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Effect of the electrode material on the breakdown voltage and space charge distribution of propylene carbonate under impulse voltage

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This paper reports three types of electrode materials (copper, aluminum, and stainless steel) that are used to measure the impulse breakdown voltage of propylene carbonate. The breakdown voltage of propylene carbonate with these electrode materials is different and is in decreasing order of stainless steel, copper, and aluminum. To explore how the electrode material affects the insulating properties of the liquid dielectric, the electric field distribution and space charge distribution of propylene carbonate under impulse voltage with the three electrode materials are measured on the basis of a Kerr electro-optic test. The space charge injection ability is highest for aluminum, followed by copper, and then the stainless steel electrodes. Furthermore, the electric field distortion rate decreased in the order of the aluminum, copper, and then the stainless steel electrode. This paper explains that the difference in the electric field distortion rate between the three electrode materials led to the difference in the impulse breakdown voltage of propylene carbonate. [http://dx.doi.org/10.1063/1.4948441]

I. INTRODUCTION

The insulating properties of a liquid dielectric are also affected by the distribution of the internal electric field.[1,2] The quantity and mode of space charge injection have a great effect on the electric field distribution in the liquid dielectric. It is helpful to analyze space charge injection and the breakdown mechanism in the liquid dielectric by measuring the distribution of the electric field and space charge inside the liquid dielectric. In the last century, the Kerr electro-optic effect began to be applied to the measurement of space charge in a liquid dielectric. Some research institutions measured the distribution of the electric field and space charge in a liquid dielectric with different voltage forms and found that the presence of space charge distorted the initial electric field and thus had some influence on the insulating properties of the liquid dielectric.[3–6] The quantity and mode of space charge injection with different electrode materials is different, which affects the initial electric field to a different degree and may lead to the distinction in the insulating properties of the liquid dielectric. Research has shown that there is difference in the AC and impulse breakdown voltage with different electrode materials in the liquid dielectric such as water, liquid nitrogen and transformer oil.[7–9]

Therefore, the effect of the electrode material on the insulating properties of the liquid dielectric cannot be ignored. However, the physical mechanism of the different electrode materials on the insulating properties of the liquid dielectric is not yet clear. Thus, further study on the influence of the electrode material on the liquid dielectric breakdown properties is needed. Propylene carbonate is safe and has good transmission of light. Furthermore, the Kerr effect of propylene carbonate

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is relatively significant for its high Kerr constant. In our previous works,[10–14] Kerr electro-optic measurement method is applied to investigate the space charge behaviors in liquid dielectrics such as propylene carbonate and transformer oil. Based on the space charge measurement results, the physical mechanism of space charge's effect on the breakdown process of liquid dielectrics is presented. In this paper, based on those long-term continuous studies, propylene carbonate was chosen as the liquid dielectric and copper, aluminum, and stainless steel were chosen as the electrode materials. The impulse breakdown voltage of propylene carbonate was measured with the three types of electrode materials and the difference in breakdown voltage was measured. Additionally, the electric field distribution and space charge density of propylene carbonate were measured with the three electrode materials based on the Kerr electro-optic effect to explore the effect of electrode material on the impulse insulation strength of propylene carbonate.

II. TESTING PROCEDURE

A. Impulse Breakdown Test

Three types of electrodes, namely copper, aluminum, and stainless steel, were chosen as the test electrodes. To eliminate the influence of polarity effect, a plate electrode that was $100 \times 12 \times 5$ mm^3 with a 3-mm gap between the plates was chosen. The edge of the plate electrode was polished to prevent breakdown occurring at the edge. The electric field generated between the plate electrodes was uniform in the structure of plate shown in Fig. 1.

The impulse breakdown test was based on the IEC60897 standard. There was no polarity effect between the plate electrodes, so the influence of the electrode material on the impulse breakdown voltage of propylene carbonate was measured under the negative switching impulse (250 µs/2500 µs) generated by the Marx Generator. The test started from a low voltage to ensure that the insulating medium would not break down. The voltage was then increased step by step at the speed of 1–2 kV per level until the sample broke down. To ensure the stability and reliability of the breakdown data, the increase in voltage was applied at least five times before each breakdown with the voltage kept at the same level at least three times. The time interval between the two impulses should be 1 min to ensure the stability of the sample. The oscilloscope was used to record the breakdown voltage and the breakdown time during the entire test. Each procedure mentioned above was repeated 10 times to obtain the average breakdown voltage with one electrode material. This was repeated with the other electrode materials.

B. Space Charge Measurements

To explore how the electrode material affects the impulse breakdown voltage of propylene carbonate using the breakdown test, an experimental setup (shown in Fig. 2) based on the Kerr electro-optic effect[15] was used to measure the electric field distribution and the distribution of space charge in propylene carbonate under the impulse voltage between different electrode materials.

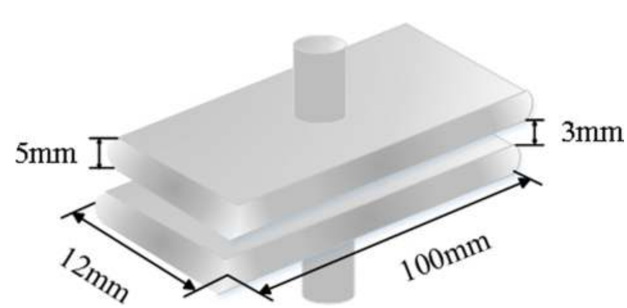

FIG. 1. The structure of the plate electrodes.

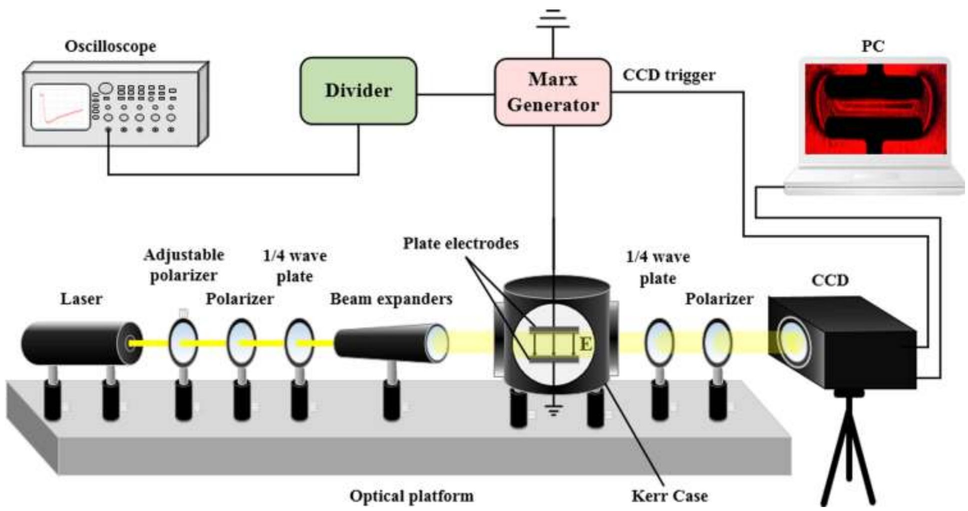

FIG. 2. The experimental setup to measure space charge in a liquid dielectric.

The measurement system is composed of three parts, which are the Kerr electro-optic effect system, the light intensity receiving system, and the Marx Generator. Linearly polarized light with a wavelength of 632.8 nm was generated by the He-Ne laser. This light passes through the adjustable polarizer, the polarizer, the quarter wave plate, the beam expander, the Kerr case, the quarter wave plate, and then the analyzer and finally is received by the high-speed CCD (Charge Coupled Device). The light intensity signal was input to the computer for data processing later. The electrodes used in the breakdown test and the space charge measurement test were the same. The Marx Generator was used to generate the impulse voltage waveform applied to the Kerr case and the trigger signal to the CCD, which causes the CCD to collect the light intensity signal after a certain time delay. The delay can be adjusted.

The voltage applied to the test was the negative switching impulse (250 µs/2500 µs) with a peak value of 25 kV. To prevent disturbance of the liquid after applying an impulse voltage, the time interval between two impulses was 1 min. After the CCD recorded the electro-optical field pattern of the three types of electrode material at different times, the electric field distribution with different electrodes could be calculated from the relationship between the light intensity and electric field.[16] Then, the space charge distribution could be calculated from the Poisson equation.

III. TEST RESULTS

Table I shows the switching impulse breakdown voltage of propylene carbonate with different electrode materials. As shown in the table, the switching impulse breakdown voltage of propylene carbonate with each electrode material differs. The breakdown voltage of propylene carbonate with a stainless steel electrode is 13.8% higher than the copper electrode and 21.2% higher with the aluminum electrode. Furthermore, the breakdown voltage of propylene carbonate with the copper electrode is higher than that with the aluminum electrode with an improvement of 6.5%. The

TABLE I. The switching impulse breakdown results for propylene carbonate with different electrode materials.

electrode material	polarity	The average breakdown voltage (kV)	Standard deviation (kV)	The average breakdown time (µs)
Stainless steel	-	44.6	1.4	425
Copper	-	39.2	1.5	507
Aluminum	-	36.8	1.1	420

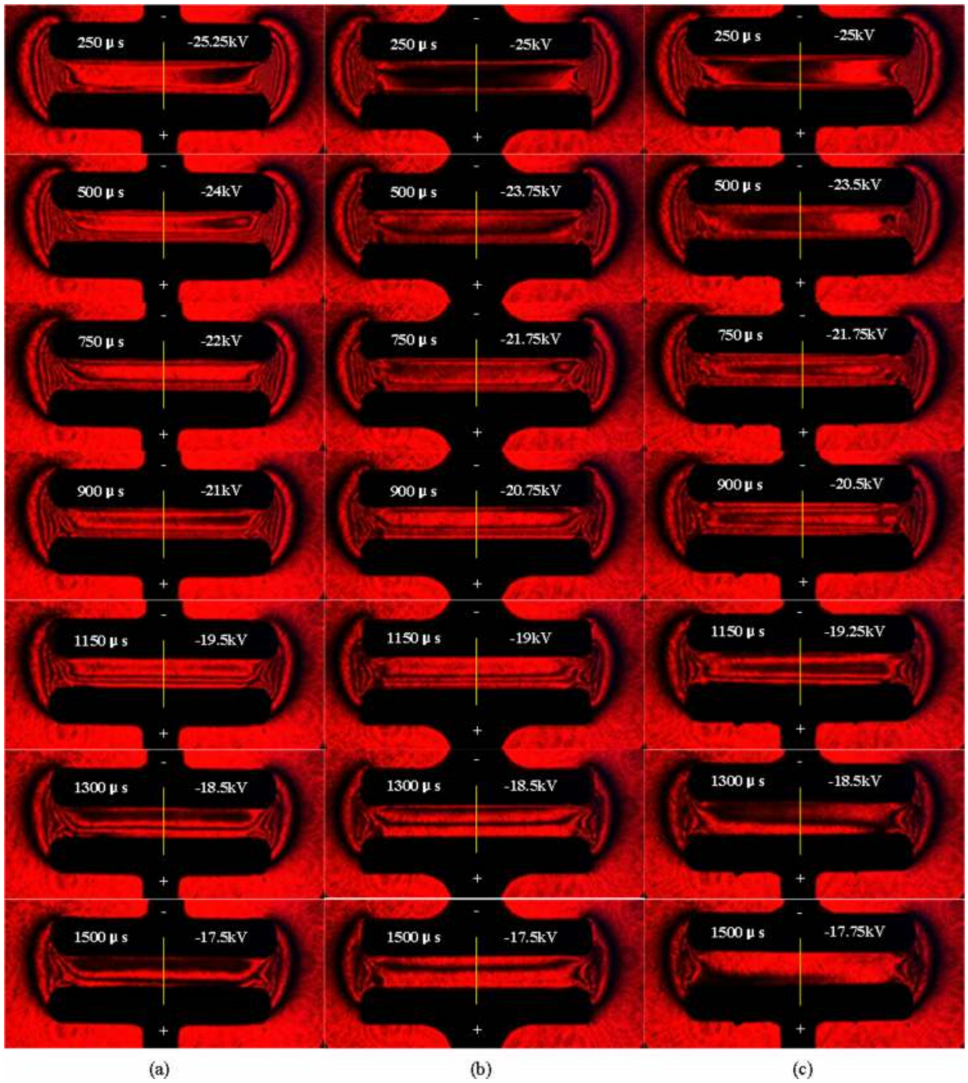

FIG. 3. The electro-optical field of propylene carbonate of the different electrode materials: (a) aluminum; (b) copper; (c) stainless steel.

breakdown time of propylene carbonate with the three electrode materials is also different. This is because the quantity of space charge injected from each electrode is not the same, which leads to different degrees of electric field distortion.

Figure 3 shows the electro-optical field pattern of propylene carbonate with different plate electrode materials collected by the CCD. The bright and dark interference fringes in the electro-optical field pattern are equipotential lines. The electric field is equal when the light intensity is the same at one interference fringe. From Fig. 3, we can obviously see the bright and dark interference fringes between the plate electrodes, which means that the electric field in the liquid dielectric under the plate electrodes is not uniform and there is a certain degree of electric field distortion between the plate electrodes. The electro-optical field pattern of propylene carbonate with the three electrode materials at the same time is different. The amount of interference fringes between aluminum, copper, and stainless steel electrodes decreased at 1150 μs, 1300 μs, and 1500 μs, respectively. This indicates that different electrode materials have different space charge-injecting abilities, which leads to a different electric field distortion degree between the plate electrodes.

Figures 4 and 5 illustrate the electric field distribution and the space charge density distribution of propylene carbonate between the three plate electrodes. These characteristics are obtained in

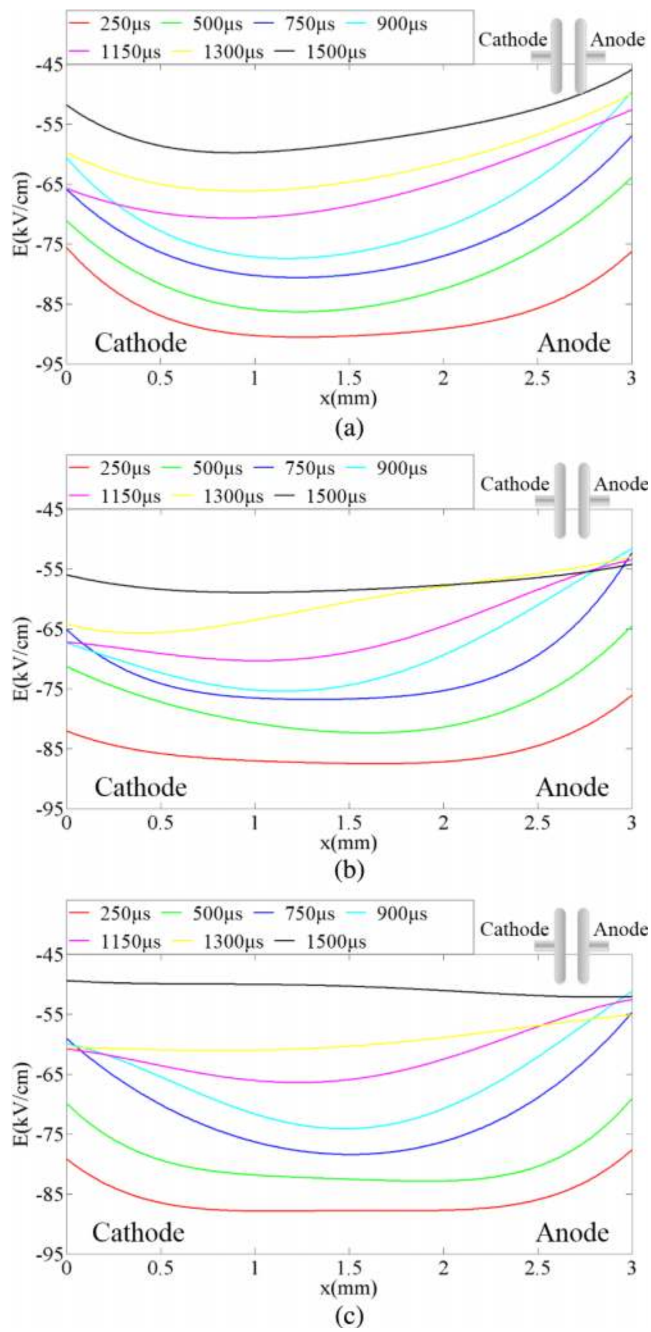

FIG. 4. The electric field distribution of propylene carbonate between different electrodes: (a) aluminum; (b) copper; (c) stainless steel.

the vertical direction (indicated by a yellow line in Fig. 3) using the inversion algorithm from the electro-optic field pattern. Comparing the distribution of the electric field between the three electrodes in Fig. 4, it can be seen that the electric field between the plate electrodes at different times has a different degree of distortion. The degree of distortion of the electric field with different electrode materials at the same time is significantly different. The distortion of the electric field with aluminum and stainless steel electrodes occurs mainly in the vicinity of both the anode and cathode while occurring mainly in the anode for the copper electrode. Comparing the space charge density distribution in Fig. 5, we found that the net space charge density near the aluminum electrode was

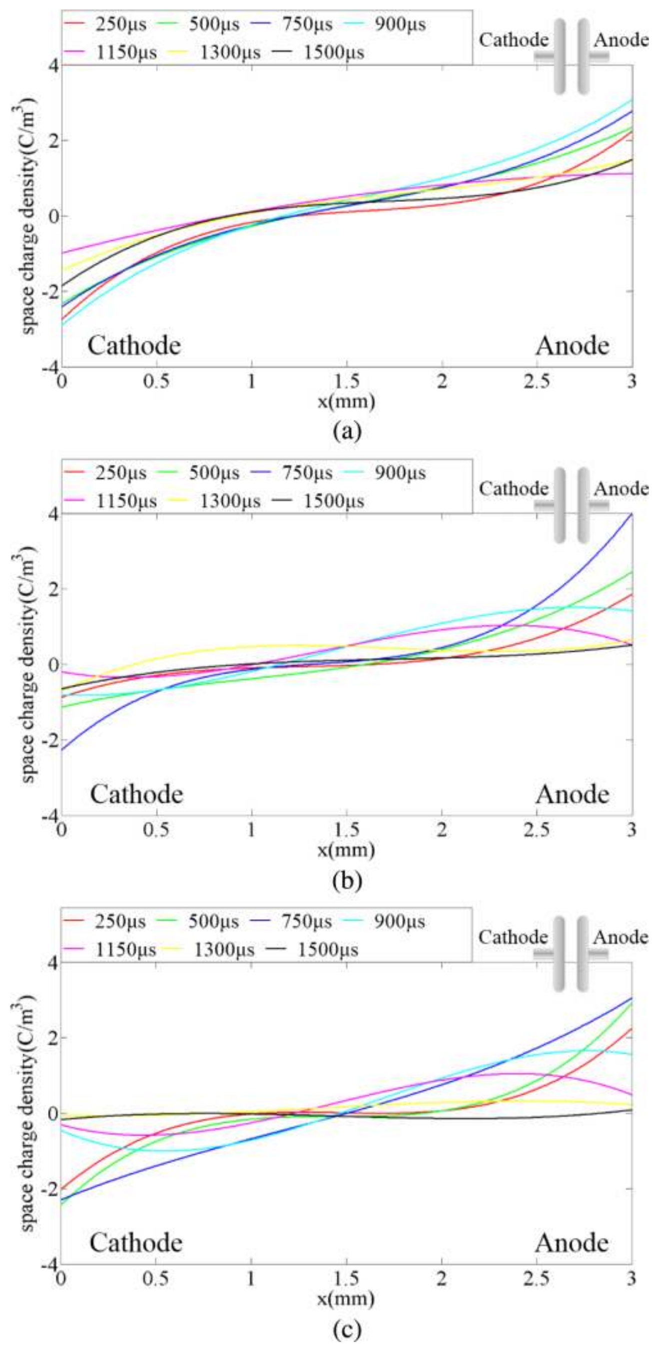

FIG. 5. The space charge density distribution of propylene carbonate between different electrodes: (a) aluminum; (b) copper; (c) stainless steel.

large (1 C/m^3 or more) at all times and the net space charge density near the anode and cathode had an approximately symmetric distribution. The net space charge density near the stainless steel electrode was large at 250 μs, 500 μs, and 750 μs but small (1 C/m^3 or less) at 900 μs (except anode), 1150 μs, 1300 μs, and 1500 μs. The maximum of the net space charge density at these four times was not in the vicinity of the electrodes but was 0.5 mm away from the electrodes (x-axis 0.5 mm and 2.5 mm) and gradually decreased over time. This means the space charge injection rate of stainless steel is slower than the space charge dissipation rate after 900 μs and the injected charge moved towards the center of the electrode under the influence of the electric field. The net space charge density of the stainless steel electrode near the anode and cathode was approximately symmetric. Figure 5(b) illustrates that the net space charge density of the copper electrode near the anode is obviously larger than that near the cathode most of the time (excluding the points at 1300 μs and 1500 μs). This means that unlike aluminum and stainless steel, the space charge injection ability of the copper anode is significantly stronger than the cathode. Therefore, the degree of distortion of the electric field near the anode of the copper electrode is higher than the cathode.

IV. THE EFFECT OF THE ELECTRODE MATERIAL ON THE LIQUID DIELECTRIC BREAKDOWN VOLTAGE

Because of the field emission and the complex electrochemical reaction near the electrode surface and the electric double layer, a certain amount of space charge is injected to the liquid dielectric from the electrode under the applied electric field.[17–19] The space charge injected from the electrode weakens the electric field near the electrode and strengthens the electric field of the central region, distorting the initial uniform electric field. We believe that different electrodes have a different space charge injection ability that distorts the electric field between the electrodes to a different degree. The more space charge injected, the more obvious the electric field distortion and the lower the impulse breakdown voltage of the liquid dielectric. Figure 5 shows that copper, aluminum, and stainless steel electrodes have different space charge injection abilities. Because of the high work function of stainless steel (5.05 eV, higher than copper and aluminum, which have work functions of 4.5 eV and 4.2 eV, respectively[9]) and a good electrochemical stability, the quantity of space charge injected is significantly less than with the aluminum and copper electrodes with the same voltage. The quantity of space charge injected from the copper electrode is obviously less than with the aluminum electrode. From Fig. 4, the distortion rate of the electric field between the electrodes with different materials at different times was calculated using Equation (1):

$$D = \frac{|E - E_{avg}|_{\max}}{E_{avg}} \times 100\%, \tag{1}$$

where D is the distortion rate, $|E\text{-}E_{avg}|_{max}$ is the maximum value of the electric field distortion between the plate electrodes, and E_{avg} is the value of the average electric field between the plate electrodes. The results are shown in Table II.

Table II illustrates that the electric field between the copper and stainless steel electrodes distorts the greatest at 750 μs, while the electric field between aluminum electrodes distorts the greatest at 900 μs. Most of the time, the electric field distortion rate was highest for aluminum, followed by copper, and then the stainless steel electrodes. The aluminum electrode maintained a high rate of electric field distortion at all times while the stainless steel electrodes had a high electric field distortion rate at 500 μs, 750 μs, 900 μs, and 1150 μs. The copper electrode was generally somewhere in between. This indicates that the space charge injection ability of aluminum, copper, and stainless steel electrodes under the same voltage level is in descending order so the electric field

TABLE II. The electric field distortion rate with different electrode materials.

Time (μs)	Distortion rate (Aluminum)	Distortion rate (Copper)	Distortion rate (Stainless steel)
250	13.0%	10.9%	9.8%
500	20.3%	17.2%	13.5%
750	23.6%	27.8%	23.5%
900	29.2%	25.0%	23.4%
1150	19.6%	18.1%	15.2%
1300	19.1%	12.4%	7.1%
1500	17.7%	5.8%	2.9%

distortion rate between the electrodes is also in descending order. This may explain the difference in impulse breakdown voltage of propylene carbonate with different electrodes.

V. CONCLUSIONS

In summary, the impulse breakdown voltage of propylene carbonate was measured with copper, aluminum, and stainless steel electrodes. The electric field distribution and the space charge density distribution of propylene carbonate between the three plate electrode materials were then measured on this basis. The conclusions are as follows: (1)The electrode material has a significant influence on the impulse breakdown voltage of a liquid dielectric. The breakdown voltage of propylene carbonate with the stainless steel, copper, and aluminum electrodes was in descending order. (2) Different electrode materials have different space charge injection abilities. The space charge injection ability of stainless steel, copper, and aluminum electrodes was in ascending order. (3) The electric field between the three plate electrodes has a certain degree of distortion. The electric field distortion rate with stainless steel, copper, and aluminum electrodes was in descending order.

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