



Insulators under fire

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Abstract:

Wildfires can have multiple causes. Overhead lines often just happen to be on the path of a fire, and in this case it is critical to understand what may happen to the line and its components. Besides the risk of having phase ground faults resulting from intense arcing activity in the smoke and heat cloud, resilience is paramount and the amount of damage to lines is a direct consequence of line designs. Distribution overhead lines are obviously much closer to fires than transmission lines and therefore suffer much more of heat damage. Wood poles are clearly identified as a weak link under such circumstances but insulators can also become critical. Even for transmission lines the heat impact can be substantial but not necessarily immediately visible in the short term. Some specific physical characteristics of overhead line insulators need to be clearly identified and taken into consideration either to evaluate the risk of having a line drop during the fire or years later as a result of a weakening of the insulators which survived the fire in the first place.

Another aspect of this problem is to review insulator design features assessing the risk of insulators to be a threat triggering fires on a normal day. Insulator failures can lead to line drops and subsequently trigger fires and catastrophic situations. This is true for either distribution or transmission lines. Hardening the grid means finding more robust line designs and insulators.

In the aftermath of the Californian fires, this contribution is intended to help evaluating what can be done differently and what needs to be changed in the selection of insulators.

Introduction

The question of insulators under fire conditions can be addressed from many different directions. On one hand it is interesting to understand which parameters can be degraded or become critically deteriorated if an insulator is submitted to heat and fire, which itself depends on exposure time and of course type and design of insulator.

On the other hand, and this is perhaps more tricky, one should consider the potential collateral damage to an insulator, not necessarily directly under a fire, but close enough to suffer of heat. In this case, and besides the direct risk of failure related to heat, it is of paramount importance to be able to evaluate the possible weakness induced in the insulator which could be the root cause for a line drop and a fire later on. Some considerations will be given also to line design, especially for distribution poles and insulation methods. This paper will therefore address the following aspects:

- a. Identification of heat and fire sensitivity of the typical insulator designs used on overhead distribution and transmission lines
- b. Degradation of insulator performances when subjected to heat while still apparently operational after a fire
- c. Suggestion for grid hardening from an insulator point of view in distribution and transmission

1. Review of key design features of overhead line insulators with respect to thermal resilience

While temperatures can fluctuate dramatically during a fire it is difficult to know precisely the direct temperature in contact with a fire as well as the duration of the event. This section will therefore look into the key properties impacted by heat for polymer and ceramic insulators based on their design features.

- a. **Composite insulators** exist in a large variety of designs (figure 1) and are made of organic materials which therefore have temperature limitations. The diversity of possible designs and materials used to make these insulators dramatically increases the complexity of their long term evaluation. There are three main design features to look into as described hereafter and checked in detail in section 2.



Figure 1: typical designs of composite insulators

- The fiberglass rod is made of resin reinforced by glass fibers. Resins used for insulators can be polyester, vinyl ester or epoxy. The strongest and best performers are made with epoxy resins. Resins are defined by a thermal set point called Tg (softening point) above which the

resin is progressively losing its mechanical strength. This characteristic can be established by DSC (Differential Scanning Calorimetry). The mechanical weakening of the interface between the glass fibers and the resin in the rod (key for mechanical strength) can also be measured through a torsional strength test on a small slice cut from a rod. Figure 2 shows the test equipment and the results obtained from commercially available fiberglass rods used in the manufacturing of composite insulators. The mechanical resilience of the samples is decreasing with temperature. The sensitivity to heat is directly the result of the chemistry of the resin itself.

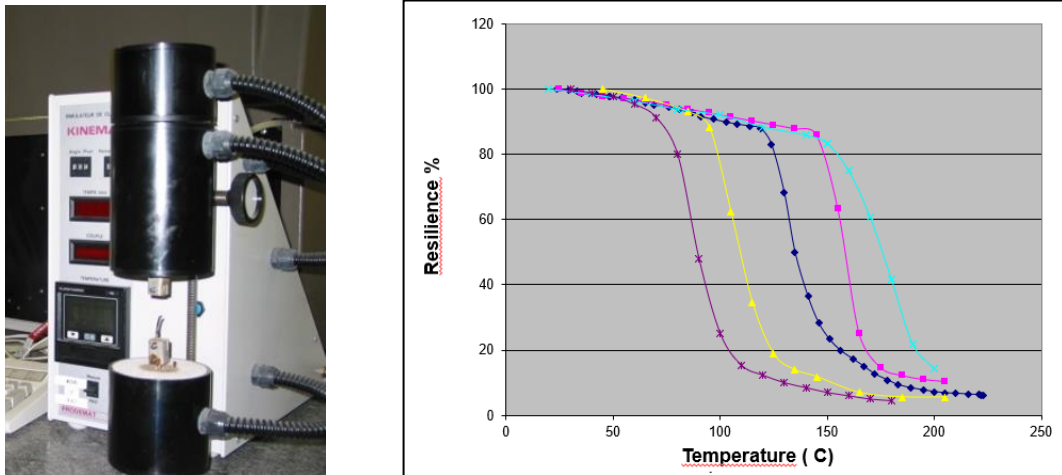


Figure 2: Torsional strength test showing the loss of resilience at the Tg set point

- The housing, typically silicone rubber, is a material designed to chalk and not burn (in most cases). Silicone rubbers exist in numerous chemistries but the most popular silicone compounds contain a fire retardant filler such as ATH (Alumina TriHydrate). For erosion and electric tracking resistance the amount of this additive in the silicone is usually above 45% and can be measured by Thermo Gravimetric Analyses (TGA). Figure 3 shows the graph obtained by TGA of a silicone rubber. The decrease in weight during the test is typical of the loss of water from the ATH molecule during heating. Normally ATH is decomposing around 250C (482 F). Silicone rubber subjected to excessive heat will display a white powderish surface as shown in figure 4.

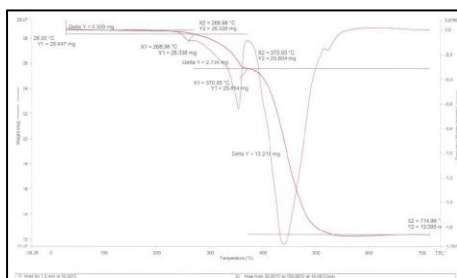


Figure 3: TGA curve of silicone

Figure 4: white powderish aspect of heated silicone

- The end fittings of modern composite insulators are normally crimped by compression (like cable joints). The particularity of this process is to ensure enough pressure through the end fitting (made of steel, cast iron or aluminum) to ensure a sufficient grip on the fiberglass rod which is not a metal. To avoid a thermal relaxation during the molding of the rubber housing onto the core, the end fittings are usually crimped after the housing is in place. Figure 5 shows

this process and the compressive stress distribution into the rod which must be preserved from any damage such as cracks during the crimping (this is still a sensitive operation despite the use of compression sensors intended to control the process)



Figure 5: crimping process and internal stress distribution on a fiberglass rod/fitting connection

b. Porcelain insulators, besides their end fittings (cap in cast iron and pin made of forged steel) are made of mineral materials. The cement is either alumina cement, or (usually) portland cement. The assembly is usually not made with pure cement but with a mortar containing silica (sand) and other minerals. The stability of the cement with temperature is high and the resilience of such an assembly is mostly driven by the design of the head and the coupling of the thermal expansion coefficients between the end fittings, the cement and the porcelain body. Figure 6 shows the linear expansion coefficients of typical porcelain insulator components. The particularity of the porcelain body is related to its heterogeneous structure of porcelain which contains crystals having themselves different properties. This aspect of porcelain is what leads to the inherent ageing of the dielectric with possible punctures of internal crack propagation (figure 7). This parameter needs to be taken into consideration for resilience performance under heat (see section 2).

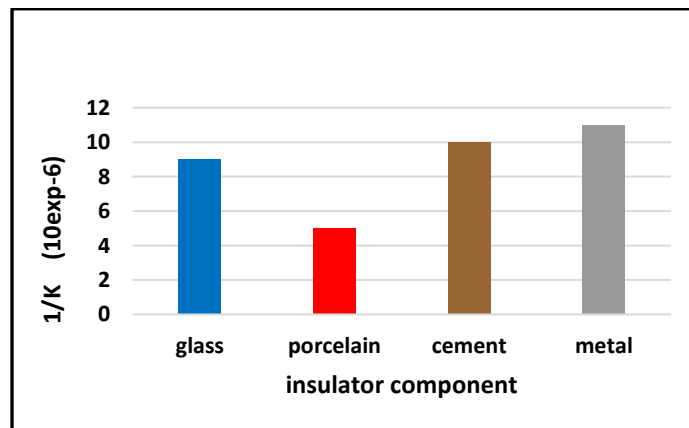


Figure 6: linear expansion factor coefficient of glass and porcelain insulators and their components

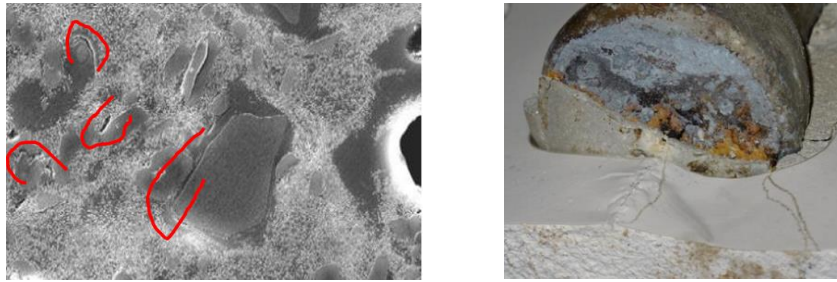


Figure 7: microstructure of porcelain and internal microcracks leading to punctures of the dielectric

- c. **Toughened glass insulators** are assembled like porcelain insulators with cement (usually alumina cement but sometimes portland) but do not have any microstructure and the coupling of the thermal expansion factors is more homogeneous as seen in figure 6. The glass is toughened for strength purposes and the prestresses built in the bulk thickness of the dielectric are a balance of compressive and extension forces (figure 8). The mechanical shield represented by this toughening operation makes glass immune to any crack propagation or puncture. A toughened glass insulator will either be intact or shatters if any excessive adverse stress is applied. In this case the glass insulator becomes a so called “stub” (figure 9) which electro mechanical performance remains intact (no internal puncture, and high residual strength). When subjected to heat the glass can suffer of superficial chips or can shatter if exposed to brutal and immediate heat. It is important to understand that the toughening prestress is permanent unless the glass shell is exposed to a permanent temperature of 700°C (1300F) for a duration of 6 hours or more, which will not happen since the insulator will shatter at a temperature of approximately 400F leaving a stub which remains sound. In the next section such properties will be described in detail.

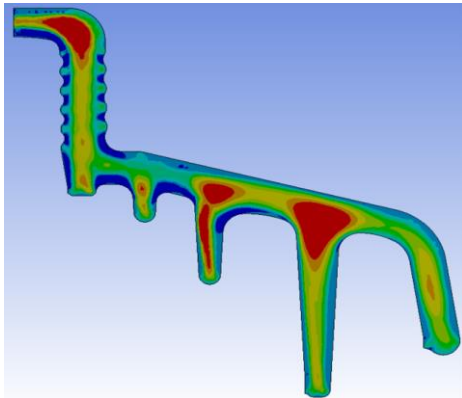


Figure 8: toughening internal prestresses



Figure 9: typical aspect of a “stub”

2. Resilience tests of various insulator designs under heat

- a. **Polymer insulators**: The combination of the crimping compression of the end fitting over the fiberglass rod itself sensitive to heat (see figure 2) can be feared as a weak point under heat conditions. In order to establish this property tests were performed with various composite insulators (mostly distribution dead ends). Samples were introduced in an oven for 3 hours and pull tested while still hot until failure occurs. Figure 10 shows the normalized results with a reference at 100% corresponding to their ratings. It appears clearly that the strength goes rapidly below the everyday load design of the line.

An additional test was performed with insulators exposed at 300°C (572F) for short durations. Figure 11 shows again normalized strength with reference to the rating of the insulators. It appears that very

quickly (less than 30 minutes the strength goes down to 30% to 40% with serious risks of line drop whenever such loads are encountered.

In most cases the rod slips out of the fitting as shown in figure 12. It can be interesting to note that the best values (but still very weak results are obtained with forged steel fittings and fiberglass rods which have a very high Tg. (Tg > 180°C, 360F)

This test sequence shows a major risk for having a line drop with polymers exposed at high temperatures. At some point they will not sustain everyday normal loads.

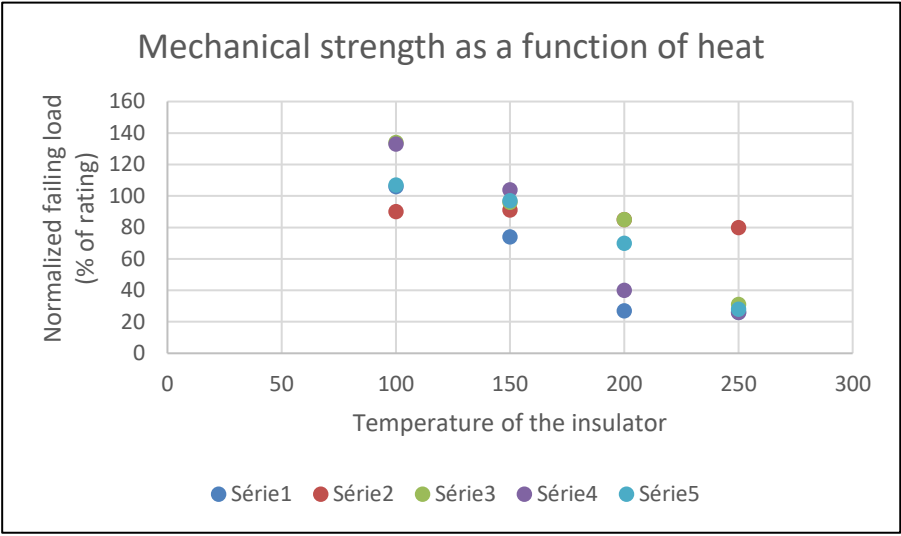


Figure 10: mechanical resilience of composite insulators at different temperatures (temperature in °C.)

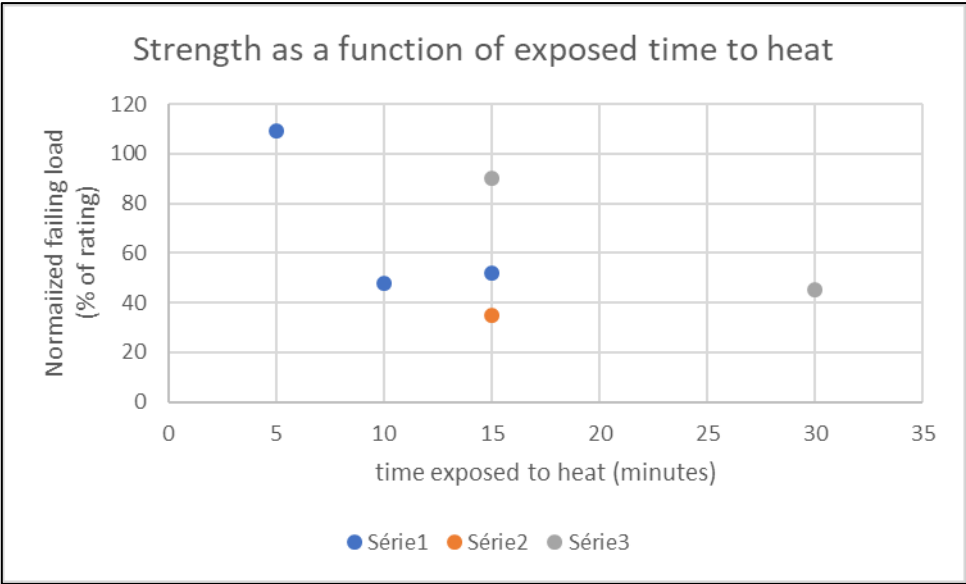


Figure 11: strength of various composite insulators as a function of time after being exposed to 300°C (572F)



Figure 12: typical aspect of the tested units after the mechanical pull test

- b. **Porcelain insulators** underwent a similar test with various insulators placed in a furnace for 3h before being pull tested. Given the risk for porcelain to puncture the relevant test in this case is the ANSI M&E test. A number of units failed with cracks either visible or not. As expected, the difference in expansion between components favors this type of failure. However, and while most units survived their mechanical stress with no separation below the rating, most failed electrically from internal punctures not visible from the outside. This demonstrate that once porcelain insulators have been directly or not in contact with high heat there is a major risk for having hidden defective units on a power line. Figure 13 shows the M&E test results and figure 14 the typical physical aspects of the units after test.

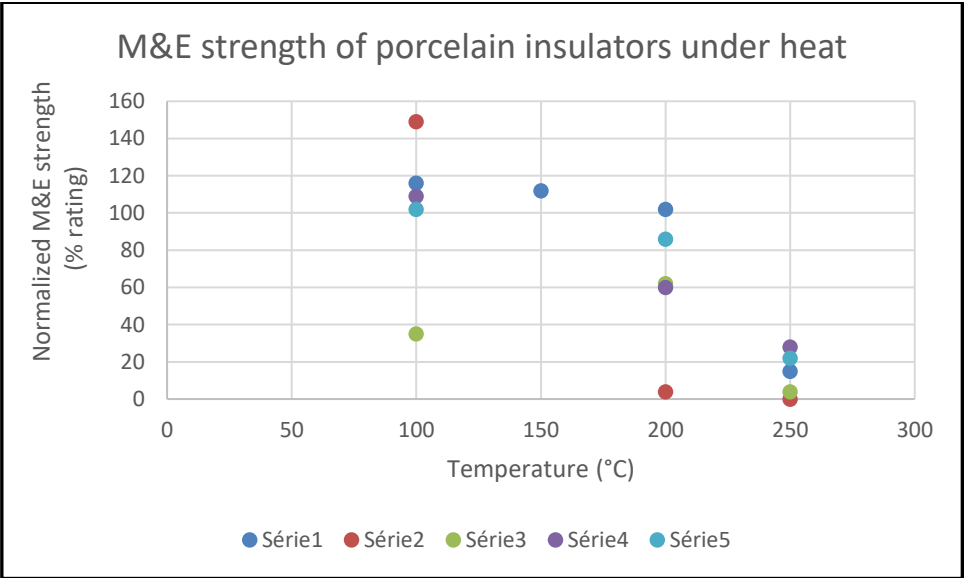


Figure 13: M&E test results of porcelain insulators subjected to heat prior to pull testing



Figure 14: overall aspect of the insulators after the test

It can be noted that while these results show only an M&E failure, old porcelain insulators carrying already deeper and older cracks internally might lead to a string separation which could adversely under such conditions drop a conductor. (simulation in a thermo mechanical test as shown in figure 15). The cement itself (in fact a mortar) shows no specific heat sensitivity. The dehydration of the cement could generate some slight crumbling but by design the head works under compression leading to a wedge effect. The tested units were all assembled with Portland cement. The separation of the head is strictly the result of the porcelain body cracking in two pieces.

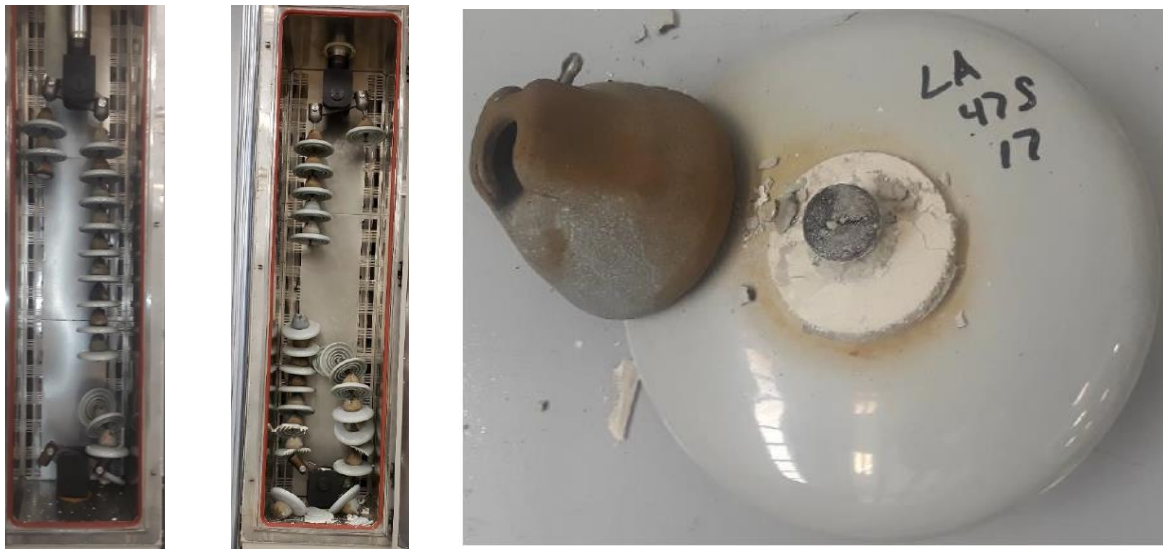


Figure 15: string separation during a thermo mechanical test performed on weak porcelain units containing already cracks from years of ageing.

- c. **Toughened glass insulators** were tested with the same procedure. The insulators were pre heated in an oven for a duration of 3h but in this case up to 400°C (752F) since, as shown in figure 16 not much was happening. (Toughened glass does not puncture, and as per ANSI, the test is a mechanical test only, no use for an M&E combined given the fact that toughened glass does not generate cracks but shatters). The test was carried out to the maximum temperature of the oven.

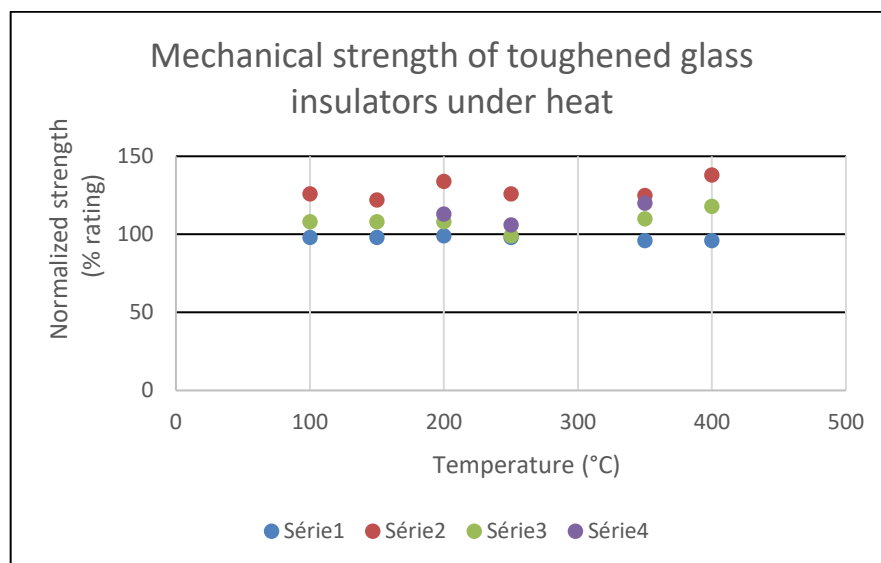


Figure 16: Mechanical test results on toughened glass insulators (normalized to the rating)

In a few cases the glass shattered before the mechanical separation, but in all the other cases the failure mode was a breakage of one of the fitting, usually the pin as shown in figure 17. It is also interesting to note that, while all the results seem very stable the lowest performer was assembled with Portland cement. Without enough elements to come to any conclusion on the influence of cement, it can be interesting to remember that Alumina cement is a better thermal refractory than Portland.



Figure 17: Typical aspect of the glass units after the test

Since toughened glass can shatter, an additional test was carried out on stubs which were preheated as well and pull tested. Figure 18 shows the normalized test results. All the failure modes were identical with a pin pull out taking out the cement with the pin from the inside of the head of the insulator as shown in figure 19. All the values remain above 65% of their initial rating, which is the requirement in ANSI for new insulators tested for their residual strength.

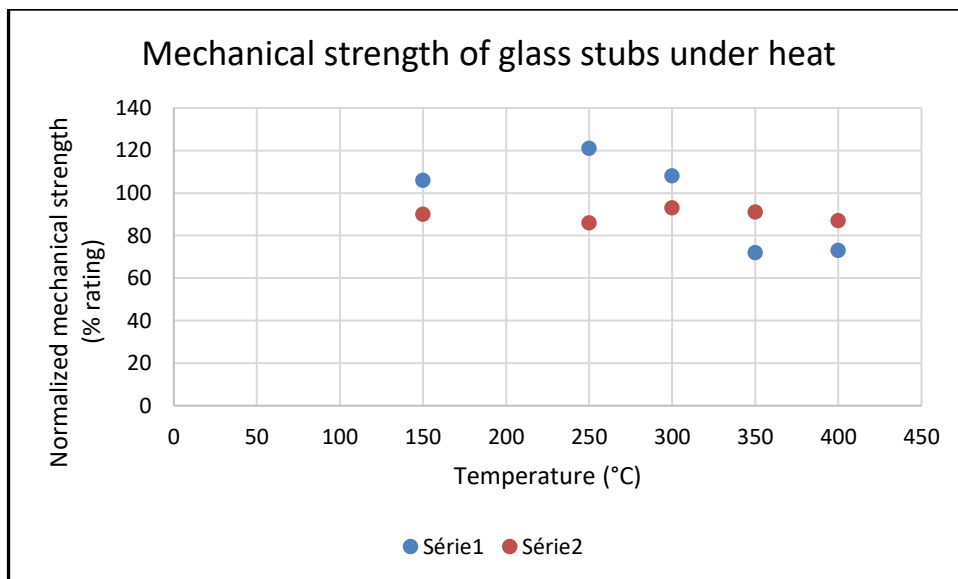


Figure 18: Normalized mechanical strength of stubs preheated and pull tested at different temperatures



Figure 19: Overall aspect of the stubs after the mechanical test under heat conditions

3. After fire considerations

In the previous section we analyzed the risk factor for having a line drop or a major accident related to an insulator during a fire. At this stage we know that polymer insulator most likely can snap and drop a conductor. Porcelain, less likely unless the insulators are old. Glass present no risk either intact or broken (stub). The next question is related to the management of the lines from a maintenance aspect after the fire is over. Is there a risk to leave some insulators which were previously near a fire source and subjected to heat?

Porcelain insulators, as shown earlier will not recover from their degradation and if punctured they will be a possible liability for the future life of the line. Glass insulators are almost totally immune, and the only change might be a few units shattered. This is easy to spot, and does not constitute a risk (stubs keep their mechanical strength and are not electrically punctured).

Composite insulators are different. Two questions are open:

- What is the mechanical strength of a polymer which survived the heat event after it cooled off?
- What is the condition of the silicone housing and are there risks to leave them on the line?

a. Mechanical strength of polymers after cooling

One question left after investigating the behaviour of polymers under fire is to know their residual strength once they cooled off. Tests were performed on insulators which had previously been subjected to heat maintained for 2h at 300°C (572F). The results are shown in figure 20 with a strength between 20% and 30% of the rating. This result can be compared with the results on broken glass (stubs) largely above the standard requirement for residual strength.

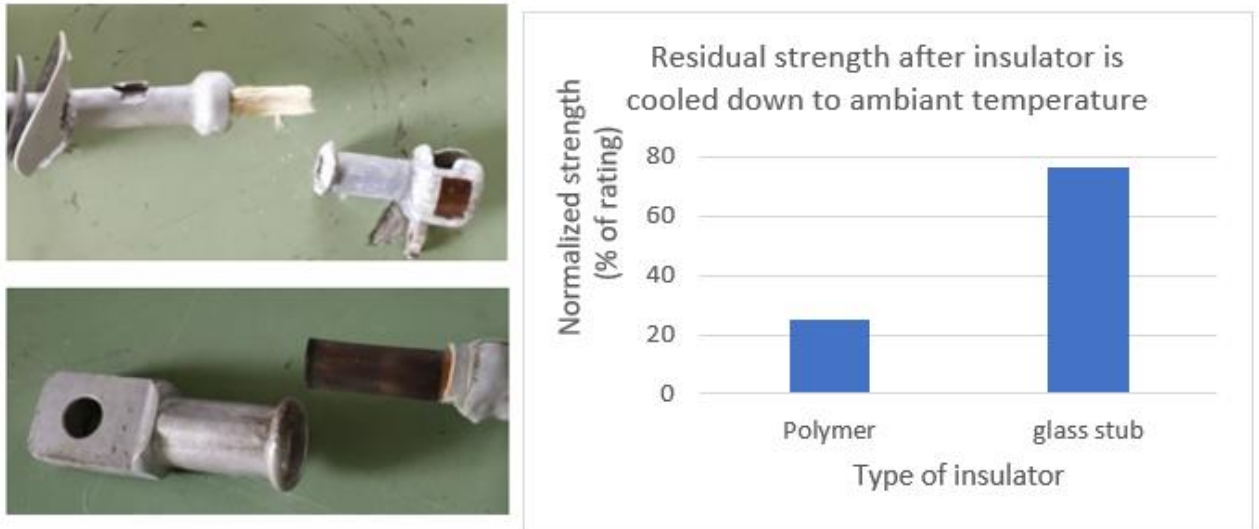


Figure 20: Fitting pull out after the insulators were cooled down after a heat cycle at 300°C and comparison with results on glass stubs tested in the same conditions

b. Housing permanent degradation and associated risks

In section 1 we described the chemical mechanism of protection offered by ATH in silicone compounds. The main target is not to be a fire retardant, even if the chemical used is classified as such. The main attribute of the addition of this filler is to slow down the erosion of the silicone during dry band arcing or pollution related activity. At some point in time the rubber will fail leading to cracks on the core (figure 21). Of course the rubber does not burn, and many compounds used in the overhead line industry are classified HB and V0 in IEC60695, but once cracks appear the insulator is doomed to fail either electrically (internal tracking) or mechanically (brittle fracture, decay fracture...). It is important also to consider the existence of sulfuric acid and other fire related acids which will destroy progressively the core of the insulator. In most cases these degradations are not easy to spot visually as shown in several cases presented in figure 21.



Figure 21: Cracks in silicone housing left after being subjected to heat for a few hours

4. Possible recommendations for grid hardening

Starting from a basic concept that any type of equipment capable to burn should be banned, wood poles should no longer be used especially on distribution lines; replacing those with steel, or concrete poles would be the most effective choice

Strengthening the pole brings the weak link on the insulators especially if they are pin or post types working under cantilever which limits are driven by stubs, bolts and the intrinsic strength of the pin or post itself. It appears also that a tensile load is easier to secure consistently than bending loads. Therefore a line design where deadends are strictly made of glass with tangent structures made of concrete with suspension glass cap and pins would offer the best resilience. The grid hardening would result from insulators immune to heat and a mechanical structure where heavy duty strings working systematically in tension with ratings which could go up to 20kips or 30 kips or more are being used. Figure 22 gives examples of such systems using glass insulators for their strong resilience to adverse environments such as those encountered in fire driven environments or areas where conductors are not allowed to touch ground under any circumstances.



Figure 22: examples of resilient distribution lines using concrete poles and toughened glass insulators in suspension and tension.

Conclusion

The findings of this program are pointing out typical weaknesses and strengths of the different insulator designs:

- Composite insulators mechanical strength drops quickly leading to major risks of line drop under heat or significant reduction of strength after the fire is over
- The degradation of the housing of composite insulators under heat and fire can breach the integrity of the housing leading to moisture and acid ingress. Future failures and line drops after the fire is out could occur if these small cracks are not spotted and the insulators replaced.
- Porcelain insulators would not drop a conductor unless already old and aged in their microstructure. However the large gap between the thermal expansion factors of the components of porcelain insulators will lead to punctures or internal cracks not visible from a visual inspection.
- Toughened glass insulators do not lose their performance. If a thermal shock breaks the glass the stub left remains mechanically safe even at high temperature. Visual inspection is obvious after the fire with no urgency to be replaced.

The grid hardening can benefit of these results with the following recommendations:

- Use glass especially for deadends but also for tangent structures
- Modify the design of the distribution lines design replacing pin and post types by suspension strings working only in tension and installed on concrete poles.
- Transmission lines should use glass only.