# Electrical Insulation Characteristics and Mechanisms of Low Dielectric Loss Materials for High-Voltage HTS Cables

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***Abstract*—Toward the practical development of high-voltage high-temperature superconducting (HTS) cables, high electrical insulation characteristics and low dielectric loss become important. Dielectric loss drastically increases with the increase of operation voltage of HTS cables. Therefore, it is highly expected to find a novel insulating material with low dielectric loss for the high-voltage HTS cables. We have focused on Tyvek®, polyethylene (PE) nonwoven fabric, and Tyvek®/PE, a syntactic paper bonding PE-sheet on Tyvek® by heat, as low dielectric loss materials. In this paper, we investigated fundamental partial discharge (PD) inception characteristics and their mechanisms of Tyvek® immersed in liquid nitrogen ($LN_2$). In addition, we compared the electrical insulation characteristics of Tyvek®, Tyvek®/PE, and polypropylene laminated paper (PPLP®), and discussed their mechanisms.**

***Index Terms*—electrical insulation, liquid nitrogen, superconducting cables, porous paper, dielectric loss**

## I. Introduction

HTS power transmission and distribution cables have been developed in the world [1]–[2]. Especially, for the transmission cables, a 275 kV HTS cable has been developed in Japan [3]. As one of the technical problems of such high-voltage HTS cables, high electrical insulation characteristics and low dielectric loss become crucial. For the electrical insulation structure of the HTS cables, $LN_2$ / PPLP® composite insulation system has been adopted. In the case of the Japanese 275 kV HTS cable, the dielectric loss (0.6 W/m) is three times larger than AC loss (0.2 W/m). This is attributed to the high operation voltage, the high relative permittivity ($\varepsilon_r$) and dielectric loss tangent ($\tan\delta$) of PPLP®. Therefore, a novel insulating material with high insulation characteristics and low dielectric loss is required, instead of PPLP®, for the high-voltage HTS cables.

From the above background, we have focused on DuPont™ Tyvek® with porous structure as the low dielectric loss material [4]. The dielectric loss factor $\varepsilon_r\tan\delta$ of Tyvek® is 20% of that of PPLP®. However, the insulation characteristics of Tyvek® are poor due to its porous structure. Therefore, we have also proposed Tyvek®/PE. Tyvek®/PE has exhibited the same level of partial discharge inception strength in $LN_2$ as that of PPLP®. However, the electrical insulation characteristics and mechanisms of Tyvek® and Tyvek®/PE have not yet been enough understood.

In this paper, we investigated the fundamental insulation characteristics of Tyvek® calendared with different thickness and void ratio in $LN_2$. We discussed the partial discharge (PD) and breakdown (BD) characteristics of Tyvek®, Tyvek®/PE and PPLP®, focusing on the void ratio and $LN_2$ volume in each porous insulating material.

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## II. Experimental Setup and Methods

Fig. 1 shows the experimental setup. The cryostat has a FRP capacitor bushing, which is PD free at 150 $kV_{rms}$ in $LN_2$. The test sample configuration is shown in Fig. 2. The insulating materials were sandwiched between parallel plane electrodes, and immersed in $LN_2$ at 77 K and 0.1 MPa. AC high voltage of 60 Hz was applied to the test sample at the increasing rate of 1 $kV_{rms}$/s in order to obtain PD inception voltage (PDIV) and BD voltage (BDV). The PDIV was repeatedly measured 20 times at the same condition, and PDIV with 50% probability (50% PDIV) was calculated by the Weibull analysis. We varied electrode diameter (40-70 mm), stack number (4-16 sheets) and void ratio (24.6-53.6%) of Tyvek® and Tyvek®/PE by calendaring.

Specifications of the test samples are shown in TABLE I. The void ratio $\alpha$ (%) is defined as the volume ratio of voids in the test sample with porous structure. In addition, when the test sample is immersed in $LN_2$, the voids are filled with $LN_2$. Then, the $LN_2$ volume $V$ ($mm^3$) inside the test sample can be obtained with $\alpha$, as follows;

$$\alpha = 1 - M/(\rho \cdot t) \quad (1)$$

$$V = \alpha \cdot n \cdot t \cdot S \quad (2)$$

where $M$ is the basis weight ($g/mm^2$), $\rho$ is the true density of material ($g/mm^3$), $t$ is the thickness (mm), $n$ is the stack number, and $S$ is the electrode area ($mm^2$).

Fig. 3 shows the calculation model of test samples immersed in $LN_2$ for electric field analysis. Test samples immersed in $LN_2$ were simplified to layered structural models of sheet materials and $LN_2$. The measured 50% PDIV and BDV were converted into electric field strength, i.e. 50% PD inception electric field strength (50% PDIE) and BD electric field strength (BDE) in $LN_2$, taking into account the relative permittivity of each material.

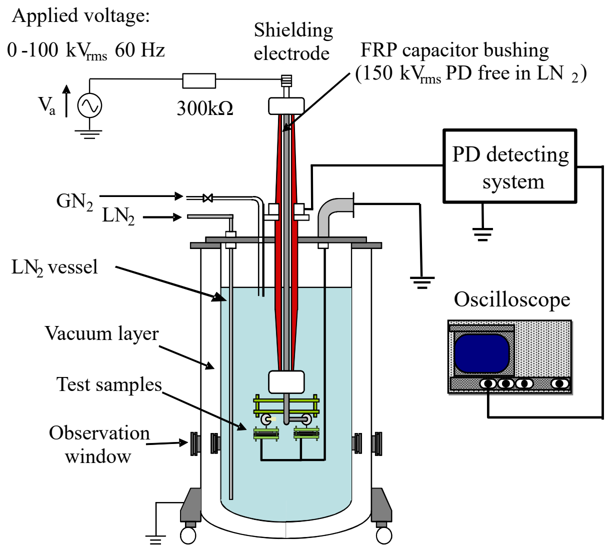


Fig. 1  Experimental setup

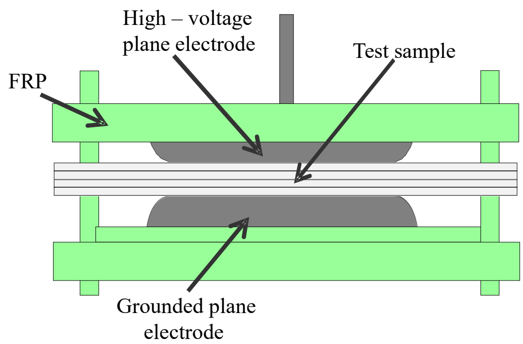


Fig. 2  Test sample configuration

TABLE I  SPECIFICATIONS OF TEST SAMPLES

| Material | Tyvek® | Tyvek®/PE | PPLP® |
|---|---|---|---|
| Thickness $t$ [mm] | 0.097 – 0.163 | 0.131 – 0.137 | 0.115 – 0.117 |
| Basis weight $M$ [g/mm$^2$] | (6.38 – 7.76) $\times 10^{-5}$ | (8.32 – 9.85) $\times 10^{-5}$ | $1.10\times 10^{-4}$ |
| Stack number $n$ | 4 - 8 | 4 - 16 | 4 - 16 |
| Area of electrode $S$ [mm$^2$] | (1.25 – 3.85) $\times 10^3$ | (1.52 – 3.85) $\times 10^3$ | (1.25 - 3.85) $\times 10^3$ |
| Void ratio $\alpha$ [%] | 24.6 – 53.6 | 21.8 – 35.6 | 13.8 – 21.0 |
| $LN_2$ volume $V$ in test sample[mm$^3$] | 152 – 2376 | 205 – 2918 | 102 – 1511 |

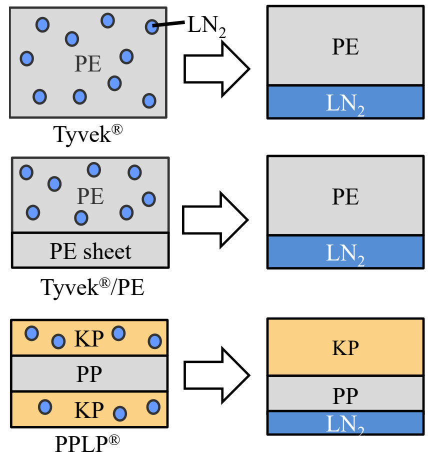


Fig. 3  Calculation models of test samples immersed in $LN_2$ for electric field analysis

## III. EXPERIMENTAL RESULTS AND DISCUSSION

### *A. Void Ratio and $LN_2$ Volume Dependence of PDIE of Tyvek®*

Fig. 4 shows the void ratio dependence of 50% PDIE of Tyvek® for different electrode diameter (ϕ = 40, 70 mm). The error bars represent the standard deviation. In Fig. 4, 50% PDIE decreased with the increase in the void ratio. This is attributed to the increase in the number of microscopic bubbles in the voids, i.e. $LN_2$, which can be the weak points of electrical insulation. However, the trend of reduction of 50% PDIE depends on the electrode diameter. This means that 50% PDIE of Tyvek® is determined not only by the void ratio, but also the electrode diameter, i.e. $LN_2$ volume.

Then, the $LN_2$ volume dependence of 50% PDIE of Tyvek® is shown in Fig. 5. In this figure, 50% PDIE decreased with the increase in the $LN_2$ volume on the same approximate line, irrespective of the electrode diameter and the stack number of Tyvek®. This means that the $LN_2$ volume in Tyvek® is decisive for 50% PDIE of Tyvek® in $LN_2$, which can be interpreted by the volume effect [5].

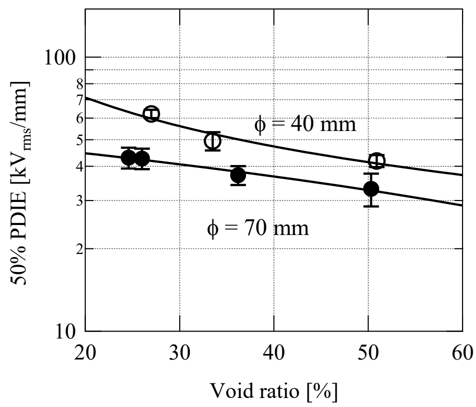


Fig. 4  Void ratio dependence of 50% PDIE of Tyvek® in $LN_2$ for different electrode diameters

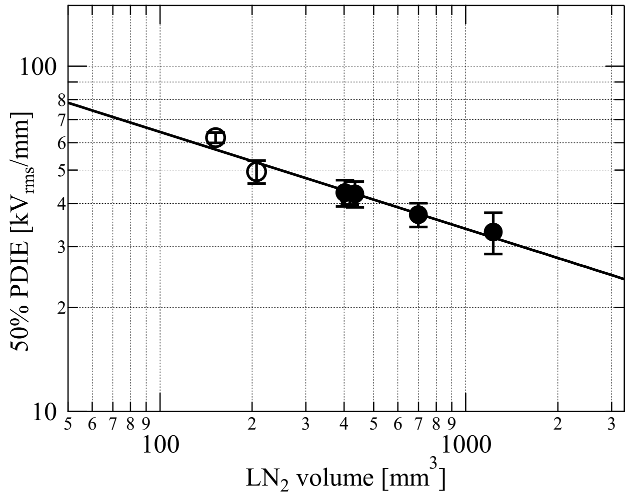


Fig. 5 50% PDIE as function of $LN_2$ volume in Tyvek® immersed in $LN_2$

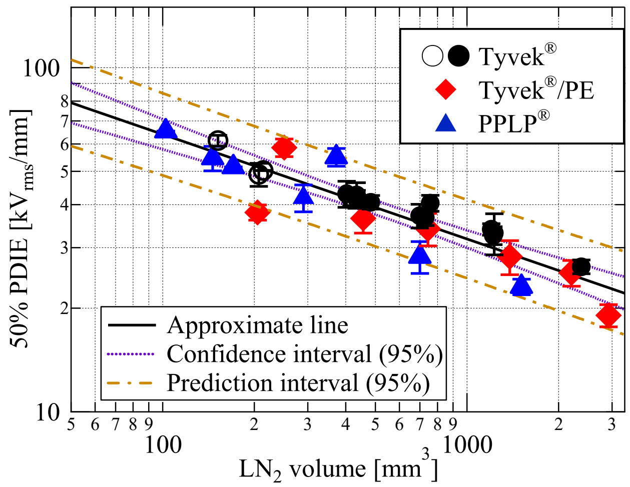


Fig. 6 50% PDIE as a function of $LN_2$ volume for different porous papers in $LN_2$

## B. $LN_2$ Volume Dependence of PDIE of Various Insulation Papers

Fig. 6 shows the $LN_2$ volume dependence of 50% PDIE of various insulation papers: Tyvek®, Tyvek®/PE and PPLP®. The confidence interval and prediction interval of 50% PDIE mean the dispersion of approximate line and plots, respectively. 50% PDIE of various insulation papers decreased on the same approximate line with the increase in the $LN_2$ volume, irrespective of the void ratio, stack number, electrode diameter and insulation paper. This result verifies that PDs occur in $LN_2$ in the voids of insulation papers with porous structure.

Fig. 7 shows the schematic illustration of volume effect on 50% PDIE of insulation papers immersed in $LN_2$ for different void ratio, stack number and electrode diameter. When these parameters increase, the $LN_2$ volume including the micro bubbles as the weak points of electrical insulation also increases. Therefore, the PD occurrence probability becomes high, i.e. 50% PDIE decreases. From the above mechanism of PD occurrence, PD inception characteristics depend on the volume effect.

When the insulation papers of HTS cable are wound, butt gaps are formed and filled with $LN_2$. Then, 50% PDIE of insulation papers with butt gaps [6] were added and evaluated in Fig. 8. In this figure, the approximate line, confidence interval and prediction interval are the same as those in Fig. 6. The $LN_2$ volume in Fig. 8 includes the butt gap volume, however the ratio of the butt gap volume is quite small in the total $LN_2$ volume. Therefore, the 50% PDIE of test samples with butt gap decreased on the same approximate line as that in Fig. 6 with the increase in the $LN_2$ volume including the butt gap volume. In addition, we confirmed that the other researchers' data [7] could also be plotted within the prediction interval in Fig. 8. These results mean that electrical insulation of HTS cables requires the consideration of the $LN_2$ volume in the insulation papers, especially in the case with porous structure.

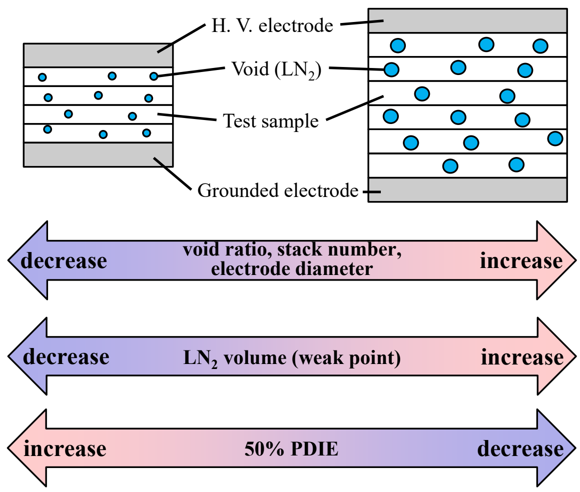


Fig. 7 Schematic illustration of volume effect in porous papers immersed in $LN_2$

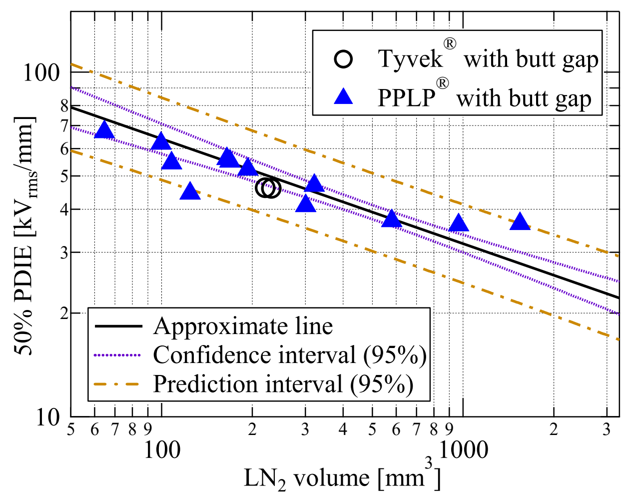


Fig. 8 50% PDIE as a function of $LN_2$ volume for different porous papers with butt gaps in $LN_2$

### C. $LN_2$ Volume Dependence of BDE of Tyvek®

Fig. 9 shows $LN_2$ volume dependence of BDE of Tyvek®. In this figure, the approximate line of 50% PDIE is the same as that in Fig. 6. BDE of Tyvek® also decreased with the increase in the $LN_2$ volume, i.e. volume effect. In addition, the decrease in BDE is steeper than that of 50% PDIE, and the approximate lines of 50% PDIE and BDE are asymptotic with the increase in the $LN_2$ volume. It should be noted that the breakdown of Tyvek® might be induced without partial discharge in the large $LN_2$ volume of electrical insulation layers of HTS cables.

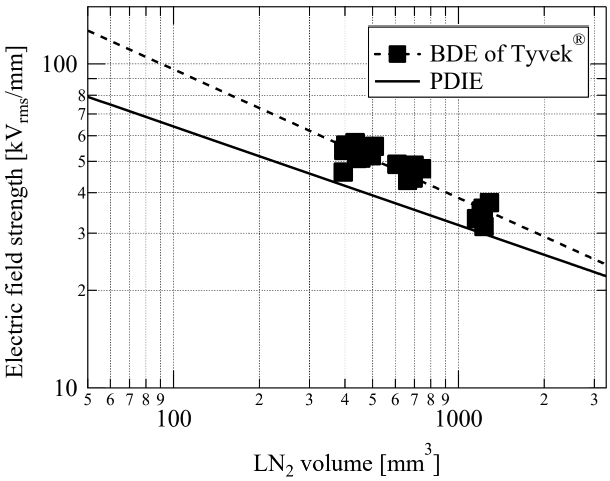


Fig. 8 Comparison of 50% PDIE and BDE of Tyvek® in $LN_2$

## IV. CONCLUSION

This paper described the electrical insulation characteristics and mechanisms of Tyvek® as the porous insulation paper with low dielectric loss factor for high-voltage HTS cables. The main results in this paper can be summarized as follows:

1. 50% PDIE of Tyvek® immersed in $LN_2$ decreased with the increase in the void ratio and the $LN_2$ volume in Tyvek®. This is because of the increase in the number of microscopic bubbles in the voids, i.e. $LN_2$, which can be weak points of electrical insulation.
2. 50% PDIE of Tyvek®, Tyvek®/PE and PPLP® decreased on the same approximate line with the increase in the $LN_2$ volume in each insulation paper. This result verifies that the PDs occur in $LN_2$ in the voids of insulation papers with porous structure.
3. The decrease in BDE of Tyvek® is steeper than that of 50%PDIE. Both approximate lines of BDE and 50% PDIE are asymptotic with the increase in the $LN_2$ volume.

The above electrical insulation characteristics and mechanisms of porous insulation papers will contribute to the rational and reliable insulation design, as well as the dielectric loss reduction for the development of high-voltage HTS cables.

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