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Upon notification and agreement from all co-authors, it has been brought to our attention that one author was unintentionally omitted from the original publication. The following author has now been officially added to the author list:

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Contribution: Contributed to execution of experiments and data collection.

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Electric Field Analysis of XLPE Under Normal and Contamination Conditions Using Comsol Multiphysics

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Abstract

Cross-linked polyethylene (XLPE) cables are extensively used for power transmission and distribution due to their superior resistance to heat, moisture, and chemicals, making them ideal for challenging environments such as underground or underwater installations. However, power cables carrying over 100kV often face technical issues, including ageing, mechanical failures, insulation moisture, and current overloading, which can degrade the dielectric strength of XLPE cables over time. This study aims to determine the mass and relative permittivity of XLPE under normal and contaminated conditions and to analyze the electric field intensity characteristics using COMSOL Multiphysics software. Four samples were examined: Sample 1 (Virgin XLPE), Sample 2 (XLPE + Distilled Water), Sample 3 (XLPE + Distilled Water + Iron Oxide), and Sample 4 (XLPE + Distilled Water + Calcium Carbonate), with the latter three immersed in distilled water. Using Keysight 16451B, relative permittivity values were measured, and electric field intensities were simulated with COMSOL Multiphysics. Results indicated that Sample 1 (Virgin XLPE) exhibited the highest electric field intensity at 4.7453 MV/m in the sphere-sphere configuration, while Sample 2 recorded 4.7054 MV/m, Sample 3 showed 4.7104 MV/m, and Sample 4 had 4.7196 MV/m. These findings suggest that the maximum electric field intensity is influenced by the permittivity of the XLPE, with variations attributed to the presence of moisture and other materials, altering the dielectric properties and causing localized oscillations in the electric field distribution. This study underscores the importance of environmental factors in applying and maintaining XLPE cables, highlighting the need for regular monitoring and assessment to ensure optimal performance and longevity.

1. Introduction

In the electrical system, high-voltage (HV) insulators are crucial components. The primary function of these insulators is preventing the undesired current flow by harnessing their dielectric strength, which is the capacity to withstand HV levels without allowing conduction [1]. In addition, the HV insulator is crucial to ensure the reliable and safe operation of power transmission and distribution systems to prevent undesired events such as electrical breakdowns and disruptive discharges, such as arcs and sparks, that could lead to system failures or damage.

As the name indicates, insulators are used for outdoor applications, such as in HV contexts. For instance, overhead insulators serve a few purposes, which include supporting wires mechanically and protecting the electrical distribution network [1]. Each type of insulator offers different technical characteristics: the electrical field and the permittivity values. Tenaga Nasional Berhad (TNB) uses other insulators in Malaysia, considering surrounding factors, such as weather and geology.

Cross-linked polyethene (XLPE) cable is an electrical cable extensively used for power transmission and distribution. Because XLPE cable is constructed of a thermoset substance, it is highly resistant to heat, moisture, and chemicals. This makes it an excellent alternative for applications involving extreme environmental conditions, such as underground or underwater installations [2,3].

Malaysia's most frequent underground power cables are XLPE. XLPE cable is widely used in various applications, including power distribution in buildings, industrial facilities, and utility grids. It is available in multiple sizes and configurations, including single-core, multi-core, and screened cables [3]. XLPE cable is helpful in plumbing, mining, and various electrical applications. XLPE cables are widely used in the chemical and commercial and domestic heating industries.

Nevertheless, the power cables that carry more than 100kV sometimes have technical limitations, leading to faults. The fault happens for many reasons, including ageing, mechanical failure, moisture in the insulation, and current overloading [4]. In Malaysia, for instance, the flood that hit Peninsular Malaysia caused losses of more than RM6.1 billion, as reported by Sinar Harian on 23rd February 2023 [5]. This event could indirectly affect the XLPE power cable underground throughout the year, leading to a fault or short circuit. Thus, this could affect the dielectric strength of the cable [6].

Therefore, this research has been conducted using COMSOL Multiphysics to investigate the electric field analysis of XLPE under normal and contamination conditions.

2. Research Methodology

This chapter sections the methodology for conducting research and ensuring its successful completion. Meticulous planning and preparation are crucial for achieving research objectives. The experiments were conducted in the Electronic Physics Laboratory at UTHM Pagoh. A detailed discussion on simulating the electrical field distribution using COMSOL Multiphysics is also provided.

2.1 Sample Absorption Process

Referring to Table 1, the medium used for the experiment included Distilled Water, Iron Oxide, and Calcium Carbonate. Initially, the weight of all samples was measured before the immersion process. Throughout the experiment, the weight of the XLPE sample is anticipated to increase as XLPE tends to absorb moisture progressively.

Table 1 *Conditions of the sample*

Sample	Conditions of the sample
Sample 1	Virgin XLPE
Sample 2	XLPE + Distilled Water
Sample 3	XLPE + Distilled Water + Iron Oxide
Sample 4	XLPE + Distilled Water + Calcium Carbonate

Every sample was in a transparent container, securely sealed with a lid. Furthermore, a strip of tape was attached to the lid to distinguish between the samples. The impurity and water absorption strongly affect the material's dielectric response [9]. Fig. 1 illustrates the samples immersed under different conditions.

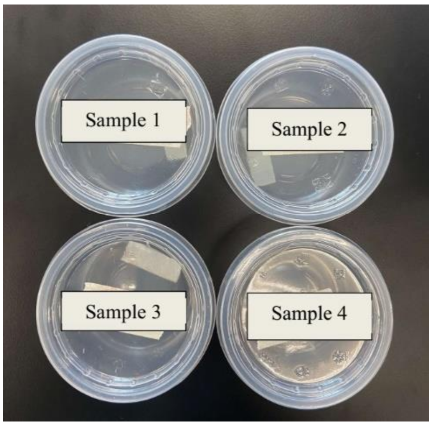


Fig. 1 *Sample in different conditions*

There are several methods for evaluating the water absorption of solid materials. The simplest and quickest method involves measuring the increase in the mass of specimens by weighing them. First, each specimen's initial mass (M0) is recorded before immersion in water. Over a 100-day period, the increase in mass (ΔM) is periodically monitored. The moisture content (M) within the specimens is determined by calculating the difference between the initial mass (M0) and the gained moisture (ΔM). Equation (1) provides the formula to calculate the percentage of water absorption.

$$M = \frac{\Delta M}{Mo}\, x\, 100 = \frac{M - Mo}{Mo}\, x\, 100 \tag{1}$$

2.2 Relative Permittivity Test

This section outlines the procedure for conducting a relative permittivity test using Dielectric Test Fixture 16451B. First, the sample's thickness is measured with a digital calliper. The sample is then placed between two electrodes, ensuring there are no air gaps to maintain accuracy. Fig. 2 illustrates the sample's placement between the electrodes in the dielectric test fixture. The relative permittivity, which varies for each sample, is crucial for estimating a model's electric field. The dielectric constant of the samples is measured using the Keysight 16451B Dielectric Test Fixture.

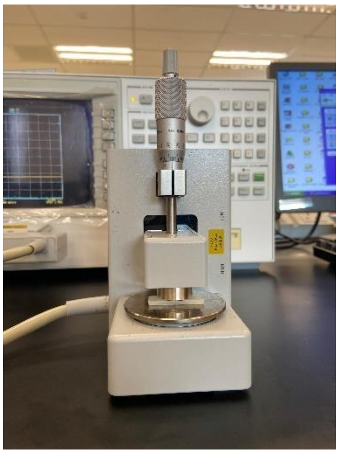


Fig. 2 *Sample in different conditions placed between the electrode of the test fixture*

2.3 Electrode Configuration

Fig. 3 illustrates the configuration of a cylindrical aluminium electrode, designed according to the IEC 60243-1 standard using COMSOL Multiphysics software [3]. The rectangular sample, with a diameter of 30 mm and a thickness of 2 mm, is positioned between two electrodes. Each cylindrical electrode measures 25 mm in diameter. The top electrode is supplied with a high voltage of 10 kV, while the bottom electrode serves as the ground.

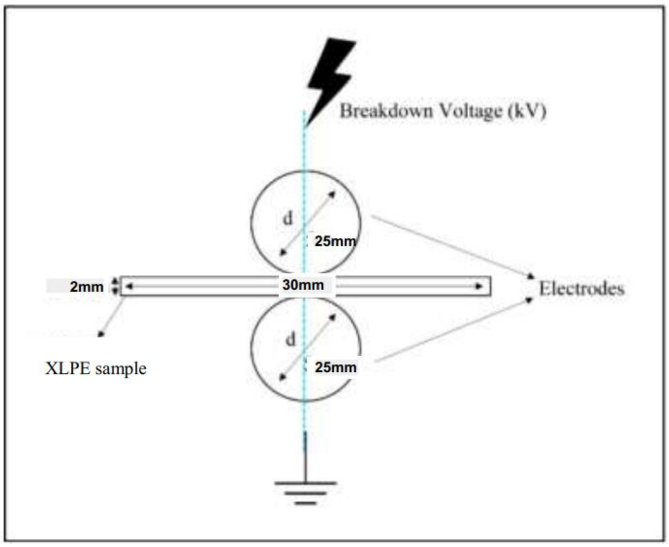
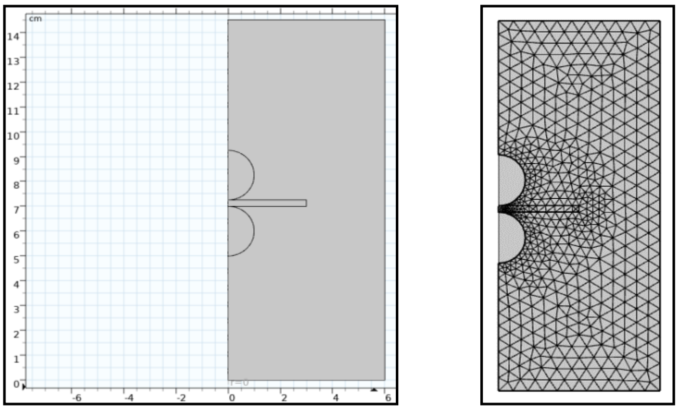


Fig. 3 *Electrode configuration for sphere-sphere aluminium electrode*

2.4 Development Of Electrostatic Model Using COMSOL Multiphysics

Fig. 4(a) displays the final electrode configuration designed using COMSOL Multiphysics software. The pressure chamber is a rectangle measuring 6 cm in width and 14.5 cm in length, accommodating the sphere-sphere aluminium electrode. This dimension was chosen to accurately replicate the actual experimental condition in the lab. The sphere is 25 mm in diameter the top side indicates the high-voltage terminal, and the bottom side represents the ground terminal. The rectangular sample has a diameter of 30 mm and a width of 2 mm. Fig. 4(b) shows the mesh for the sphere-sphere electrode, utilising a finer mesh. This finer mesh, comprising more and smaller elements, allows for a more accurate representation of the geometry and field distribution.



(a) **(b)**

Fig. 4 *Electrode configuration for sphere-sphere aluminium electrode*

3. Result and Discussion

This section presents the results of the electric field intensity in XLPE. These results were obtained through simulations using COMSOL Multiphysics software. The sample's voltage and electric field distribution were analysed, with observations and comparisons made for each sample. Detailed discussions cover the percentage of water absorption, relative permittivity, and electric field intensity.

3.1 Percentage of Water Absorption

Fig. 5 shows the water absorption percentage over a 100-day period. It demonstrated that Sample 1 reached saturation in 60 days, followed by Sample 2 at 70 days, Sample 3 and Sample 4 at 90 days. The result indicates that Sample 3 and Sample 4 took longer to reach saturation than Sample 1 and Sample 2. Therefore, it can be concluded that addition of additive can prolong the duration of saturation of the sample.

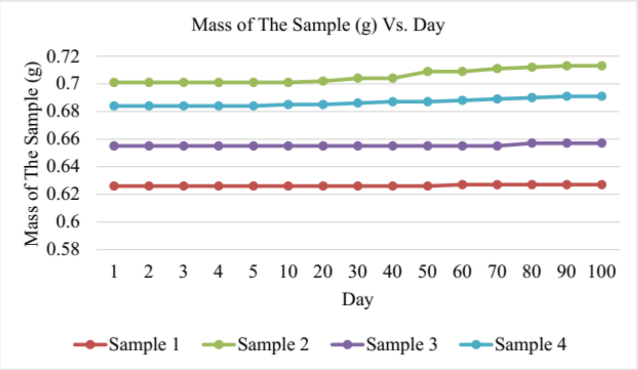


Fig. 5 *Graph Mass of the sample (g) Vs. day*

3.2 Relative Permittivity of The Sample

Table 2 shows the relative permittivity of the samples under normal and contaminated conditions. Sample 1 is uncontaminated, whereas sample 2, sample 3 and sample 4 contain contaminants. The presence of contaminants in samples 2, sample 3 and sample 4 results in higher relative permittivity compared to normal conditions. This shows that water absorption can modify the properties of the sample, leading to higher relative permittivity.

Table 2 *Permittivity value for electric field computation*

Sample	Conditions of the sample	Relative Permittivity
Sample 1	Virgin XLPE	2.6461
Sample 2	XLPE + Distilled Water	2.4909
Sample 3	XLPE + Distilled Water + Iron Oxide	2.5101
Sample 4	XLPE + Distilled Water + Calcium Carbonate	2.5461

3.3 Voltage And Electric Field Distribution

Fig. 6 illustrates the voltage distribution with a legend for the voltage density plot in a sphere-sphere electrode configuration. The voltage density plot employs a rainbow colour map to depict the voltage distribution across the model. A voltage of 10 kV is applied to the top electrode, while the bottom electrode serves as the ground. A sample, tested under normal and contaminated conditions, is placed between the rod electrodes.

The top electrode is depicted in dark red, indicating high voltage and strong electric field intensity, while the bottom electrode is shown in blue, representing the ground with the lowest voltage [6]. The colour map also highlights the presence of the sample, with a white area appearing between the electrodes. This white area signifies the voltage and electric field distribution not penetrating the sample positioned between the electrodes.

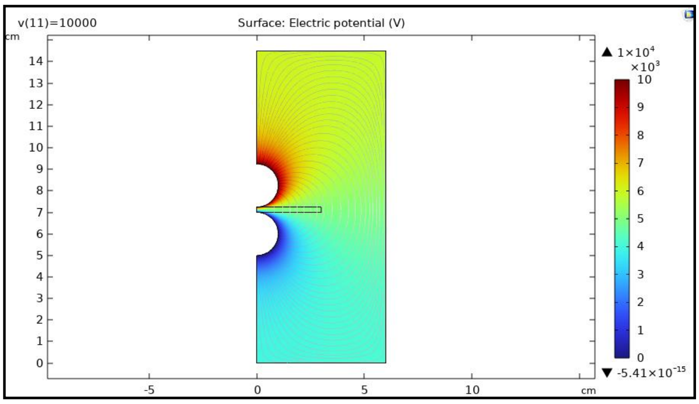


Fig. 6 *Voltage distribution and legend for the voltage density plot*

Fig. 7, Fig. 8 and Fig. 9 display a curve representing the maximum and minimum electric field intensities between the sphere-sphere aluminium electrodes. The highest electric field intensity occurs at the surfaces of the top and bottom electrodes, while the lowest intensity is observed at the centre of the dielectric sample [7]. This analysis indicates that the electric field intensity increases near the surfaces of the electrodes. As the distance from the electrodes increases, the electric field becomes more distributed, leading to a decrease in intensity in the middle of the sample and an increase again near the bottom electrode [8,9]. Consequently, the graph exhibits a 'U' shape.

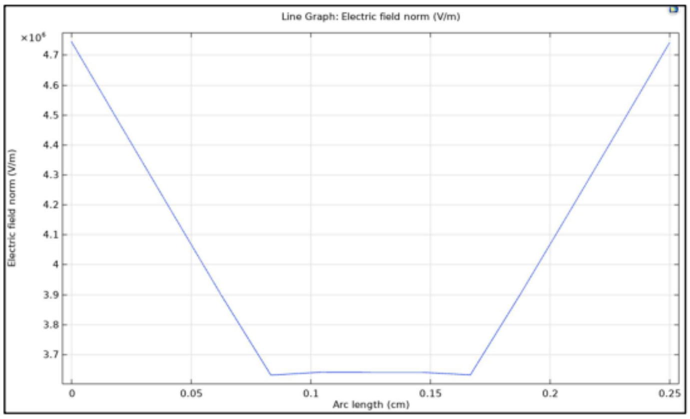


Fig. 7 *The graph for electric field intensity versus length*

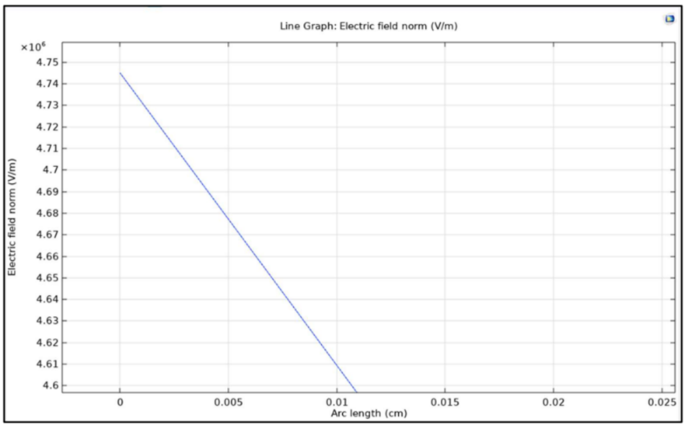


Fig. 8 *The graph for maximum electric field intensity versus length*

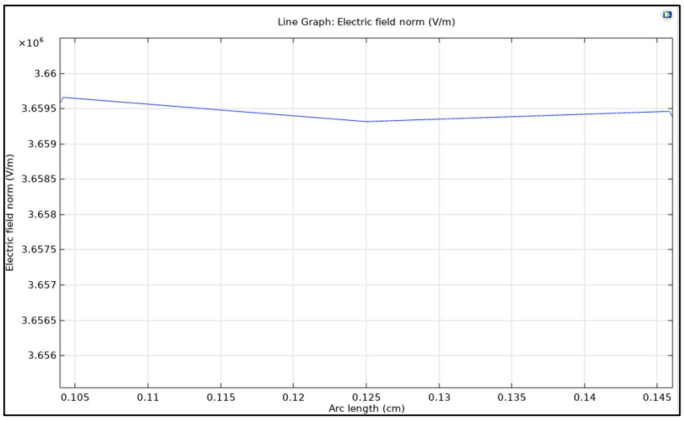


Fig. 9 *The graph for minimum electric field intensity versus length*

3.4 Electric Field Distribution Simulation Result

Table 3 presents the maximum and minimum electric field intensities for XLPE under two conditions: normal and contaminated. The relative permittivity of the samples varied for each experiment. The data revealed that as the relative permittivity of XLPE decreased, the maximum electric field intensity also decreased. Sample 1, virgin XLPE, exhibited the highest maximum electric field intensity among all the samples. In contrast, Sample 2 showed the lowest maximum electric field intensity compared to Sample 1, Sample 3, and Sample 4.

Table 3 *Electric Field Intensity under normal and contamination conditions*

Sample	Relative Permittivity	Minimum Electric Field, Emin (MV/m)	Maximum Electric Field, Emax (MV/m)
Sample 1	2.6461	3.6409	4.7453
Sample 2	2.4909	3.6592	4.7054
Sample 3	2.5101	3.657	4.7104
Sample 4	2.5461	3.6527	4.7196

4. Discussion and Analysis

Each XLPE sample has an individual permittivity value [10]. The electric field's intensity decreases with increasing distance from the source [10]. The top electrode has the most vigorous electric field intensity since it receives the most extensive voltage supply, while the bottom electrode has a weaker electric field intensity. Note that blue contours indicate low electric field intensity, while red outlines indicate high electric field intensity. This can be used to illustrate the point. Interestingly, the top electrode, which receives the highest voltage supply, and the vicinity of the sphere gap have significantly larger electric field intensities.

As previously mentioned, the XLPE sample's relative permittivity value is greatly influenced by its absorption coefficient, which in turn influences the strength of the electric field. To explore this, four distinct samples were prepared and labelled in preparation for this experiment: Sample 1 (Virgin XLPE), Sample 2 (XLPE + Distilled Water), Sample 3 (XLPE + Distilled Water + Iron Oxide), and Sample 4 (XLPE + Distilled Water + Calcium Carbonate). The experiment outcomes demonstrated how these substances' effects and the absorption process affect the XLPE samples' changes in dielectric constant. The relative permittivity value was also impacted by this modification, as shown by the subsequent findings. Consequently, the strength of the electric field was changed to have comparatively reduced relative permittivity, which has a weak effect on the electric field.

All the XLPE samples were sent to the lab for the dielectric test using the Keysight 16451B dielectric test fixture to determine their relative permittivity values. However, the relative permittivity of the samples indicated that their dielectric constants changed when they underwent the 100-day absorption process. This shows that minimal changes affect the samples' dielectric properties from absorption.

COMSOL Multiphysics was used to simulate the electric field intensity after the Keysight 16451B lab test. This simulation assists researchers and technical specialists in their specific fields of expertise with troubleshooting. This simulation confirmed that most of the electric field intensity levels in the circuit are low. In particular, the previously mentioned materials were absorbed by the XLPE sample, which caused the electric field intensity values to decrease—in comparison to Sample 1 (Virgin XLPE), which had an observed electric field intensity of 4.7453 MV/m, Sample 4 (Distilled Water and Calcium Carbonate) had an electric field intensity that was lower at 4.7196 MV/m. This result aligns with the literature review on relative permittivity , which states that virgin XLPE have higher electric field than contaminated XLPE [7].

5. Conclusion

The project's objectives were achieved through simulations conducted using the COMSOL Multiphysics tool. The primary goal was to determine the mass of XLPE under normal and contamination conditions. The sample was successfully immersed in distilled water containing iron oxide and calcium carbonate for 100 days, and its mass was determined using a weight scale. The masses of the samples are as follows: Sample 1 (Virgin XLPE) is 0.627 g, Sample 2 (Distilled Water absorption) is 0.713 g, Sample 3 (Distilled Water and Iron Oxide) is 0.657 g, and Sample 4 (Distilled Water and Calcium Carbonate) is 0.691 g. The objective of measuring the relative permittivity values of each sample has been successfully achieved using Keysight 16451B. The measured data are as follows: Sample 1 (Virgin XLPE) has a relative permittivity of 2.6461, Sample 2 (Distilled Water absorption) is 2.4909, Sample 3 (Distilled Water and Iron Oxide) is 2.5101, and Sample 4 (Distilled Water and Calcium Carbonate) is 2.5461. These relative permittivity values were then used to analyse the electric field intensity. The third objective was to investigate the electrical field intensity of XLPE under normal and contamination conditions using COMSOL Multiphysics software. COMSOL Multiphysics successfully built an axisymmetric electrostatic model with a sphere-sphere gap electrode. The simulation may examine the electric field intensity for all samples. The electric field intensity of Sample 1 (Virgin XLPE) was found to be higher compared to another based on simulation results. Sample 1 (Virgin XLPE) had a value of 4.7453 MV/m in the sphere-sphere configuration, whereas Sample 2 (Distilled Water absorption) had a value of 4.7054 MV/m, Sample 3 (Distilled Water and Iron Oxide) had a value of 4.7104 MV/m, and Sample 4 (Distilled Water and Calcium Carbonate) had a value of 4.7196 MV/m. Generally, the maximum electric field intensity depends on the permittivity of the XLPE. These differences in electric field intensities can be attributed to the presence of moisture and other materials in the samples, which cause changes in the dielectric properties and localized oscillations in the electric field distribution.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the paper's publication.

Author Contribution

The authors confirm their contribution to the paper as follows: ***study conception and design:*** *Muhammad Fakhrul Aqiuddin Mohd Nasir, Nor Akmal Mohd Jamail;* ***data collection:*** *Muhammad Fakhrul Aqiuddin Mohd Nasir;* ***analysis and interpretation of results:*** *Muhammad Fakhrul Aqiuddin Mohd Nasir, Nor Akmal Mohd Jamail;* ***draft manuscript preparation:*** *Muhammad Fakhrul Aqiuddin Mohd Nasir, Nor Akmal Mohd Jamail, Qamarul Ezani Kamarudin; All authors reviewed the results and approved the final version of the manuscript.*

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