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Experience of composite insulators on HV substation: Some French examples

Giulio ROCCHETTI *
Reinhausen France (RFR)
France
G.Rocchetti@reinhausen.com

Jens SEIFERT
Reinhausen Power Composites (RPC)
Germany
J.seifert@reinhausen.com

Ngoc-Minh NGUYEN,
RTE
France
ngoc-minh.nguyen@rte-france.com

Christian PONS
EDF
France
christian-1.pons@edf.fr

Eric MOAL
CAE Impuls'ions
France
moaleric@gmail.com

SUMMARY

Composite housings are nowadays a solution implemented in electric grids worldwide for their performance in polluted environment, safety and reduced maintenance costs. RTE specifies composite hollow core insulators for some HV station equipment housing, such as cable termination or instrument transformers. Thousands of composite insulators are installed since more than 20 years in French grid with a very good return of experience.

RTE has been an early precursor to experiment the use of composite insulators in the HV equipment with silicone composite insulators for the housing of HV Circuit Breaker 72,5 kV class since 1993, in the substation of Balaruc in the south of France. Since 1980s EDF and later RTE, decided to submit the composite insulators to be installed on network to the 5000 hours accelerated ageing test according to IEC 62730. Furthermore, to gain long term experience and verify the consistency with laboratory tests, two composite insulators for 245KV cable termination with same material and technology were placed in the outdoor EDF Research Station near Martigues (south of France) and monitored since 1998. The test was performed during more than 10 years under extreme environmental conditions and completed in 2008 with very positive results.

A second long term ageing test started at Martigues EDF Station on 2008 and 2016 is still ongoing on 400 kV insulators with different designs and silicone housing materials (HTV, LSR), creepage distance and shed profile).

The performance of composite insulators is strongly related to the selection of the materials, the manufacturing process and the electrical and mechanical design in relation to the specific application. Composite insulators housing are available with different technologies and silicone compounds: each type of silicone compound (LSR/HTV) has a different formulation.

The physical and chemical characteristics therefore differ resulting in different electrical and mechanical insulating performances. Raw materials evolve over the time, the implementation of the environmental regulations REACH «Registration, Evaluation and Authorization of Chemicals», oblige to align all chemicals to the environmental regulation and therefore updated qualifications to follow the evolution of materials and design become necessary. IEC 61462 standard for Hollow Core Composite Insulators that is currently under revision will not include any specifics for the HV equipment application. IEC standards for material and design qualification may not be sufficient to assure the long-term performances and should be integrated by additional specifications for material selection and qualification according equipment manufacturers (OEM) and utility requirements. Material fingerprinting according to CIGRE TB 595 as silicone identity of qualification should be required for record of the qualified materials.

The paper analyzes the different experiences and relevant results and compare IEC standard tests and utility accelerated ageing test with natural test station experiences. The future perspective is to perform a larger study on the composite insulators for various HV applications installed on the French Network and eventually develop in situ diagnostic of the external housing and improved apparatus monitoring.

KEYWORDS

Composite insulators, long-term experience, long-term test, HTV silicone, LSR silicone, silicone ageing, natural test ageing test stations, material fingerprint

1. Introduction

Composite insulators are known as alternative solution to standard porcelain insulators for different reasons among which good performances under polluted conditions, earthquake stress, light weight and especially for safety in case of failure [1]. For HV equipment, the rupture of porcelain insulator could be a consequence of a mechanical stress (e.g. choc with vehicles inside substation) or an internal arc. The debris of porcelain can be projected for up to 100 m, causing a serious safety problem, both for personnel and for installation inside substation (Figure 1).

Figure 1: Rupture of insulator housing during a destructive mechanical stress test and projection of debris

Figure *2* presents the part of equipment with composite housings in RTE parc. For cable terminations, composite housings have been adopted for almost 30 years, and since 2010 all new cable terminations must be equipped with this technology. For capacitive voltage transformers and surge arresters, composite insulators have only been qualified recently, but the adoption speed has accelerated in recent years. For circuit breaker, composite insulator is nowadays limited to some specific applications, but more installation is expected from 2022.

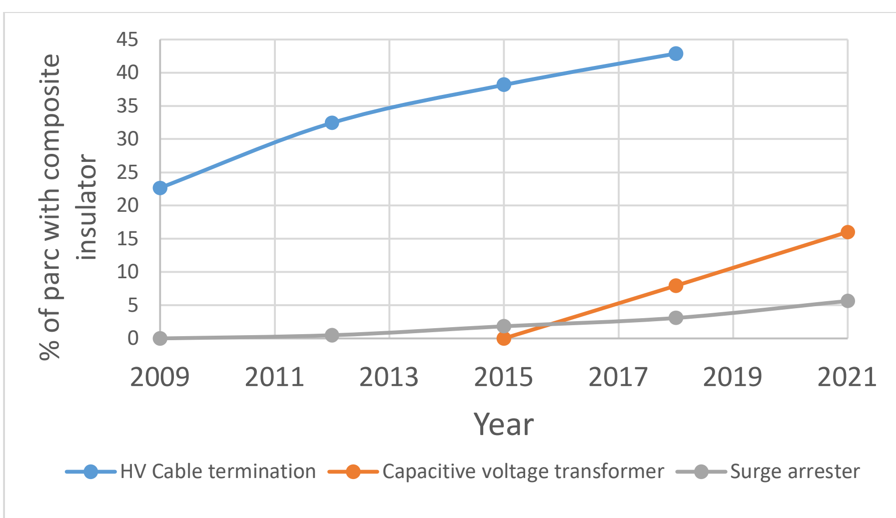


Figure 2 : Adoption of composite insulator for HV equipment of RTE network (72 kV to 420 kV)

So far, RTE has a general good return of experience with this insulator technology. However, the expected lifetime of composite insulators still needs some investigations. Those studies are necessary to define a suitable asset management strategy for equipment applying composite insulators.

2. Investigation in Balaruc substation

In order to investigate the aging mode of composite insulators, a circuit breaker equipped with this technology in Balaruc substation has been selected. The substation (225/63 kV) of Balaruc is in south of France, Mediterranean coast close to Sète & Montpellier. The circuit breaker chosen for study is the very first 72,5 kV Live Tank Circuit Breaker equipped with HTV extruded silicone sheds on hollow core composite insulators manufactured by Sediver in early 1990s. The circuit breaker has been installed since 1993 in RTE network with a standard maintenance mode, without periodic cleaning of insulator. There are so far no major incidents on the circuit breaker.

Figure 3: Geographic location of Balaruc substation. Dark yellow zones indicated heavy saline pollution zones identified by RTE.

As shown in **Figure *3***, due to the proximity of the sea and the Thau lagoon (salinity of 27 to 40 psu), the site is located in a heavy saline pollution zone. Balaruc is also a very sunny site, with an average of nearly 13 sunny hours per day in summer (**Figure 4**), which generate high UV stresses on insulators. Those conditions make Balaruc a very good site for aging investigation of composite insulator.

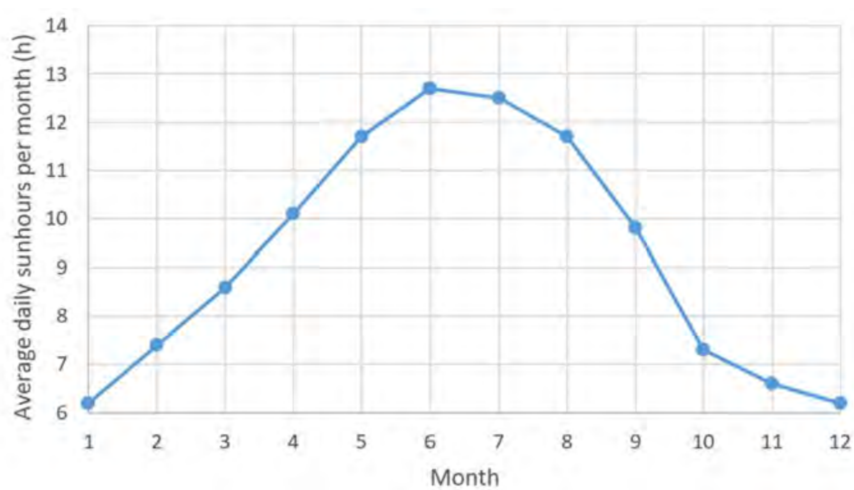


Figure 4: Average daily sunhours per month in Balaruc

2.1 Pollution level characterization

One shed was cleaned in order to quantify its level of pollution by the ESDD/NSDD measurements [2]. The measurements were performed by measuring the conductivity of dirty water collected with cottons used to clean the surface, combined with weight and chemical analysis of non-soluble remained pollutants according the procedure presented on IEC/TS 60815-1(2008) Annex C [2]. As indicated in Figure 5, the level of the insulator pollution has been measured as class d-heavy class [2]:

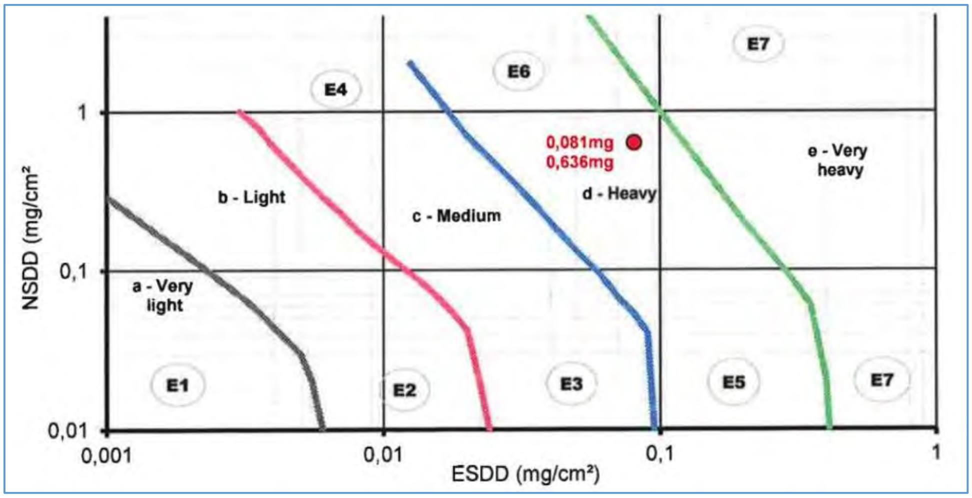


Figure 5 : Characterization of pollution level of the insulator by using figure 2 of following IEC/TS 60815-1 (2008) [2]

2.2 Visual inspection and hydrophobicity characterization

Inspection has been carried out in 2019 on the circuit breaker of Balaruc substation. During visual inspection, no erosion, no tracking on the silicone sheds of the insulators have been observed. The applied HTV silicone rubber housing shall protect the mechanical load-carrying FRP tube from environmental influences (moisture, UV, pollution) and shall supply the required creepage distance for the polluted outdoor conditions.

Figure 6: Characterization of pollution level of the insulators by using figure 2 of following IEC/TS 60815-1 (2008) [2]

The hydrophobicity test has also been carried out on site according to IEC 62073 (2016-02) Annex D Spray Method [3]. The hydrophobicity was very good (level HC1 to HC3), as shown on Figure 7 (left). No major change has been observed compared to the measurement done in 1996 (Figure 7 (right)).

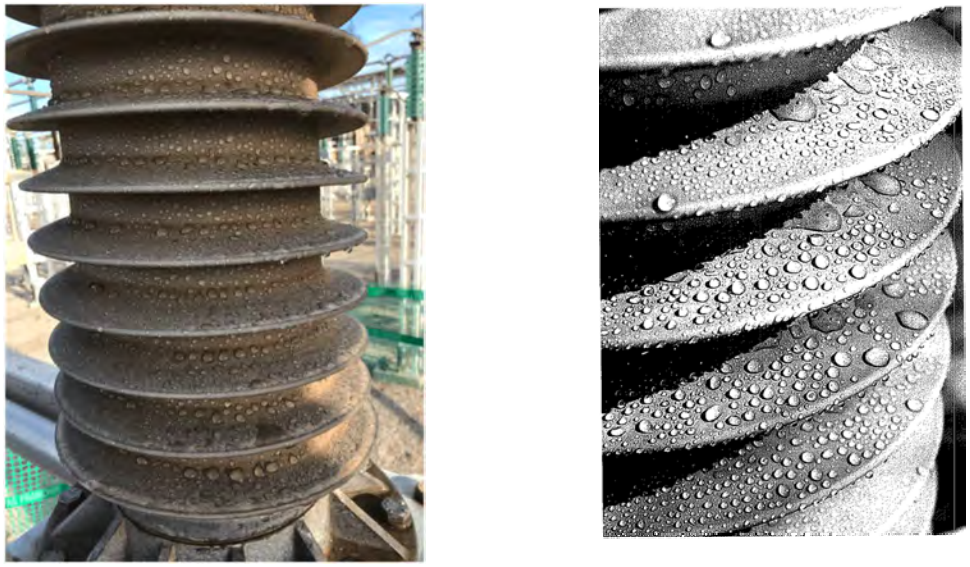


Figure 7: Inspection of hydrophobicity of 72,5 kV hollow core composite insulators, measurement in 2019 (left) vs. measurement in 1996 (right)

2.3 Investigation by semi-destructive sampling

For further investigation, one small sample of shed was cut, so we could also get the physical and chemical measurements as:

- Hardness according to ISO 868:2003
- TGA according to ISO 9924-3:2009
- Angle of water drops according to IEC 62073: 2016 method A
- Density (1,57 g/cm³) according to ISO 2781:2018 method A
- FTIR (silicone material fingerprint) as recorded in Figure 8

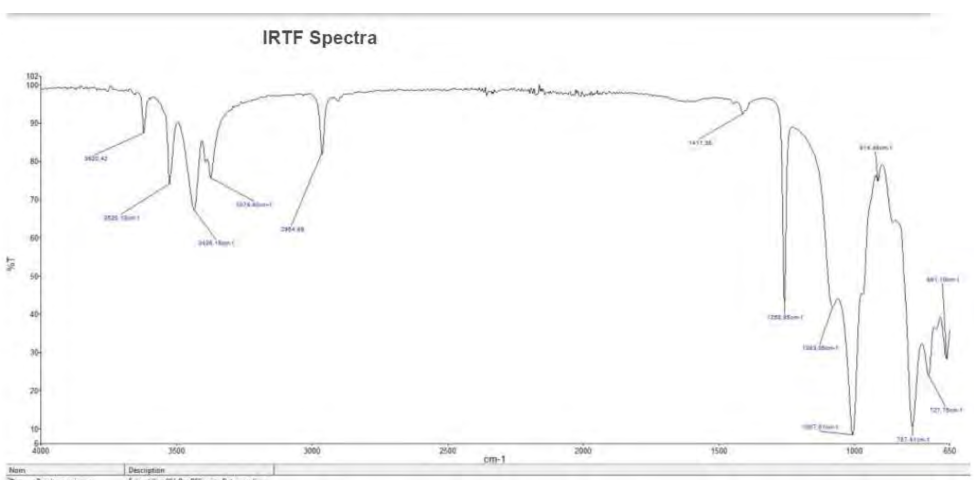


Figure 8: FTIR spectra measurement (typical for HTV with the signature of ATH = $Al(OH)_3$ around 3500…3000 cm^{-1})

The target was to evaluate this exceptional long excellent experience with extruded sheds HTV silicone (first generation of HTV silicone, vulcanized at high temperature). A "new" silicone sample from the same period (unpolluted, not in service) was used as a reference to perform the Soxhlet analysis, and to compare above measurement (hardness, density, mechanical properties) with onsite aged sample. Similar comparison has been performed on HTV silicone rubber shed samples from Martigues ageing test (Chapter 3). Table 1 shows the comparison of new and aged samples taken from Balaruc and Martigues. The purpose of the Soxhlet analysis on silicone sheds is to evaluate the percentage of low molecular weight (LMW) compounds of silicones which are responsible for the important hydrophobicity characteristics (loss, recovery, transfer) of the housing performance.

Table 1: Material Characteristics in new and aged conditions

	Balaruc		Martigues	
Test	"New"	Aged	New	Aged
Hardness (Shore A)	78	79	83	85
ATH content (%)	55	54	56	56
Angle of water (°)	>60	131	>60	not measured
Hydrophobicity class (HC)	1	1	1	1-2
Density (g/cm^3)	1,57	1,57	1,61	1,61
Soxhlet analysis (%LMW)	2,89*	0,93	1,12	1,24

*Sample was stored indoor and developed LMWs during this time

The diminution over time in LMW levels is measured only for the Balaruc sample. For the Martigues sample, one can even see the opposite phenomenon with a slight increase in the rate with aging. These measurements demonstrate that the silicone material is still effective in terms of hydrophobic performance (transfer and recovery), since the LMW remain close to 1%, even for the Balaruc sample after about 30 years aging. For the Martigues sample, the increase in LMW levels with aging may seem surprising at first. This is because the rate is not affected by aging while the material has been electrically stressed. However, it is known in the field of silicones that electrical activity can lead to the creation of low molecular weight chains by cutting the long chains of the polymer matrix. The rate measured on the aged sample is therefore the result of the LMW diminution due to the transfer to the pollution layers over time counterbalanced by the regeneration of short chains by cutting the chains of the polymer matrix under the action of electrical activity. The works of Gubanski, Hillborg and co [4] describes in detail this phenomenon.

3. Investigation at EDF MARTIGUES Research Center (Natural Ageing Test Station)

For more than fifty years, EDF R&D has been carrying out ageing tests and studies of the long-term behavior of equipment under extreme natural external stress at the EDF Lab Martigues site (close to Marseille) (Figure 9a and 9b). The location meets several criteria perfectly suited to this type of study [7, 8]. The region is one of the sunniest in France with over 2800 hours of sunshine per year. This means that the materials are exposed to high levels of ultraviolet radiation. The test facility is about 10 meters from the shore. As a result, exposure to salt spray is maximum, particularly during episodes of south-south-east wind. Huge industrial complexes are in this area. The large petrochemical plant of Lavera is located two kilometers northwest of the site. The prevailing wind regime (north-northwest) carries the industry's emissions in the direction of the test station. The materials being tested are subject to a combination of marine and industrial pollution. The site pollution assessment is carried out according to IEC 60815-1 Ed. 2008 Annex E [2] using a Directional Dust Deposit Gauge device. The measurements classify the site mainly at level d (heavy) and sometimes at level c (medium). In real time, the measurement of leakage current on a reference insulator string calibrated in the laboratory allows to evaluate the current pollution level site.

Figure 9a: Industrial sites, the EDF R&D test station, the local wind rose

Figure 9b: The columns installed in the test area

In 2008, a HTV column (sample 1) was installed and in 2015 a second one (LSR sample 2). Figure 9b shows the columns in the 245 kV(phase-earth) test stand. The ESDD values measured for the HTV column are systematically lower than the same measurement on the RFR column. As a reminder, the LSR column diameter is larger than the HTV column. However, it can be assumed that the LSR column and the related housing profile captures the pollution more easily.

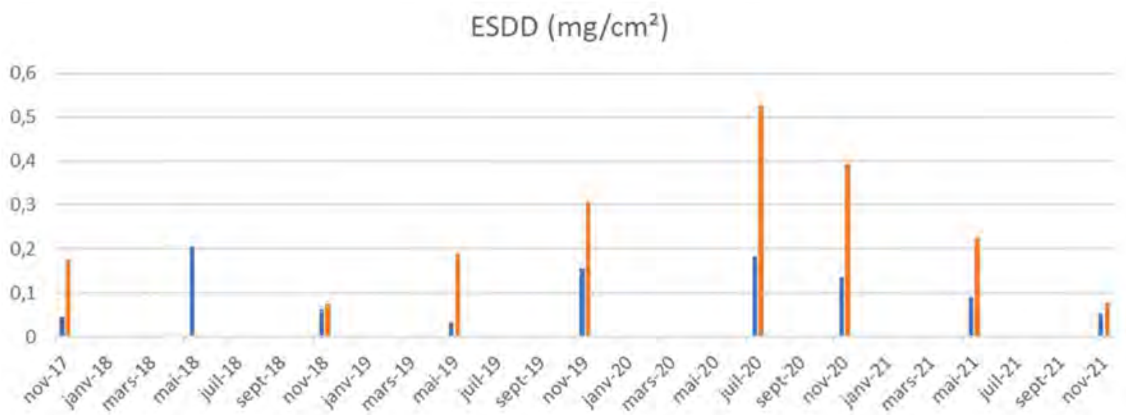
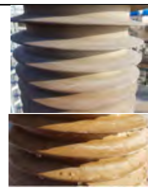
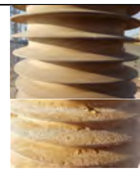
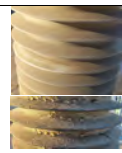
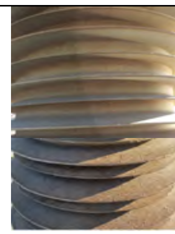


Figure 10: ESDD measured on insulators with LSR (orange) and HTV (blue) housing (the housing profiles were different). The orange material/profile seems to collect more pollution in terms of ESDD

The hydrophobicity measurements according to the standard IEC 62073 Annex (2016) [3] in Table 2 show a wide range of values.

The most hydrophilic areas are close to the electrical voltage and the lowest values are on the ground side. For the same height, the side facing north-northwest is always the least hydrophobic. Depending on the rain episodes prior to the measurement (natural washing) the material regains its hydrophobicity properties.

Table 2: Hydrophobicity status measured on HTV and LSR housings at different times/stages in Martigues test station

	HTV		LSR	
	Facing direction – Top (HV side)			
	N-NW	S-SE	N-NW	S-SE
Nov-17	 HC 5-6	 HC 3-4	 HC 3-4	 HC 3-4
Jul-20	 HC 6	 HC 6	 HC 4	 HC 4-5
Nov-21	 HC 2-3	 HC 2-3	 HC 1-2	 HC 1-2

On one of the sheds of the RFR column, a crack has appeared on the 12th shed over 6 to 7 cm. To see it, you have to bend the shed slightly (Figure 11). At this stage, the cause of the damage is probably due to mechanical shock

Figure 11: Mechanical damage of shed, most probably caused by shock impact

Under certain humidity conditions, electrical activity could be observed on the sample 2 (LSR column), especially on the face facing north-northwest. Some signs of discharges have been observed on the housing of both columns Figure 12a and 12b. An erosion trace is visible on the sample 2 (Figure 12b).

	
Figure 12 a: Sample 1 (HTV)	**Figure 12b:** Sample 2 (LSR)

Leakage current records show low values on both columns. The graph (Figure 13) below shows the evolution of leakage flows during a specific pollution episode (Class 2 to 3 according to first edition of IEC 60815-1986 [5]). The currents follow each other perfectly and remain particularly low.

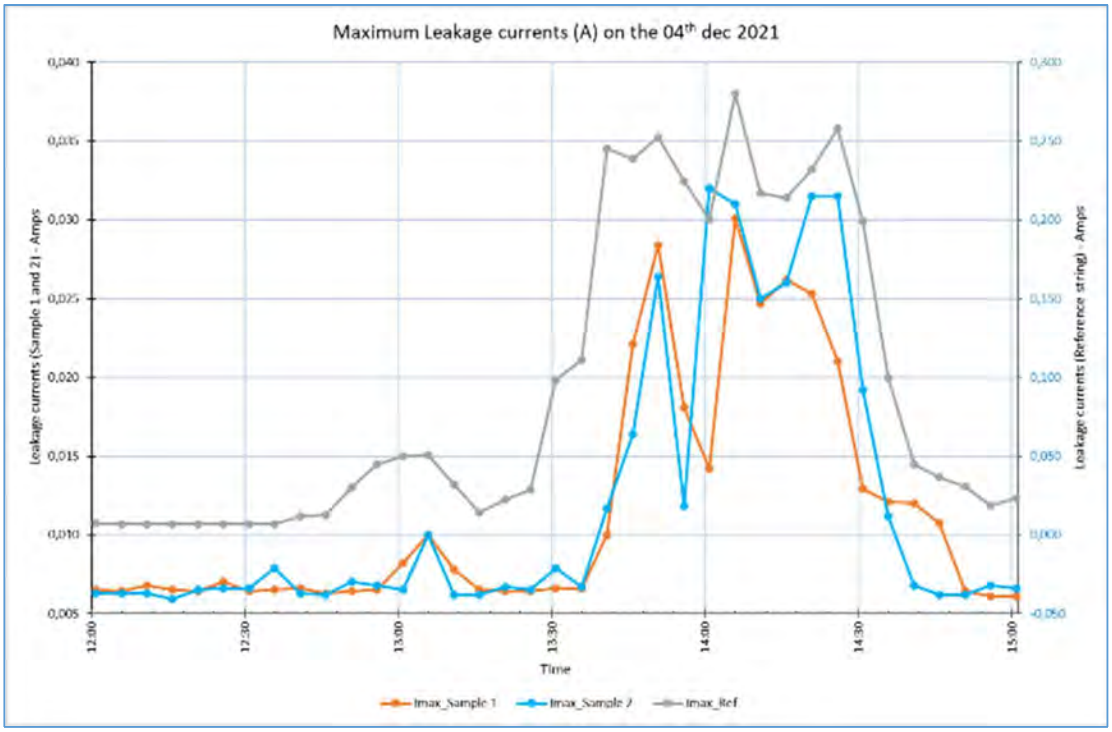


Figure 11: Recorded leakage currents on sample 1, sample 2 and the reference insulator during pollution event

In this case, the leakage currents of both silicones (HTV, sample 1 and LSR, sample 2) are significantly lower than the reference insulator string (glass disks with hydrophobic surface). The hydrophobicity and the related transfer mechanism to pollution layers (HTM) is suppressing the leakage current by almost a factor of 10 compared to the reference insulator. To date, no flashover has been observed on the two test objects. The two columns (sample 1 and 2) are maintained in tests at the EDF R&D site under the same conditions.

The LSR insulator (sample 2) was erected in Martigues to gain lifetime-outdoor experiences with materials and design in general. The creepage was not specially adjusted to the locality, but an existing type for very high pollution was used instead. The erosion took place on the lower side of a large shed (above a small shed) 14 large and small sheds above the earth electrode (not flange). The shed profile is meant for higher pollutions (>31mm/kV). By shortening the creepage was adjusted, but the arcing distance was also shortened to 2,5 m, increasing the electrical stress probably too much. The arcs start at the trunk surface and move out, where it stabilized at the end of the small shed and the lower side of the large shed. This electrical discharge based ageing process is known from other experiences with natural ageing test stations, g. in KIPTS South Africa [6]. LSR reacts more sensitive to erosion compared to HTV but incorporates better HTM (Hydrophobicity Transfer Mechanism) properties. The probability for erosion would have been reduced on the original arcing distance (and original creepage). The observed erosion is the result of a design issue, not a material issue as already stated in other publications [6] and in the Annex A of IEC 60815-3 [7], the creepage should be selected according to the local pollution. Too much creepage or too high creepage factors result in lower long-term performance (although the CF recommendation of IEC TS 60815-3 is still respected).

Table 2: Design Parameters of Test Station Insulators and Samples for Ageing Tests

Parameter	Martigues 2016 - today			STRI 5000h test	KEMA 5000h test	Balaruc 72,5kV LTB	HTV Martigues 1998-2008 (245kV Cable Termination)
Material	LSR	LSR*	HTV	HTV	LSR	HTV	HTV
Average Diameter [mm]	475,5	475,5	273	208	183	230	520
Kad	1,09	1,09	1,009	1	1	1	1,12
CD total	14490	10000	10600	735	1160	2053	7005
CF	4	4	3,26	3,13	2,26	3,3	3,47
SCD corrected	37,6	25,9	25,5	20	20	28,32	31,23
s/p	1,07	1,07	0,78	1,03	1	1,03	1
profile	alternating	alternating	uniform	uniform	alternating	uniform	alternating

The respective diameter correction is performed in accordance with IEC 60185-3 [7] considering potential temporary loss of HTM. The LSR* insulator was shortened in order to adapt the specific creepage distance (SCD) for comparison reasons to the HTV sample.

Additionally, the material properties in Table 3 were investigated for comparison between "New" and "Aged" condition.

4. CONCLUSIONS

4.1 Ageing Performance

The pollution performance of silicone housings with HTV and LSR under harsh conditions (Martigues natural ageing test station as well as in the Balaruc substation) is good. The hydrophobicity and the hydrophobicity transfer to the pollution layers is functional active (transfer and recovery). As a result, electrical activity has no major impact on degradation of the housing. For the HTV housing only traces of dry band arcing but no erosions are visible. For the LSR housing a minor trace of erosion has been occurring on one shed. This kind of minor erosion is more likely caused by the housing profile design (stable discharge due to high creepage factor) rather than by the tracking and erosion strength of the material. The good hydrophobicity transfer performance is confirmed by LMW content determined by the Soxleth method. The Soxleth method is a helpful tool for the assessment of long-term material conditions. Both installation experiences confirm the well working coaction of hydrophobicity and tracking and erosion performance.

4.2 Suggestion of Long-term tests for material qualification

The insight about long-term (multi years) experiences in service supported by those from natural test stations led to the development of artificial ageing tests. The 5000h multiple ageing test seems to reflect the harsh conditions in France (UV, salinity, dry spells) best and is less time consuming (some months testing time) rather than gaining experience with natural test stations (some years). Anyhow, the results from service and test stations are required as calibration references. This information collected during laboratory tests and under real conditions in natural ageing stations are complementary.

4.2 Fingerprinting of materials

The performance of composite insulators is strongly related to the selection of the materials, the manufacturing process and the electrical and mechanical design in relation to the specific application.
The experiences and results shown above are related to specific HTV & LSR silicone compounds, Insulator's design and manufacturing technologies. Each type of silicone compound (LSR/HTV) has a different formulation. the characterization of the composite hollow insulators and the silicone identity may be defined with fingerprinting Tests to verify: a) during the product certification phase, the quality

of the polymeric material and the compliance with the regulations on the external insulation b) upon End-User request, the match of the material provided with the certified material.
The CIGRE TB 595 suggests the characterization of the polymeric material through the following analytical methods:

- Thermogravimetry (TGA)
- Differential Scanning Calorimetry (DSC)
- Infrared Spectroscopy (IR)
- Density measurement

IEC 61462 -20xx for Hollow Core Insulators under revision will not include any specificity for the HV equipment application. IEC Standards for material and design qualification may not be sufficient to assure the long-term performances and should be integrated by additional specifications for material selection and qualification according Equipment manufacturers /Utilities Requirements.

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