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High Voltage Insulation Performance of Cryogenic Liquids for Superconducting Power Apparatus

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Abstract **- This paper describes high voltage insulation technology of cryogenic liquids for superconducting power apparatus. The insulation of a superconducting transformer is classified into several insulation components. Moreover, we investigate fundamental insulation characteristics peculiar to the superconducting and cryogenic circumstances: area and volume effects on breakdown strength, V-t characteristics, quench-induced dynamic breakdown characteristics and so on. Finally, we systematize the electrical insulation of cryogenic liquids, and propose the flow chart for the practical insulation design of superconducting power apparatus.**

I. INTRODUCTION

As one of the most promising candidate for realizing a large power transmission system in the next generation, strong attention has been paid to superconducting technology [1,2]. Application of superconducting technology to electric power apparatus such as generators, transformers, fault current limiters, cables, energy storage and even to their integrated systems, will give rise to enhanced efficiency and capacity of the power supply. Then, research and development of superconducting technology has rapid progress in the variety of researches [1-5].

In order to realize the superconducting electric power system, it is necessary to establish the electrical insulation technology of cryogenic liquids. In particular, superconducting power apparatus and systems should be developed on the premise of higher voltage operation [3,4]. At this stage, the high voltage insulation technology at cryogenic temperatures becomes important as the common basic technology of the superconducting apparatus. Fundamental and applied studies on the insulation performance of cryogenic liquids have been promoted eagerly up to now in the world [6,7]. However, useful and applicable data to the practical insulation design are less satisfactory than those of the conventional transformer oil, SF_6 gas, etc. Aiming at the practical use of superconducting technology, not only basic but also applied-level systematization of the insulation characteristics for cryogenic liquids are well-timed and highly desired.

From the above viewpoints, we have been investigating the insulation performances of liquid helium (LHe) and liquid nitrogen (LN_2) [8-11]. In this paper, firstly, the insulation of superconducting transformers is classified into several insulation components with various kinds of insulation phenomena peculiar to the superconducting environment considered. Secondly, the results of measurement and analysis on some issues in the above classification are described: i.e. area and volume effects of breakdown strength, V-t characteristics, quench-induced dynamic breakdown characteristics. Finally, a flow chart for high voltage insulation design of superconducting power apparatus is systematized.

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II. INSULATION PERFORMANCE OF CRYOGENIC LIQUIDS

A. *Insulation Component*

For insulation design of the superconducting apparatus, insulation tests should be carried out as in the case of the conventional ones. At the same time, one has to introduce and establish the concept of the safety margin in order to obtain operational reliability and the longest life under cryogenic environment. Consequently, the conventional concept of insulation coordination should be kept, so that overvoltage analysis on ac voltage and surges which occur also in the superconducting system is necessary. Investigation of insulation coordination allows one to determine the relationship between the rating of the superconducting apparatus and the test voltage. In other words, as the specification of the superconducting apparatus for the high voltage is clarified, insulation design of the apparatus can be realized.

Since transformers include many kinds of insulation types and in general tend to be exposed to high voltage condition, let us take the transformer as an example. Figure 1 shows the classification of the insulation design in the superconducting transformer. Although Fig. 1 basically resembles that of the conventional high voltage oil-filled transformer, it also contains some elements peculiar to the superconducting and cryogenic insulation. To clarify insulation characteristics in each part ① - ⑨ as shown in Fig.1, many insulation characteristics of cryogenic liquids should be experimentally investigated. In this chapter, as the common and fundamental insulation characteristics in Fig.1 ① - ⑨, we examine the area and volume effects on

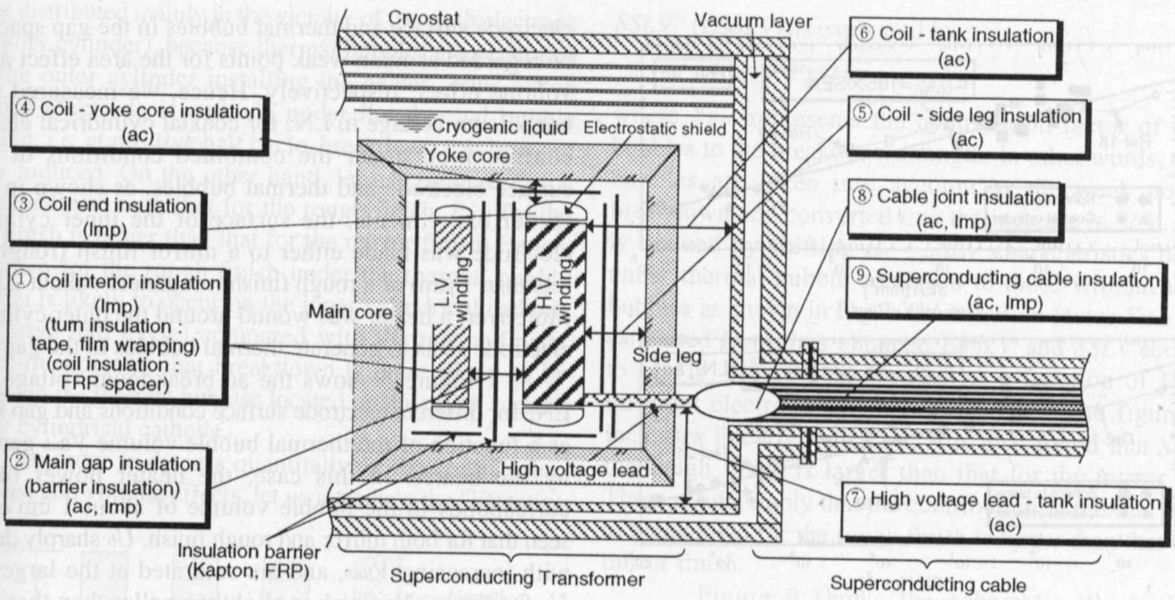


Fig.1 Classification of insulation component for pool cooling superconducting transformer and cable.

breakdown strength, V-t characteristics and quench-induced dynamic breakdown characteristics peculiar to cryogenic environment.

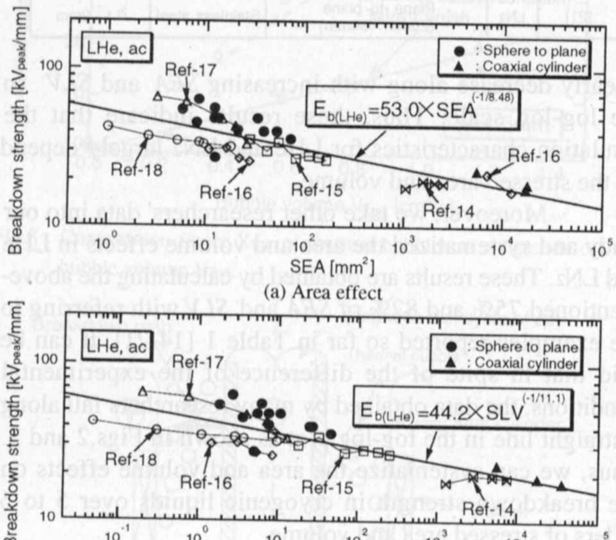
B. Area and Volume Effects of LHe and LN_2

As far as the insulation characteristics for gases and liquids are concerned, the area and volume effects in the breakdown characteristics are as important as the gap length dependence. For the insulation design of the actual apparatus, these characteristics are the most important for determining the size of apparatus.

In order to investigate the area and volume effects over a wide range of the electrode size, we used two kinds of electrode configurations; sphere-to-plane electrode and coaxial cylindrical electrode [11]. These electrode configurations in our experiment allowed stressed electrode area (*SEA*) and stressed liquid volume (*SLV*) to be varied from 10^0 to 10^5 mm^2 and from 10^{-1} to 10^5 mm^3, respectively. We immersed these electrodes in LHe at 4.2 K or in LN_2 at 77K at atmospheric pressure and measured ac breakdown voltage fifty times for each experimental setup.

When the area and volume effects are considered, it is needed, first of all, to determine the electric field region to which the insulation design covers. Investigation of Weibull statistical analysis for sphere-to-plane electrode configuration tells us the electric field values required for the insulation design to be 75% and 82% of the maximum electric field strength for LHe and LN_2, respectively. These values are experimentally verified by observing distribution of the breakdown traces on the sphere electrode surface. Another report shows that 85% of the maximum electric field strength should be taken as a criterion with the area and volume effects for LHe considered [12]. Note that these values are lower than 90% for SF_6 gas and the insulating oil [13] conventionally reported. This means that the larger electric field region should be considered in the insulation design for the cryogenic liquids.

Figures 2 (a) and (b) show the ac breakdown strength $E_{b(LHe)}$ in LHe as a function of *SEA* and *SLV*. Whereas Figs.3 (a) and (b) show the ac breakdown strength $E_{b(LN_2)}$ in LN_2 as a function of *SEA* and *SLV*. Note that we took *SSEA* and *SSLV* for data by the authors. *SSEA* and *SSLV* represents the statistical stressed electrode area and liquid volume, both of which are derived using the Weibull distribution. These statistical parameters are calculated by integrating the area and volume units multiplied by the relative breakdown probability over the whole area and volume, respectively, while considering the calculated electric field distribution [9]. It is found that both $E_{b(LHe)}$ and $E_{b(LN_2)}$



(a) Area effect

(b) Volume effect

Fig.2 ac breakdown strength in liquid helium as a function of SEA and SLV (●,▲ : data by the authors; ○,△,□,◇,⋈, : data by Table1).

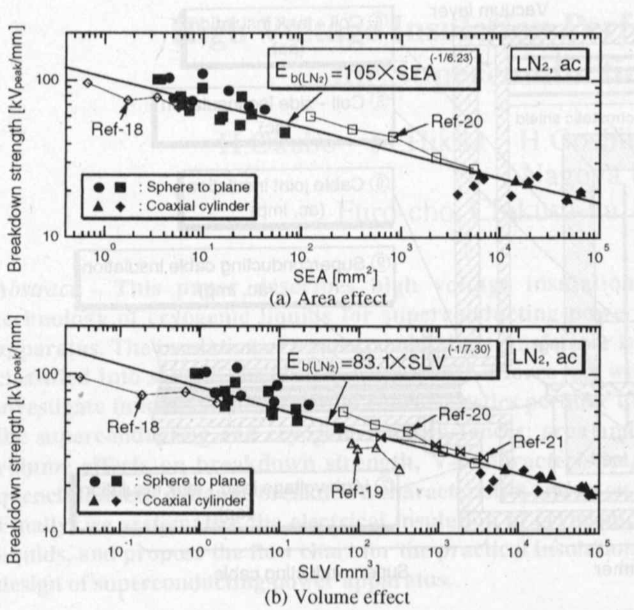


Fig.3 ac breakdown strength in liquid nitrogen as a function of SEA and SLV (●,■,▲,◆ : data by the authors; △,□,◇,⋈, : data by Table1).

Table 1 Experimental conditions for various researchers' results.

Reference	Liquid	Electrode configuration	Material	Gap length
[14]	LHe	Sphere-to-plane (250mm in diameter)	Brass	2-12mm
[15]	LHe	Sphere-to-sphere (50mm in diameter)	Stainless steel	0.5-3mm
[16]	LHe	IEC electrode (50mm sphere) & Coaxial Cylinder	Brass	0.2-0.6mm
[17]	LHe	Sphere-to-plane (15mm in diameter)	——	0.1-1mm
[18]	LHe & LN$_2$	Sphere-to-sphere (12.5mm in diameter)	Stainless steel	0.075-1.25mm
[19]	LN$_2$	Plane-to-plane (25mm in diameter)	Brass	0.1-1mm
[20]	LN$_2$	Plane-to-plane (ϕ 15-54mm)	Brass	0.5mm
[21]	LN$_2$	Plane-to-plane (20mm×90mm)	Stainless steel	0.1-2mm

linearly decrease along with increasing *SEA* and *SLV* in the log-log scale. Thus, these results indicate that the insulation characteristics for LHe and LN_2 largely depend on the stressed area and volume.

Moreover, we take other researchers' data into our study and systematized the area and volume effects in LHe and LN_2. These results are obtained by calculating the above-mentioned 75% and 82% of *SEA* and *SLV* with referring to the examples reported so far in Table 1 [14-21]. It can be said that in spite of the difference of the experimental conditions, the data obtained by many researchers fall along a straight line in the log-log plot as shown in Figs.2 and 3. Thus, we can systematize the area and volume effects on the breakdown strength in cryogenic liquids over 5 to 6 orders of stressed area and volume.

C. Mutual Contribution of Area and Volume Effects

In this section, we discuss the contribution of the area effect and the volume effect to the breakdown strength in LN_2. In cryogenic liquids, micro protrusions on the electrode surface and thermal bubbles in the gap space may be regarded as main weak points for the area effect and the volume effect, respectively. Hence, we measured the ac breakdown voltage in LN_2 for coaxial cylindrical electrode configuration under the combined conditions of rough surface electrode and thermal bubbles, as shown in Fig.4. In our experiments, the surface of the inner cylindrical electrode was made either to a mirror finish (roughness : less than 1 μm) or a rough finish (roughness : about 200μm). Moreover, a heater was wound around the outer cylindrical electrode so as to generate thermal bubbles in the gap space.

Figure 5 shows the ac breakdown voltage U_b in LN_2 for different electrode surface conditions and gap lengths as a function of the thermal bubble volume V_{Bub} generated by the heater. In this case, the heater power of 1 W corresponds to the bubble volume of about 1 cm^3/s. It is seen that for both mirror and rough finish, U_b sharply decrease with increasing V_{Bub}, and are saturated at the larger V_{Bub}. U_b for the rough finish is slightly smaller than that for the mirror finish. Thus, it is obvious that both thermal bubbles and the electrode surface condition affect simultaneously the breakdown voltage in LN_2.

Figures 6 (a) and (b) show the probability P_r that breakdown occurs at positive or negative half cycle of the applied ac voltage to the inner cylinder for different V_{Bub} for mirror and rough finish, respectively. When the thermal bubbles are generated, $P_{r(+)}$ becomes larger than $P_{r(-)}$ for the mirror finish as shown in Fig.6(a). Thermal bubbles

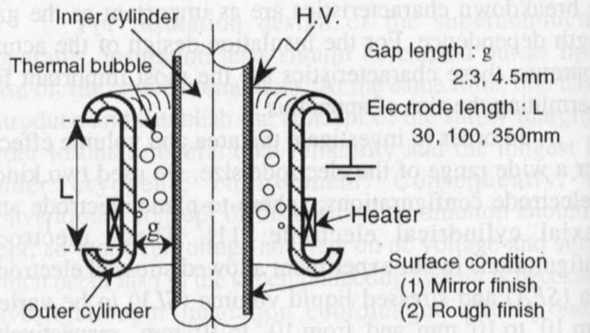


Fig.4 Coaxial cylindrical electrode configuration under combined conditions of rough surface electrode and thermal bubbles.

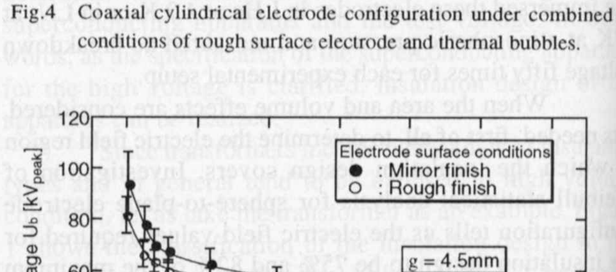


Fig.5 Breakdown voltage U_b as a function of bubble volume V_{Bub} for different electrode surface conditions and gap lengths.

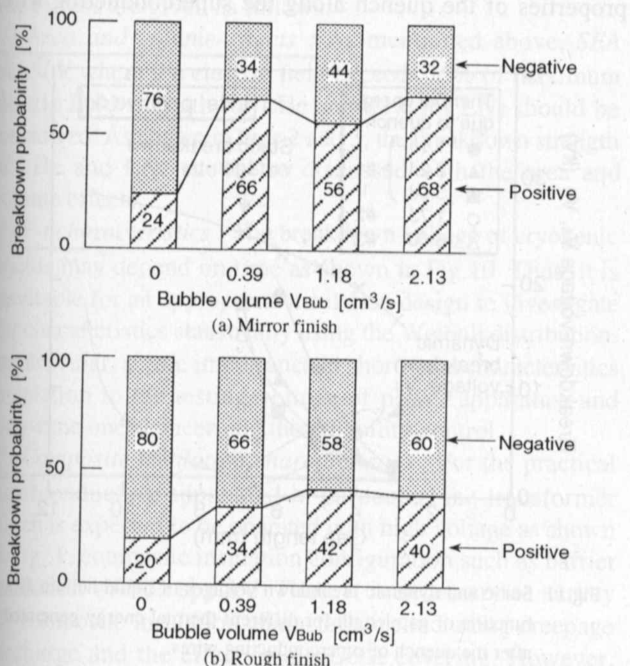
may be distributed mainly in the vicinity of the earth electrode side (outer cylinder), because thermal bubbles are generated from the outer cylinder installing the heater. Thus, when the earth electrode is cathode under the thermal bubble condition, i.e. at positive half cycle, breakdown can be more readily induced. On the other hand, let us compare P_r for the mirror finish with that for the rough finish. $P_{r(-)}$ for the rough finish is larger than that for the mirror finish. Hence, breakdown for the rough finish under the thermal bubble condition is likely to occur on the inner cylindrical cathode (at negative half cycle) compared with the mirror finish. This result indicates that breakdown is more likely to be triggered in the thermal bubbles located on the rough surface of inner cylindrical cathode.

In order to discuss quantitatively the contribution of the area and volume effects, let us introduce the "Effective SSLV" (ESSLV) as expressed by

$$ESSLV = SSLV(1 + X_{Bub}) \quad (1)$$

where X_{Bub} represents the contribution factor of thermal bubbles to the breakdown strength. In other words, thermal bubbles are taken into account as the weak points of breakdown and converted into the increase in SLV. $ESSLV$ is derived by shifting E_b - $SSLV$ characteristics obtained under thermal bubble condition to those without thermal bubbles as shown in Fig.7. Contribution factor X_{Bub} is then estimated from thus obtained $ESSLV$ and $SSLV$ according to Eq.(1). Figure 8 shows X_{Bub} as a function of V_{Bub} for different electrode length L. As seen in the figure, X_{Bub} increases linearly with V_{Bub}. It is also found that X_{Bub} for the rough finish is larger than that for the mirror finish. These results imply that the contribution of thermal bubbles to breakdown for the rough finish is larger than that for the mirror finish.

Figure 9 shows the schematic illustration of breakdown under combined conditions of rough surface electrode and thermal bubbles. Breakdown in LN_2 can be triggered by breakdown in thermal bubbles due to their low withstand level. In the case of the rough surface on the inner cylindrical electrode, the electric field enhancement due to micro protrusions facilitates breakdown in thermal bubbles. The above explanation for the thermal bubbles conditions suggests that breakdown in LN_2 is primarily determined by the volume effect of thermal bubbles, while it is mutually affected by the area effect of electrode surface condition. Consequently, the mutual correlation between



(a) Mirror finish
(b) Rough finish

Fig.6 Breakdown probability at positive or negative half cycle of applied ac voltage for different bubble volume V_{Bub}.

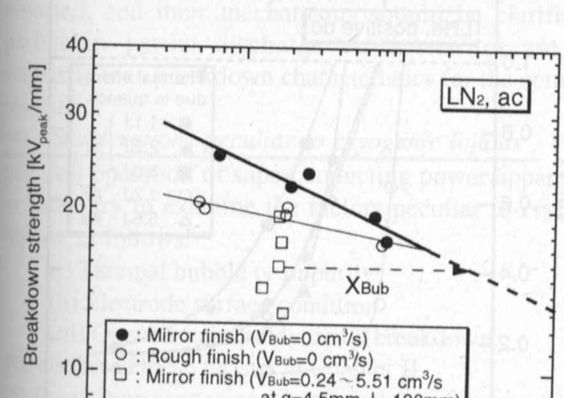


Fig.7 Breakdown strength as a function of SSLV with and without thermal bubble.

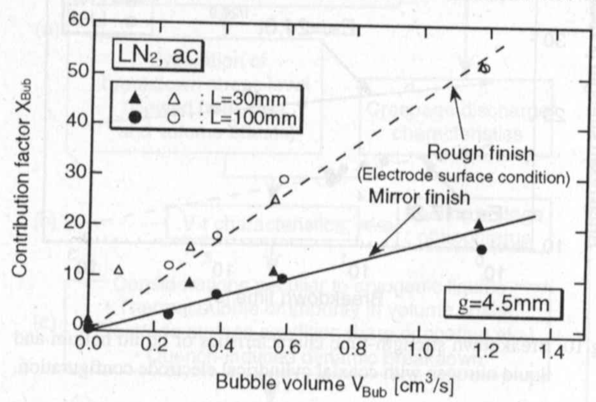


Fig.8 Contribution factor X_{Bub} of thermal bubbles as a function of bubble volume V_{Bub}.

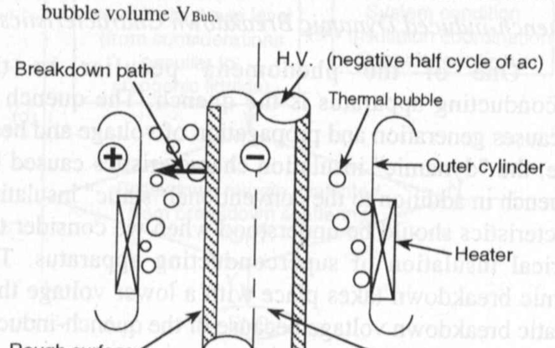


Fig.9 Schematic illustration of breakdown under combined conditions of rough surface electrode and thermal bubbles.

the area effect and the volume effect is expected to appear in the breakdown strength in LN_2. This mutual correlation may be a phenomenon peculiar to cryogenic liquids being likely to generate thermal bubbles. Therefore, it is very important to consider both thermal bubbles and electrode surface condition for high voltage insulation of superconducting power apparatus.

D. V-t Characteristics

Rating determination of the apparatus and system as well as insulation coordination among the apparatus should be investigated. To realize them, it is required to investigate V-t characteristics of the superconducting apparatus and the cryogenic coolant.

Figure 10 shows a result of V-t characteristics of LHe and LN_2 for coaxial cylindrical electrode configuration as shown in Fig.4. Inclination *n* of V-t characteristics results in 15-32 for LHe and 8-27 for LN_2, respectively. Compared with n=38-58 for insulating oil [22], the values are rather small. It seems to be caused by the fact that cryogenic coolants at atmospheric pressure generate more bubbles than insulating oil because of the lower latent heat. In the future, it will be necessary to obtain V-t characteristics based on composite insulation system in consideration of electrode covering. In this case, V-t characteristics of not only breakdown but partial discharge inception become important.

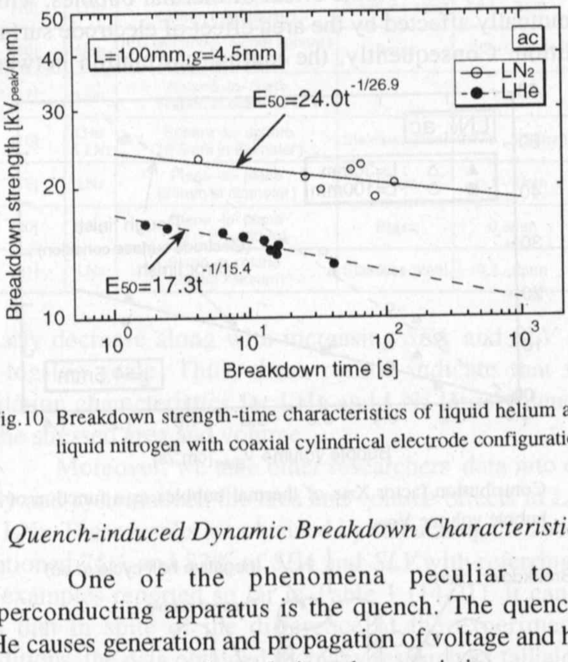


Fig.10 Breakdown strength-time characteristics of liquid helium and liquid nitrogen with coaxial cylindrical electrode configuration.

E. Quench-induced Dynamic Breakdown Characteristics

One of the phenomena peculiar to the superconducting apparatus is the quench. The quench in LHe causes generation and propagation of voltage and heat. Hence, the "dynamic" insulation characteristics caused by the quench in addition to the conventional "static" insulation characteristics should be understood when we consider the electrical insulation of superconducting apparatus. The dynamic breakdown takes place with a lower voltage than the static breakdown voltage because of the quench-induced disturbance.

We have investigated the dynamic breakdown characteristics of LHe induced by the quench of superconducting wires exposed to high electric field under the plane electrode [10]. Figure 11 shows the static breakdown voltage V_s and dynamic breakdown voltages V_d of LHe as a function of gap length for different thermal energy generated after the quench of superconducting wires. In our experiment, the thermal energy varied with both prospective current without quench and specification of superconducting wires #1 - #3, e.g. matrix ratio (NbTi : Cu : CuNi) is different. Moreover, Fig.12 shows reduction of breakdown voltage (V_d/V_s) as a function of (1/gap length) for different thermal energy due to quench of superconducting wires. It is verified from Fig.12 that, under a certain condition, the dynamic breakdown voltage may reduce to 20% or even less than that of the static one due to quench. The reduction of breakdown voltage under the quench condition depends on not only gap length and electric field distribution but also generation and propagation properties of the quench along the superconducting wire,

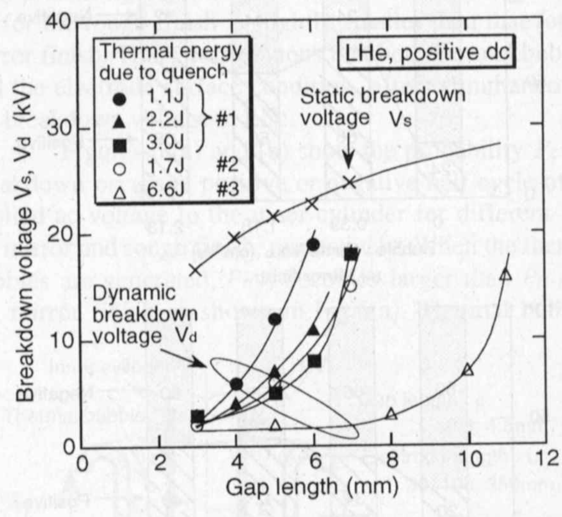


Fig.11 Static and dynamic breakdown voltages of liquid helium as a function of gap length for different thermal energy generated after the quench of superconducting wires.

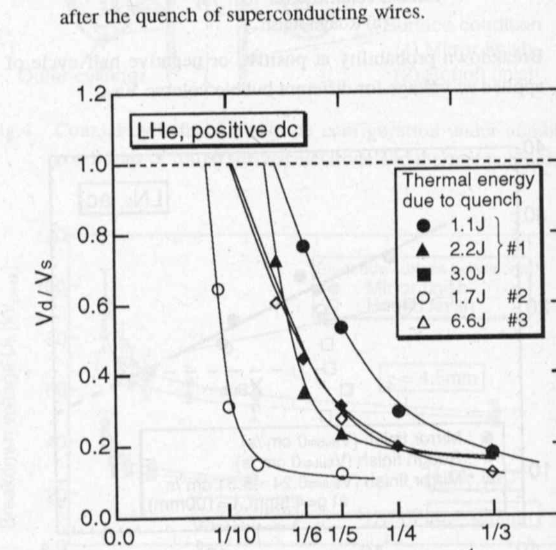


Fig.12 Reduction of breakdown voltage (V_d/V_s) as a function of (1/gap length) for different thermal energy generated after the quench of superconducting wires.

together with the related bubbles. Moreover, from measurements of partial discharge during the process from quench-onset to dynamic breakdown, it is found that the dynamic breakdown of LHe was induced by partial discharge associated with the bubble behavior after quench. Thus, the quench-induced dynamic breakdown should be considered for the practical insulation of superconducting power apparatus.

III. HIGH VOLTAGE INSULATION FOR SUPERCONDUCTING POWER APPARATUS

A. Factors for Cryogenic Insulation Design

It is necessary to consider many factors including the area and volume effects for high voltage insulation design of the superconducting apparatus using cryogenic liquids. The factors are given as follows.

(1) Area and volume effects : As mentioned above, *SEA* and *SLV* where the electric field exceeds 75% of maximum electric field strength for LHe and 82% for LN_2 should be considered. As shown in Figs.2 and 3, the breakdown strength in LHe and LN_2 should be discussed with the area and volume effects.

(2) V-t characteristics : The breakdown voltage of cryogenic liquids may depend on time as shown in Fig.10. Thus, it is inevitable for an appropriate insulation design to investigate V-t characteristics statistically using the Weibull distribution. In particular, prime importance is short-time characteristics in relation to the testing voltage of power apparatus, and long-time ones concerning the reliability control.

(3) Composite insulation characteristics : For the practical superconducting apparatus, in particular, the transformer which is expected to be operated with high voltage as shown in Fig. 1, composite insulation configuration such as barrier insulation will be applied. Thus, it is necessary to survey the composite insulation characteristics including creepage discharge and the effect of electrode covering. However, very few systematic data for the composite insulation characteristics at cryogenic temperature have been so far reported, and their mechanisms should be clarified. In particular, partial discharge characteristics are more important than breakdown characteristics for the composite insulation.

(4) Considerations peculiar to cryogenic liquids : For the practical operation of superconducting power apparatus, it is necessary to examine the factors peculiar to cryogenic liquids, as follows:

(i) Thermal bubble or impurity
(ii) Electrode surface condition
(iii) Quench-induced dynamic breakdown.

We discussed these factors in Chapter II.

(5) Breakdown scattering : In general, breakdown scattering of liquid is larger than that of gas. Thus, it is necessary to consider the breakdown margin by understanding the breakdown scattering. The breakdown scattering can be estimated from the Weibull shape parameter m. In our experiments, m for sphere-to-plane electrode is smaller than that for coaxial cylindrical electrode in both LHe and LN_2 [9,11], since it may be affected by the electric field distribution and the breakdown stress level and so on. Thus, one needs to consider the dependence of m on the electric field level and the distribution.

B. Flow Chart for High Voltage Insulation of Cryogenic Liquids

Figure 13 shows a flow chart for the high voltage insulation design of superconducting apparatus by cryogenic liquids taking into account the factors given in the previous section. At first, the electric field calculation is carried out for the determination of the specification of apparatus (electrode configuration, gap length and so on). Next, in part (a) in Fig.13, a breakdown stress level is evaluated from the viewpoints of the area and volume effects, together with the creepage discharge characteristics at the interface of cryogenic liquids/solid insulators. In part (b) in Fig.13, the V-t characteristics are considered. For the practical

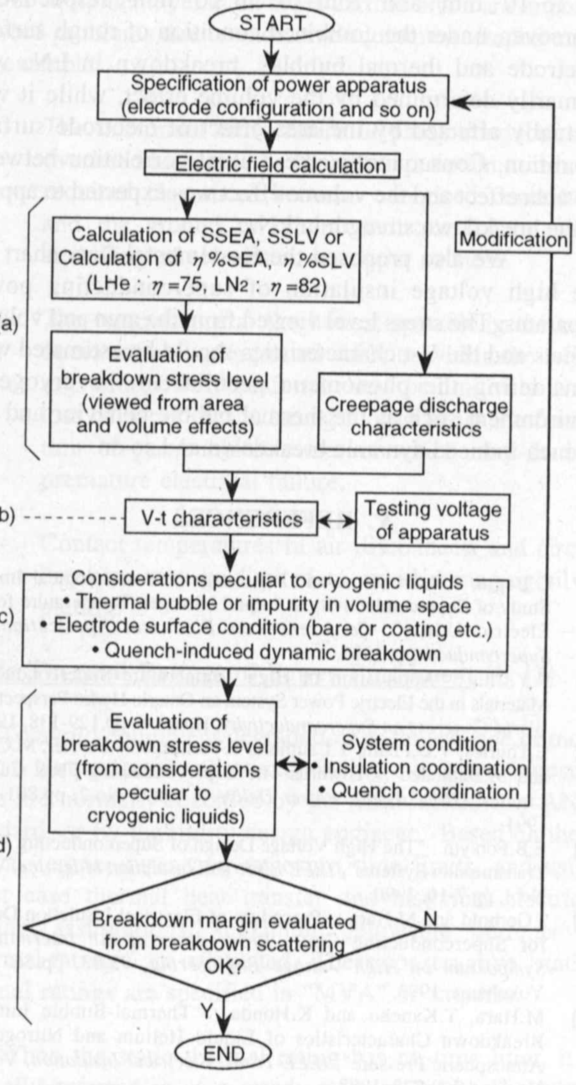


Fig.13 Flow chart for high voltage insulation of superconducting apparatus by cryogenic liquids.

electrical insulation, it is necessary to examine the factors peculiar to cryogenic liquids as listed in part (c) besides the area and volume effects, the V-t characteristics and so on.

For the breakdown stress level evaluated from the considerations peculiar to cryogenic liquids, some sort of coordination with system conditions should be considered. Moreover, the breakdown margin should be determined from the breakdown scattering. The procedure falls in part (d) in Fig.13. Through the above discussion in Fig.13, the high voltage insulation design of superconducting power apparatus may be completed for practical use.

IV. CONCLUSIONS

In this paper, we investigated the electrical insulation performances of LHe and LN_2 for the practical insulation design of superconducting power apparatus and systems. The area and volume effects on the breakdown strength in LHe and LN_2 were systematized over a wide range of the stressed electrode area and liquid volume: from 10^0 to 10^5 mm^2 and from 10^{-1} to 10^5 mm^3, respectively. Moreover, under the combined condition of rough surface electrode and thermal bubbles, breakdown in LN_2 was primarily determined by the volume effect, while it was mutually affected by the area effect of electrode surface condition. Consequently, the mutual correlation between the area effect and the volume effect was expected to appear in the breakdown strength in LN_2.

We also proposed the fundamental flow chart for the high voltage insulation of superconducting power apparatus. The stress level viewed from the area and volume effects and the V-t characteristics should be estimated with considering the phenomena peculiar to the cryogenic environment such as the thermal bubble behavior and the quench-induced dynamic breakdown and so on.

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