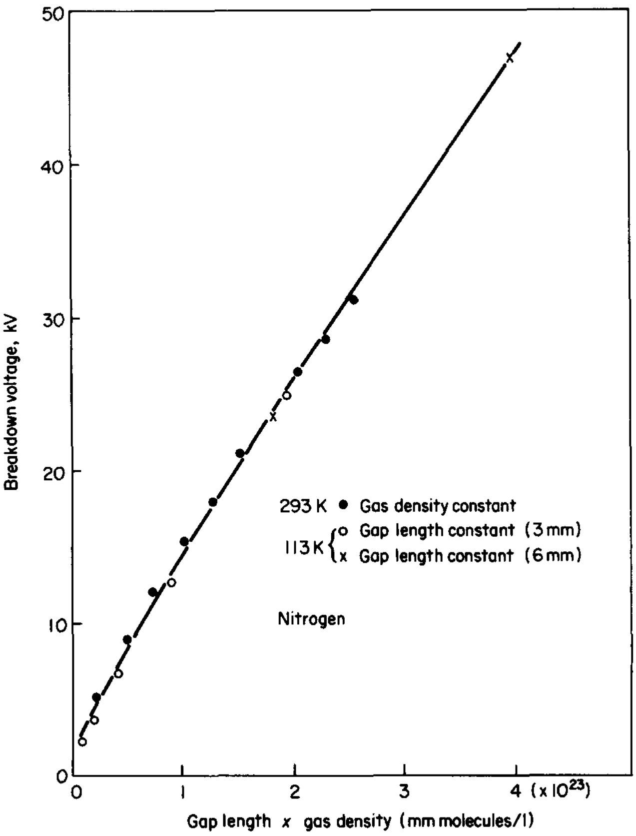

Fig. 7 dc breakdown voltages of nitrogen vs gap length multiplied by the gas density

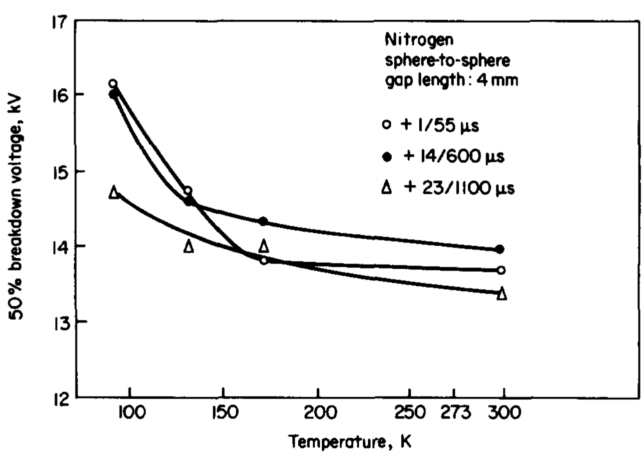

Fig. 8 50% breakdown voltages vs temperature

2. For dc and ac voltages, the voltage was raised about 500-1000 V s^{-1}. At each temperature 5-10 values of breakdown voltage were obtained.
3. For the impulse waveforms, 50% breakdown voltage was determined by the 'up and down' method with 30-40 voltage applications and the breakdown probability was taken by 20 shots at a particular voltage level. An interval of at least 30 seconds was allowed between each shot.
4. The gap length was adjusted after thermal equilibrium was achieved.
5. The gas density was fixed regardless of temperature. In the following experiment, it was 10^5 Nm^{-2} at 293 K unless referred to in particular.

50 Hz ac and dc voltage. In this section the validity of Paschen's law is established even at low temperatures. Fig. 3 shows the 50 Hz ac breakdown voltages of air at various temperatures with gap length of 10 mm. As clearly seen it does not change over the temperature range of 293 K-113 K. Fig. 4 shows the 50 Hz ac breakdown voltages of nitrogen at 293 K, 133 K and 93 K plotted against gap length from 1 mm to 10 mm. There is no difference between the three temperatures. Fig. 5 and Fig. 6 show the positive dc breakdown voltages of air and nitrogen respectively: again no disparity is noticed. The negative polarity cases, although not shown here, were the same. In air, the breakdown

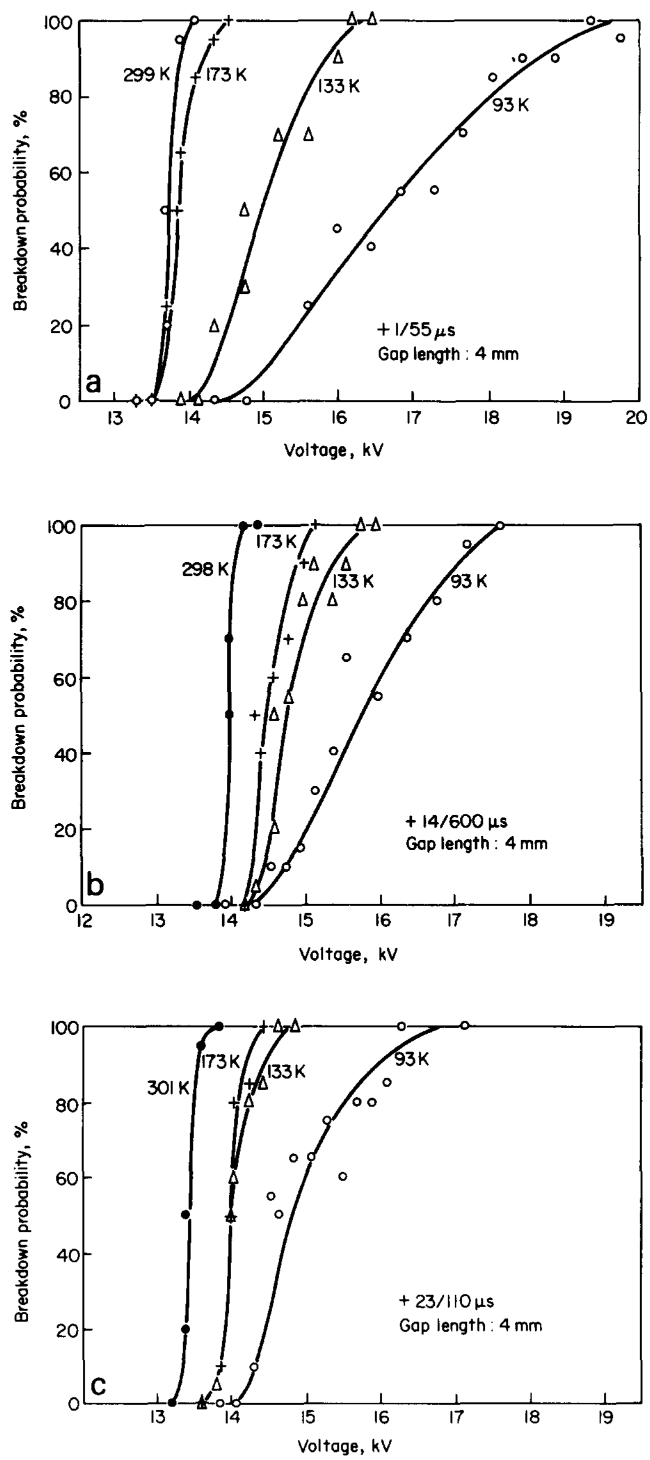

Fig. 9 Changes of breakdown probability curves in nitrogen with temperature for a — +1/55 μs, b — +14/600 μs, and c — +23/1100 μs

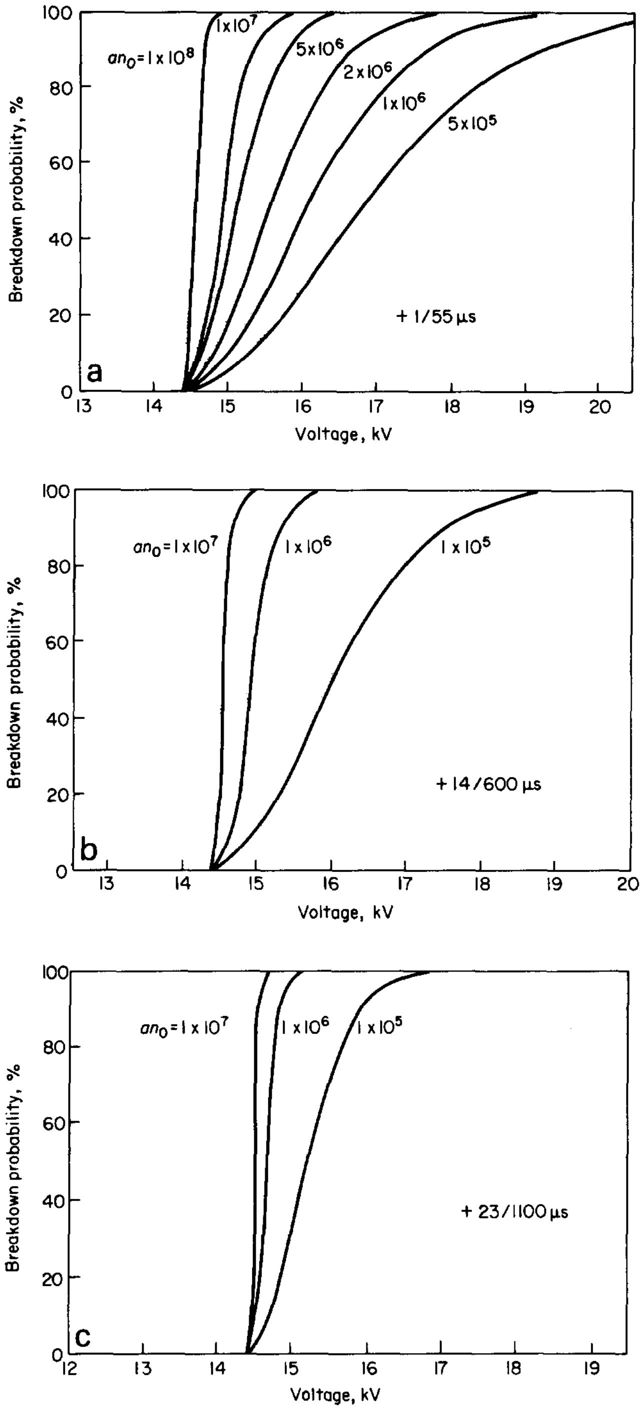

Fig. 10 Theoretical values of breakdown probability curves in nitrogen for a — +1/55 µs, b — +14/600 µs, and c — +23/1100 µs

voltages exhibited little dispersion at 113 K, probably because oxygen might become liquid on the wall near the cooling pipe.

Fig. 7 shows the relation between the dc breakdown voltages of nitrogen and σd product (σ = gas density, d = gap length) at various temperatures. All the points lie on one curve which confirms that Paschen's law is valid even at low temperatures. Then the ac and dc breakdown voltages of the uniform field gap in gases at cryogenic temperatures can be estimated from the data given at normal temperature; the increase of gas density must be taken into consideration.

Impulse breakdown voltage of nitrogen. In this section it is shown that the 50% breakdown voltages of nitrogen for impulse waveforms increase at low temperatures. Fig. 8 shows the 50% breakdown voltages for + 1/55 µs, + 14/600 µs and + 23/1100 µs impulse waves. The lower the temperature is, the higher the breakdown voltage and this tendency is more marked for shorter waveforms.

Fig. 9 shows the breakdown probability curves at various temperatures for the three waveforms in Fig. 8. The slopes of the curves decline at lower temperatures, that is, the dispersion of breakdown voltages increases. To interpret this result, the following equation should be applied.

$$P(\Delta_\infty) = 1 - \exp[-(an_0\Delta_\infty^2 T_t)/(\Delta_\infty + 1)] \qquad (1)$$

where $P(\Delta_\infty)$ is the breakdown probability for the impulse voltage that has the over voltage factor Δ_∞ above the static breakdown voltage and the time to half value is T_t, and n_0 is the number of initial electrons per second appearing in the discharging space. To drive (1), it is assumed the probability that an initial electron induces breakdown is proportional to the over voltage factor and a is this proportional constant. This assumption is often used to calculate the statistical time lag of breakdown and the waveform of the impulse voltage is also assumed as a triangle for

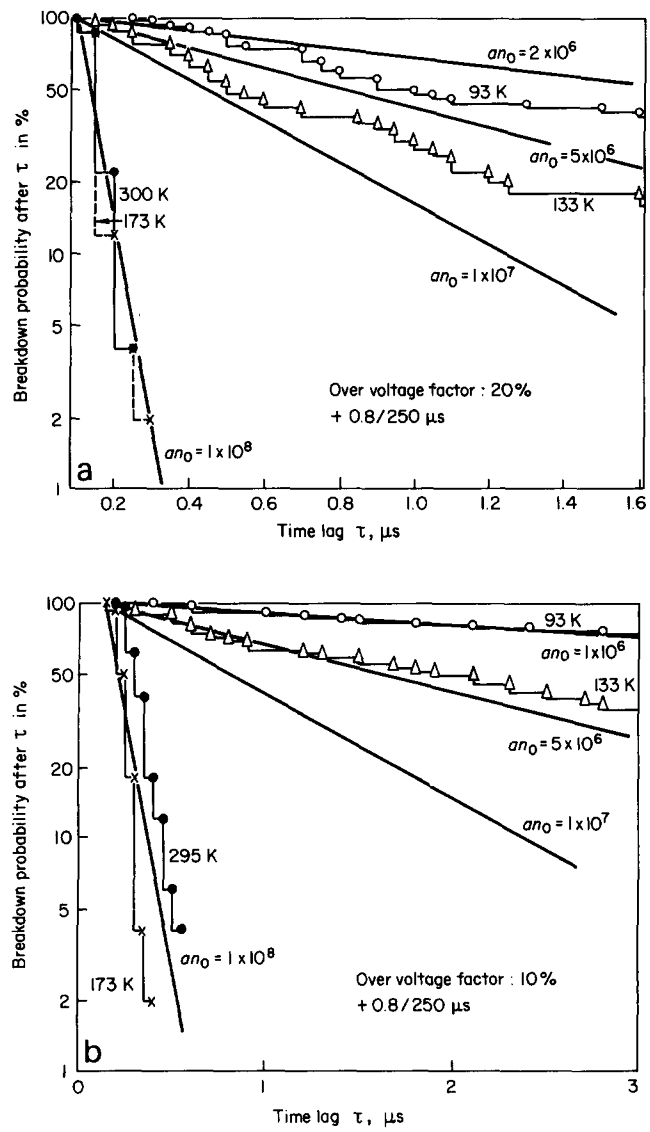

Fig. 11 Laue-plots for nitrogen where a — 20% over voltage and b — 10% over voltage

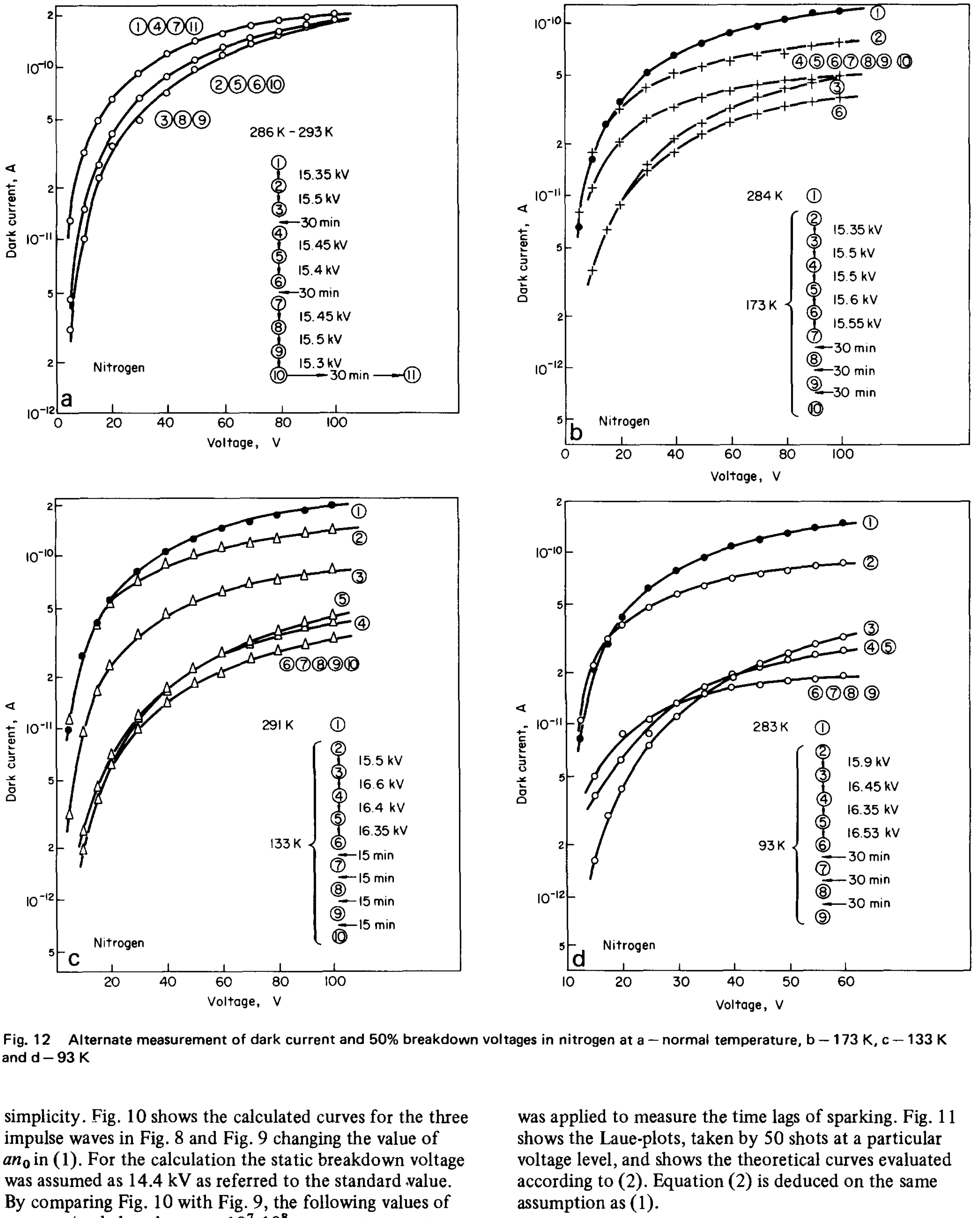

Fig. 12 Alternate measurement of dark current and 50% breakdown voltages in nitrogen at a — normal temperature, b — 173 K, c — 133 K and d — 93 K

simplicity. Fig. 10 shows the calculated curves for the three impulse waves in Fig. 8 and Fig. 9 changing the value of an_0 in (1). For the calculation the static breakdown voltage was assumed as 14.4 kV as referred to the standard value. By comparing Fig. 10 with Fig. 9, the following values of an_0 may be deduced; $an_0 = 10^7\text{-}10^8$ at room temperature, $an_0 = 1 \times 10^6\text{-}5 \times 10^7$ at 173 K, $an_0 = 1\text{-}3 \times 10^6$ at 133 K and $an_0 = 1\text{-}5 \times 10^5$ at 93 K. To explain these results, the value of an_0, in other words the initial electron number n_0, must decrease considerably. Afterwards it is shown that the proportional constant a doesn't change at any temperature of present interest.

Next, an impulse wave of + 0.8/250 μs, which can be regarded as remaining constant before breakdown occurs, was applied to measure the time lags of sparking. Fig. 11 shows the Laue-plots, taken by 50 shots at a particular voltage level, and shows the theoretical curves evaluated according to (2). Equation (2) is deduced on the same assumption as (1).

$$g(\tau) = \exp(-an_0\Delta_\infty\tau) \qquad (2)$$

where $g(\tau)$ is the probability that breakdown will occur in τ seconds, the other parameters are readily explained in (1). It is seen that the curve becomes flat at lower temperatures. The values of an_0 are estimated as follows; $an_0 = 10^8$ at room temperature and 173 K, $an_0 = 5\text{-}7 \times 10^6$ at 133 K and $an_0 = 1\text{-}3 \times 10^6$ at 93 K. These values are slightly different from those of Figs 9 and 10 because the measuring

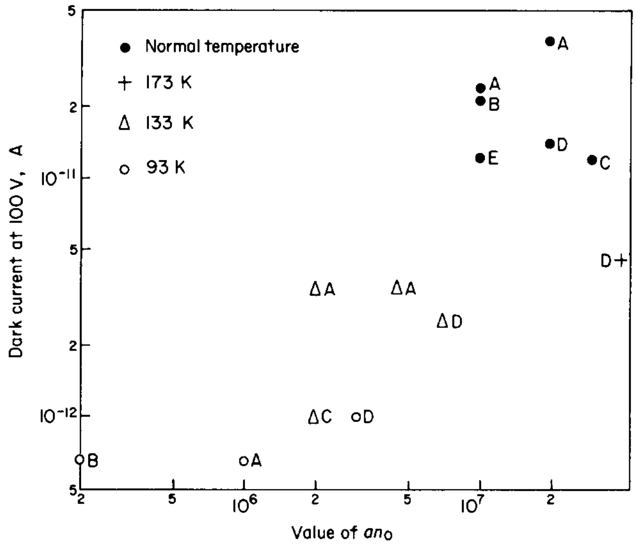

Fig. 13 Dark current vs an_0 for nitrogen; A, B, C estimated from the breakdown probability curves (A: +1/55 μs; B: +14/600 μs; C: +1/17 μs) D, E estimated from the Laue-plots (D: over voltage factor 20%, E: 10%, both +0.8/250 μs)

date, the testing gas and the surface conditions were not strictly the same. These results of the breakdown probability and the time lag of sparking suggest that the number of initial electrons decreases to one tenth or less at low temperatures as compared to normal temperatures and therefore the 50% breakdown voltage increases.

Measurement of dark current. In order to clarify directly that initial electrons liberated by uv light illumination decrease considerably at low temperatures, the dark current was measured using a vibrating reed electro-meter. This measurement was performed by the following procedure:

1. dark current was measured at room temperature;
2. the testing gap was cooled to a given temperature;
3. dark current was measured at the temperature;
4. for the impulse wave of + 1/55 μs, the 50% breakdown voltage was determined by the 'up and down' method with 30 voltage applications;
5. 3 and 4 were repeated a few times;
6. the dark current was measured;
7. 6 was repeated.

In the experiment the gap was always illuminated by uv light. These results at various temperatures are shown in Fig. 12. The number in the circle denotes the order of measurement. From this figure the following conclusions may be drawn:

1. the dark current hardly changed even at low temperatures if no breakdown occurs;
2. the dark current decreased after the gap sparked and its decrease grew as the temperature decreased.
3. the decrease of dark current quickly vanished at room temperature, but remained at low temperatures even after 90 minutes.

Now, consider the relation between the dark current, I, and number of initial electrons n_0. Since the electric field is so weak that no ionization takes place, the dark current can be written as $I = n_0 e\mu E$ (μ = electron mobility). Here, as it is unlikely that μ changed before and after the breakdown, the decrease of I should come from n_0. Then n_0 must be proportional to I and have the same dependence on temperature as I.

To confirm the connection of the dark current and the values of an_0 the breakdown probability curves and the Laue-plots were taken again and, just after that, the dark current was also measured. The parameter an_0 was estimated as before and shown in Fig. 13 together with the dark current at 100 V. In spite of the dispersion, it is evident that an_0 varies in proportion to I. From this result and the consideration mentioned above that n_0 is proportional to I, it is concluded that the constant a is equal at any temperature. The reason why the 50% breakdown voltage increases at low temperatures is revealed to be due to the initial electrons which decrease after breakdown to decline the slope of the breakdown probability curve at low temperatures. Besides, for ac and dc voltages, which last long enough, the breakdown voltages are not affected by the change of the initial electron number.

Conclusions

As a basic study about the insulation at cryogenic temperatures, the breakdown voltages of gaseous nitrogen and air were measured over the temperature range 293–93 K. A uniform field gap was used in gases of constant gas density.

For dc and 50 Hz ac voltages, the breakdown voltages of nitrogen and air obeyed Paschen's law. For impulse waveforms, the 50% breakdown voltages of nitrogen increased at low temperatures in spite of the fixed gas density. It has also been found that breakdown probability curves declined and that the time lags of sparking increased at lower temperature.

Further, at low temperatures the dark current decreased to one tenth of its value at normal temperatures after breakdown occurred and this change remained for more than 90 minutes. From these results, we conclude that the initial electrons decreased considerably at low temperatures and this was the reason why the 50% breakdown voltages increased at low temperatures.

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