SPACE CHARGE MEASUREMENTS IN XLPE INSULATED MID-VOLTAGE CABLE: CORRELATION WITH CABLE PERFORMANCE

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ABSTRACT

*Three experimental mid-voltage XLPE cables, **C2**, **C3** and **C4**, rated respectively as 'good', 'very good' and 'bad' in perforation tests, are studied. All these cables have been systematically measured by PEA as produced and after being annealed at 90ºC and 120ºC up to 672 hours. Measured internal charge of cable **C4** at least doubles that of cables **C2** and **C3**. Evolution with annealing show as well differences in the reticulation process carried out during cable **C2** and **C3** preparation, which can explain why cable **C3** performs better than **C2** in perforation tests. Infrared spectroscopy measurements (IR) showed differences in components injected from the external semiconducting layer (SC) into the isolation during annealing. These results explain other observed differences in PEA measurements with regard of the SC type of each cable. To sum up, combination of PEA and IR measurements are a useful tool in understanding charge relaxation processes and XLPE cable performance.*

KEYWORDS

PEA, XLPE, cable, charge distribution, IR

INTRODUCTION

The presence of space charge in a dielectric material not only affects the value of its electric field and its conductive properties but also plays an important role in aging processes [1]. From an applied point of view, for midvoltage cable, the study of space charge formation and relaxation processes is especially interesting as they condition cable lifetime. Polyethylene (PE) is a linear semicrystalline non polar polymer that is used in such cable insulation. Some controversy arose in the past about the glass-transition temperature (T_g) of PE, but nowadays it is well established that it is below room temperature. This is a relevant fact in the study of the conduction processes of cable insulation because its working temperature (90ºC) is above room temperature and therefore, above T_g. Because of this, the conduction processes observed can be associated with free charge [2]. In industrial applications, PE is commonly crosslinked (XLPE) by the addition of some chemical additives (crosslinking agents) and heating it up to a temperature higher than 200ºC to produce a vulcanization reaction. This process introduce several crosslinking by products that influence materials conductive properties.

The development of new techniques for determining space charge profiles in insulators [3] has renewed the interest in the study of space charge in dielectric materials in recent years. These studies have shown that the formation of space charge profiles in crosslinked polyethylene (XLPE), used in cable insulation, is greatly influenced by several factors, including the crosslinking subproducts, antioxidants, oxidation of the material, temperature, electrode type, and other circumstances of the manufacturing process that must be taken into account.[4-6]

Previous works showed that cable semiconducting shields (SC) play an important role in charge trapping processes in XLPE [7]. The charge that arises was previously trapped in defects that diffuse from the SC layers. Infrared spectroscopy (IR) analysis showed that this diffusion of defects into the XLPE bulk takes place in a continuous way when the sample is annealed at temperatures above 80ºC. Diffused defects act as traps for the charge that is injected from the electrodes if a polarizing electric field is present.

In this work three experimental cables supplied by General Cable S.A., each one with quite different perforation test results, are systematically measured. The main goal to achieve is to obtain a correlation between cable characteristics and measured results. Following this purpose, several samples were annealed at T_a=90ºC and T_a=120ºC for different times t_a between 0 and 672 hours and the charge distribution profile and the diffusion of chemical components from the semiconducting external shield into the XLPE isolation, is measured.

EXPERIMENTAL

Samples

Cable samples were supplied by General Cable S.A. and consisted of a cylindrical insulating XLPE layer with 7 and 13 mm of inner and outer radii, respectively. The samples had two 1 mm thick semiconductor layers in contact with the inner and external surfaces of XLPE.

Three experimental cables (**C2**, **C3** and **C4**) were prepared using different 'PE-crosslinking agent' base resin (PE1, PE2) and different external semiconducting shields (SC1, SC2). Cables were evaluated by perforation tests at General Cable S.A., delivering quite different results. Table 1 summarize each cable properties.

Cable	PE base resin	External SC	Perforation test
C2	PE1	SC1	good
C3	PE1	SC2	very good
C4	PE2	SC1	bad

Table 1: Summary of cable characteristics

Charge distribution measurements

Charge distribution measurements where performed by the pulsed electro-acoustic method (PEA). In this technique a pulsed electric field is applied to the sample inducing the oscillation of space charges present through the material. The resulting pressure wave, related to the space charge distribution, is recorded as a function of time. More detailed explanation of this technique can be found in excellent treatises [8].

PEA experimental set-up used in this work was a commercial PEA equipment 'Techimp PEA cable system'. A 'Spellman SL10' 130kV high voltage power supply were used to polarize cable samples and data was recorded by means of a 'Tektronix TDS 5032' digital oscilloscope. Measuring procedure consisted on a 2 hours polarization time (t_p) at room temperature and 120kV applied voltage (V_p). Charge distribution was measured continuously during polarization and 30 minutes more after removing the electric field. Samples consisted in 1.5m long cable sections conveniently arranged for measurements. The total measuring section length was 10cm.

Due to cable dimensions (28 mm diameter) measured PEA signal was very low and data have been collected working out the average of 100 seconds acquisition. Because of that calibration of PEA response has not been possible and spectra presented ahead corresponds to the direct PEA signal.

IR measurements

Fourier transform infrared (FTIR) measurements were performed with a 'Nicolet 510M spectrometer' on 6x6mm XLPE sheets. Samples 300 μm thick were cut directly from the cable at different depths by mechanical methods.

RESULTS AND DISCUSSION

As received cables

Figure 1 show compared PEA measurements of as received cables. We can observe clear differences between them. Cable C4 shows much higher internal charge than the other two cables. However, cable C3, that performs better than C2 in perforation tests, shows surprisingly higher internal charge as well. In all cases a distribution of trapped charge, injected from the external electrode, can be observed.
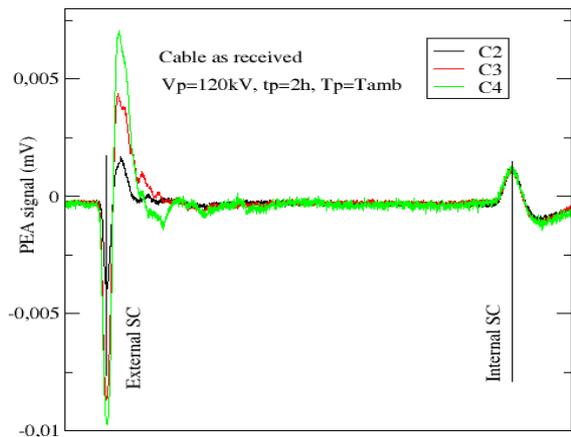
Figure 1: PEA measurements in as received cables (t_p = 2 hours, V_p = 120kV, V_p stills on)

Cables annealed at 120ºC

Evolution of charge distribution in cable samples with annealing at 120ºC up to 296 hours is represented in figures 2, 3 and 4.
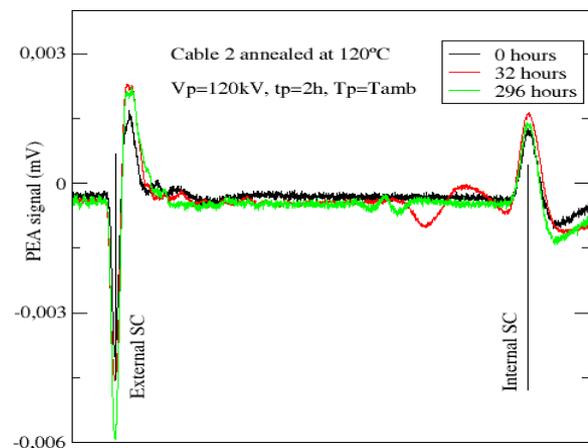
Figure 2: PEA measurements in cable C2 annealed at 120ºC (t_p = 2 hours, V_p = 120kV, V_p stills on)

Internal charge in C2 increases a bit after annealing. These increase occurs at the time new charge is generated near the internal SC shield (32 hours annealing in figure 2). This internal charge, however, disappears with further annealing of the sample. Again a clear distribution of trapped charge, injected from the external electrode, can be observed.

Curves obtained for C3 (figure 3) show quite different behaviour with a clear decrease in internal charge, probably associated with elimination of crosslinking byproducts. Generation of new charge near the internal SC shield is observed as well but in much lower degree.
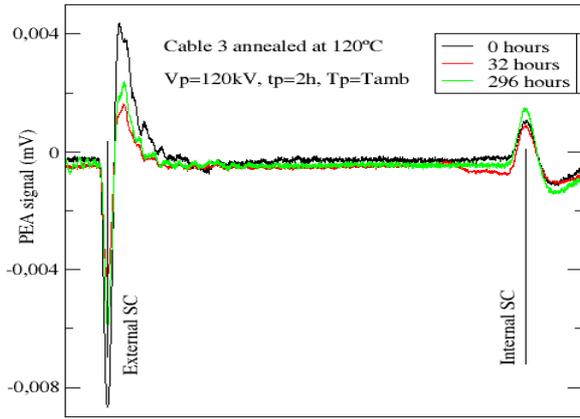
Figure 3: PEA measurements in cable C3 annealed at 120ºC (t_p = 2 hours, V_p = 120kV, V_p stills on)

Cable C4 (figure 4) show almost constant internal charge. Annealing, however, promotes the injection of new charge from the internal electrode and enhances trapping zones near the external SC.
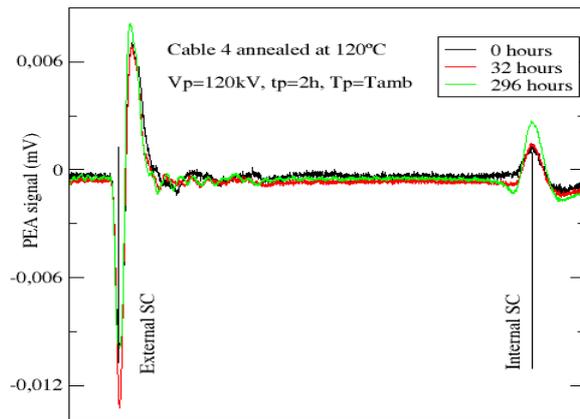
Figure 4: PEA measurements in cable C4 annealed at 120ºC (t_p = 2 hours, V_p = 120kV, V_p stills on)

Figures 5 and 6 compare results obtained in all cables after annealing for 296 hours at 120ºC. We can see that C2 and C3, that share the same PE base resin, show almost identical charge distribution. C4 shows much more internal charge than the other two cables. The trapped charge profile in C4 is as well much more marked than in C2 and C3.
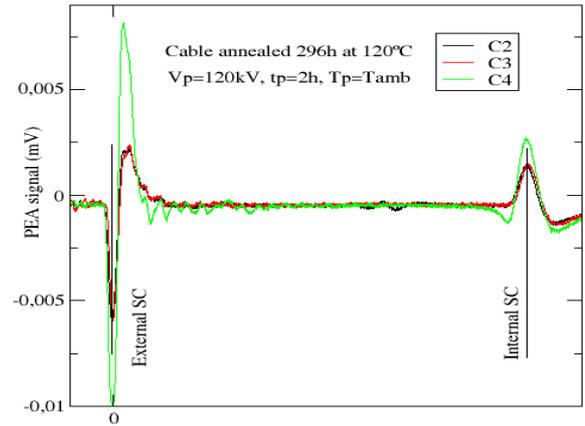
Figure 5: PEA measurements in cables C2, C3 and C4 annealed 296 hours at 120ºC (t_p = 2 hours, V_p = 120kV, V_p stills on)
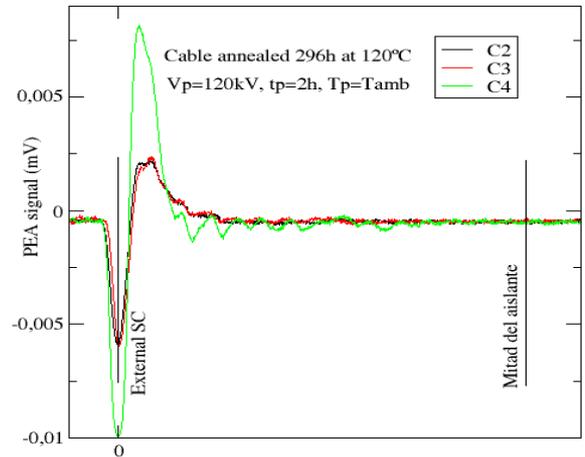
Figure 6: PEA measurements in cables C2, C3 and C4 annealed 296 hours at 120ºC (half isolation thickness, t_p = 2 hours, V_p = 120kV, V_p stills on)

Cables annealed at 90ºC

Evolution of charge distribution in cable samples with annealing at 90ºC up to 672 hours is represented in figures 7, 8 and 9.

In cable C2 (figure 7), no new generation of internal charge is detected in this case near the internal electrode. Only a global decrease in total charge is observed probably due to elimination of crosslinking byproducts.

In cable C3 (figure 8), this decrease of internal charge due to to elimination of crosslinking byproducts, is very notorious. After annealing, internal charge distribution in all cables follow similar relation as in the as received samples but with less internal charge (figure 10).
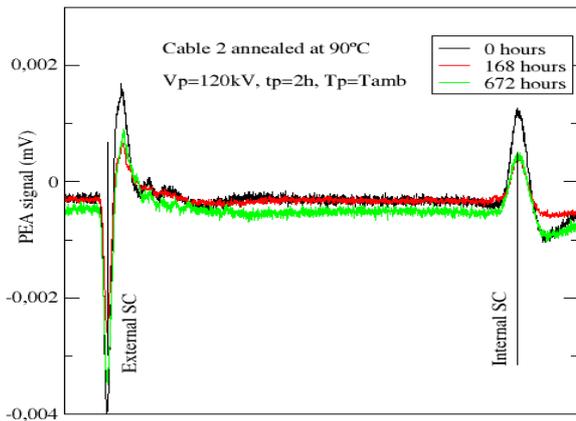
Figure 7: PEA measurements in cable C2 annealed at 90ºC (t_p = 2 hours, V_p = 120kV, V_p stills on)

Figure 8: PEA measurements in cable C3 annealed at 90ºC (t_p = 2 hours, V_p = 120kV, V_p stills on)
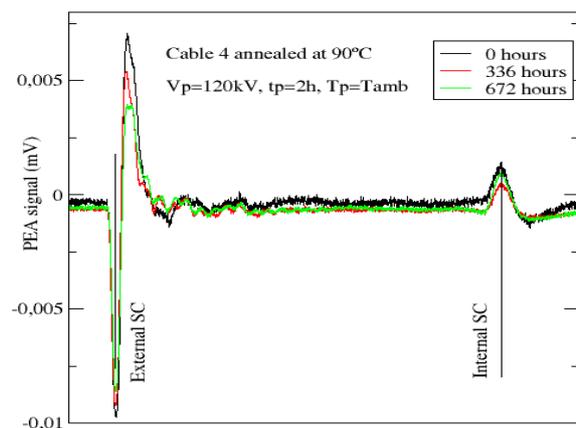
Figure 9: PEA measurements in cable C4 annealed at 90ºC (t_p = 2 hours, V_p = 120kV, V_p stills on)

Figure 10: PEA measurements in cables C2, C3 and C4 annealed 672 hours at 90ºC (half isolation thickness, t_p = 2 hours, V_p = 120kV, V_p stills on)

IR results

Infrared measurements (FTIR) were performed at different depths in the XLPE isolation of as received cable and cable annealed 8 hours and 128 hours at 120ºC. We will focus our analysis of FTIR results in the peaks corresponding to 3300, 1743, 1640 and 1558cm^{-1} identified in previous works as peaks associated with components not present originally in XLPE, that diffuses from the SC [7]. Figures 11, 12, 13 and 14 show, as an example, the evolution with annealing of the measured intensity of these peaks in cable C2. Measurements were carried out in three layers cut from the isolation surface down to 0.75mm depth (layer 1: XLPE surface in contact with the SC shield, layer 3: XLPE at 0.75mm depth).
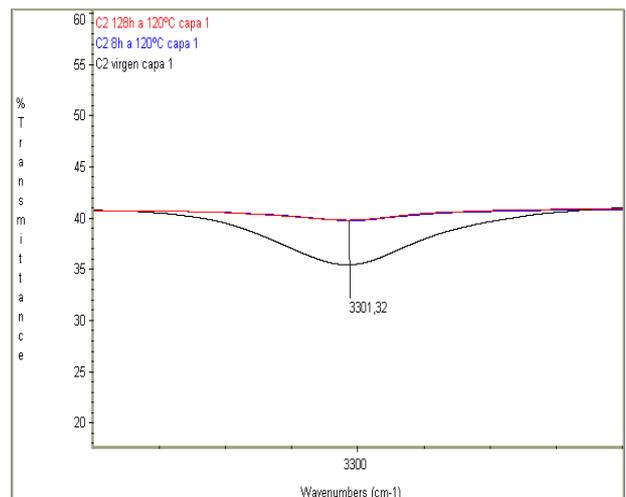
Figure 11: FTIR measurements in cable C2 layer 1 (XLPE external surface) annealed at 120ºC.
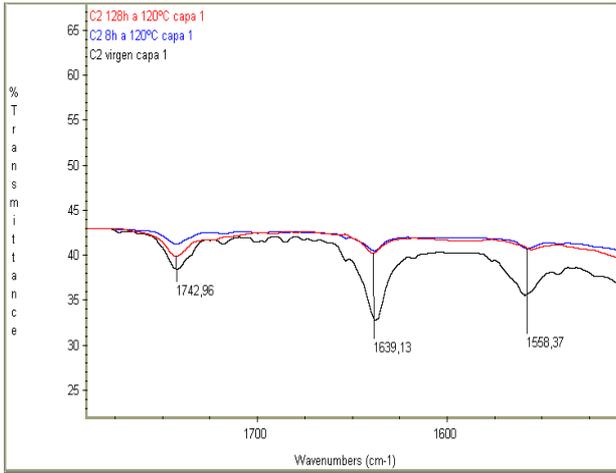
Figure 12: FTIR measurements in cable C2 layer 1 (XLPE external surface) annealed at 120ºC.
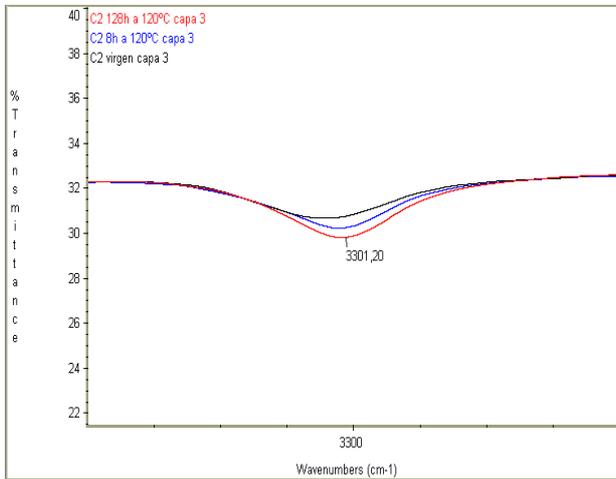
Figure 13: FTIR measurements in cable C2 layer 3 (0.75 mm depth) annealed at 120ºC.
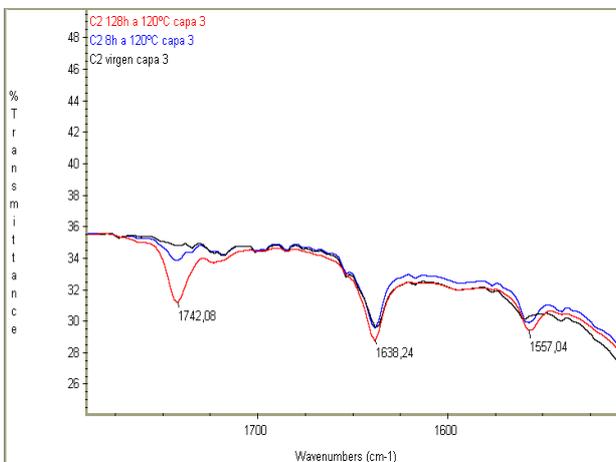
Figure 14: FTIR measurements in cable C2 layer 3 (0.75 mm depth) annealed at 120ºC.

FTIR measurements showed that the SC shield of each cable play an important role in these diffusion process. Cables C2 and C4, that share external SC shield type, show the injection with annealing of components responsible of all the reflections analyzed. On the other hand, cable C3, which have the better perforation results, only shows injection from the external SC shield of component responsible of the 1743cm^{-1} reflection (figures 15 and 16).
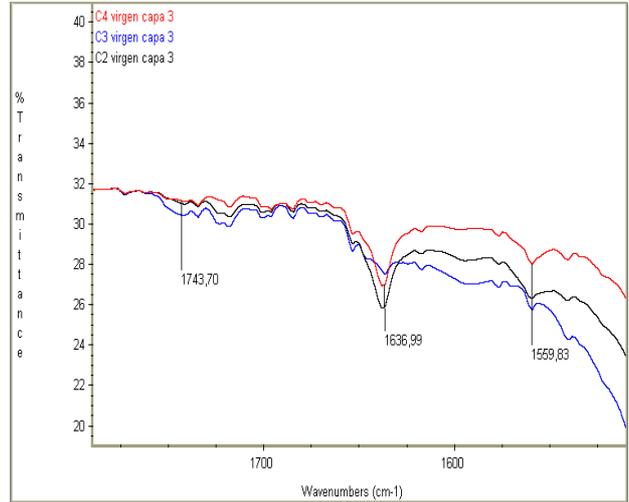
Figure 15: FTIR measurements in as received cables C2, C3 and C4 layer 3 (0.75 mm depth)
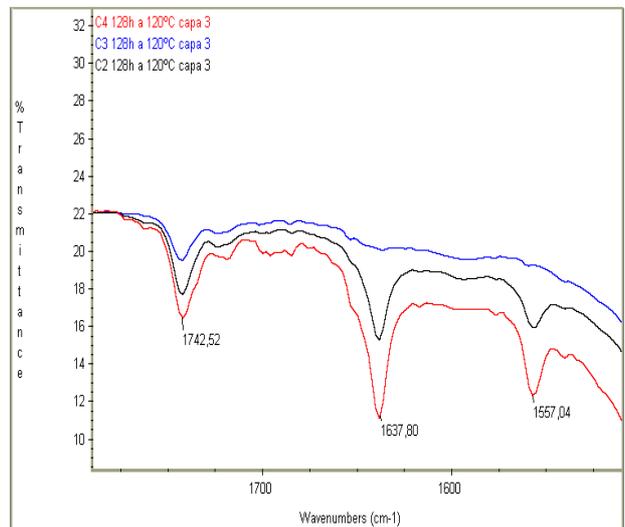
Figure 16: FTIR measurements in cables C2, C3 and C4 layer 3 (0.75 mm depth) annealed 128 hours at 120ºC

Table 2 summarize (qualitatively) the observed evolution of each peak with annealing. We can observe that cable C2 and C4 show the new injection and diffusion of all the components responsible of the four peaks studied.

as received	3300 cm⁻¹	1740 cm⁻¹	1640 cm⁻¹	1550 cm⁻¹
C2	5 ---- 1.5	5 ---- X	9 ---- 3	4 ---- 1
C3	1 ---- X	2 ---- X	1 ---- 1	5 ---- 1
C4	4 ---- 2	2 ---- X	5 ---- 3	1 ---- 1

128h at 120ºC	3300 cm⁻¹	1740 cm⁻¹	1640 cm⁻¹	1550 cm⁻¹
C2	1* ---- 2	3* ---- 4	2* ---- 4	1* ---- 2
C3	X ---- X	5 ---- 2	X ---- X	X ---- X
C4	3* ---- 4	4 ---- 4	4* ---- 8	2 ---- 3

(layer 1 ---- layer 3)

RED: maximum peak in as received cable
GREEN: diffusion during annealing (layer 3)
BLUE: new injection during annealing (layer 1)

Table 2: Evolution of intensity (arbitrary units) of peaks measured by FTIR with annealing

In the case of cable C3, we can observe initially the presence of all the components that were diffused probably during the manufacturing process. Annealing of this cable at 120ºC, however, promote only new diffusion of the component responsible of the 1740 cm⁻¹ .

CONCLUSIONS

The systematic testing procedure employed, that involves several PEA and FTIR measurements after cable annealing, allowed us to detect differences in the reticulation process carried out during cable C2 and C3 preparation.   It seems that croslinking process did no concluded during manufacturing of cable C2. These fact can explain why cable C3 performs better than C2 in perforation tests. IR measurements showed as well several differences in the chemical components injected from the external semiconducting layer into the isolation of each cable. IR results allow us to explain other observed differences in PEA measurements of each cable, that show the formation of charged regions within the isolation and their evolution with annealing. To sum up, the presented results show that   PEA, and IR measurements are highly complementary and in general necessary as a whole to correctly understand charge relaxation processes in XLPE cables and their electrical performance.

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