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Necessary Check Points & Testing for Screening the Quality of Insulators

J.M. George, E. Brocard, S. Prat, F. Virlogeux, D. Lepley
Sediver Research Center, France

Introduction

The increasing demand for overhead transmission line components (among which insulators) has brought into the international market new or unknown players creating a larger spectrum of performance and quality which is not necessarily easy to spot with existing standards or specifications (this is true for all three technologies either glass, porcelain and polymer insulators). End user's procurement offices are not yet prepared for a differentiated approach based on technical merits looking almost exclusively to buying cost and engineering still uses in most cases a relatively simple technical description strictly in line with some national standard. Today however we see more and more standards engineers asking for more stringent technical criteria to be introduced in their specification to reinforce their own selection tools and prevent them from qualifying low performers.

It might be time to review the standards and possibly redefine quality and performance to the benefit of the end users often blinded when comparing brands and products "on paper". End users themselves have their share of responsibility in the final quality of the products their buy since not all of them take the time to make detailed audits of their potential suppliers, and not all of them send one of their technicians in the factory to select randomly the samples for the acceptance tests... Travelling budget limitations favor an acceptance process based strictly on documentation review. This paper will review several key points to take into consideration, most of them covering glass and porcelain, some more specific to glass. It is also a contribution to some ongoing work intended to revise IEC 60383 which itself is the result of concern and research published in the recent past [1].

1. Current status of the major standards

The most commonly used standards for overhead line insulators are ANSI [3], IEC [2]and CSA [4]. While we recognize that many insulators are being installed in China, it remains a separate market environment with its own standards, but still, we can say that the GB Chinese standards are often based on IEC.

The standards describe test protocols but little if any material description. Quality of materials can sometimes show up only after several years of service and this should be part of the review. Likewise, experience has been gained over the years from weaknesses of some designs not yet integrated in the battery of tests which should help weeding out low performers.
The following tables describes briefly a comparison between IEC60383, ANSIC29-2B and CSA 411-1-16. It appears very rapidly that ANSI and IEC are less demanding than CSA which in many aspects goes a few steps further introducing new tests. We must also mention the separation between type tests and sample tests which differs between standards, (quantities, and test itself). The question here will be to determine if all manufacturers are capable to demonstrate consistency and if some tests should not be repeated at the level of the acceptance tests.

Test	ANSI C29-2B	CSA 411-1-16	IEC 60383-1
Low frequency dry	YES	YES	NO
Low frequency wet	YES	YES	YES on short strings
Lightning impulse test	YES	YES	YES on short strings
Dimensions/ visual	YES	YES	YES
Steep front test	NO	YES	NO (*)
Oil puncture test	YES	NO	NO
RIV	YES	YES	NO (*)
Thermo-mechanical (TM)	-30°C/+40°C 60% load / 3S	-50°C/+50°C 70% load/ 4S	-30°C/+40°C 65% load/rating +0,72S
M&E	YES 3S	YES 4S	YES 1.2S
Thermal Shock	YES Temp. diff. of 90°C	NO	NO
Residual strength	k>=0.6 **no** thermal precond.	k>=0.65 +thermal precond.	NO (*)
Impact strength	YES	YES	NO (*)
Cement expansion	Only for Portland	Only for Portland	NO (*)
Cotter key uncoupling	YES	YES	NO

Table 1: Brief summary of type/design tests described in the standards
(*) tests described in other IEC standards

Test	ANSI	CSA	IEC
Dimensions/visual	YES	YES	YES
Porosity	Porcelain only	Porcelain only	Porcelain only
Galvanization	YES	YES	YES
M&E	YES 3S	YES 4S	M only for glass. 1.2S
Puncture test	Oil test only	Oil or steep front	Oil or steep front
Coupling	YES	YES	YES
Steep front test	NO	Option instead of oil test	Option instead of oil test
Temperature cycle test	NO	YES Δ=70C	Porc. Δ=70K Glass Δ=100K
Residual strength	NO	NO	NO

Table 2: Brief summary of sample conformance tests described in standards

Test	ANSI	CSA	IEC
Colt/Hot thermal	YES 1 time glass only	YES 2 times glass only	NO
Hot/Cold thermal	YES 1 time glass only	YES 1 time glass only	NO
Flashover	Porcelain only	Porcelain only	Porcelain only
Visual inspection	NO	YES	YES
Mechanical	YES	YES	YES

Table 3: Brief summary of routine tests in standards

2. Material description

2.1 Metal end fittings

The description of the materials to be used for the components remains relatively vague in ANSI calling only for commercially available malleable ductile iron or steel. IEC 60120 does not give any detail either. This is in contrast of CSA describing in detail the type of casting and steel (minimum elongation of 10% for malleable and 12% for ductile iron, with a requirement of cold impact strength as per ASTM A370). Cotter keys also are only described in CSA with a clear reference to the type of stainless steel (ASTM A580 or 580M S30400, S32100 type 304, 314, 321 or EN 10088-1 type 1.4301 with Wicker hardness above HV150) whereas IEC 60372 doesn't specify any material reference.

2.2 Cement

Cement is another major component. All the standards today are asking for the expansion test per ASTM C151/151M whenever the insulator is made with Portland cement. For aluminous cement, there is little description and besides the nature of the cement itself aluminous cement can be cured in cold or hot water. The cheapest being cold water, is there any benefit to ask for hot cured cement and if so what are the reasons and what consequences to expect? The next section will focus on cement answering these key questions.

Table 4 describes roughly the main oxides present in the various cements. Portland cement has a much higher content of CaO than aluminous cements (approximately 40% in a final mortar mix for a content above 60% when considering a pure cement paste prior to mixing with other additives). The possible transformation into Gypsum (larger crystal) could lead to a failure of the insulator through the expansion of the cement (called cement growth as shown in figure 1) if the batch of cement is prone to expansion, which is the reason it needs to be tested as per ASTM C151 . Aluminous cements have much less CaO and much more Al_2O_3. The numbers in this table are typical of pure cement, while manufacturers use mortars where the cement is the major but not only component. The rate of Alumina should therefore be considered around 30% in an industrial mortar used in the assembly process of insulators.

Chemical elements	*Portland cement*	*Aluminous cement*
SiO_2	**19 to 25 %**	**< 6 %**
Al_2O_3	**2 to 9 %**	**> 37 %**
Fe_2O_3	**1 to 5 %**	**< 18.5 %**
CaO	**62 to 67 %**	**< 41 %**
MgO	**3% max.**	**< 1.5 %**
SO_3	**/**	**/**
TiO_2	**/**	**< 4 %**
$Na_2O + K_2O$	**1.5 % max.**	**/**

Table 4: Typical chemistries of pure cement such as those used for insulators

Checking for Portland versus Aluminous is easy and some utilities have initiated a chemical check of a sample from supplied insulators after they discovered that they had been served with Portland assembled units while the drawing was calling for aluminous cement. A simple chemical analysis will show the respective contents of CaO and Al_2O_3. Aluminous cements should exhibit at least 30% of Alumina oxide.

Figure 1: Example of radial crack in porcelain after Portland cement growth

The curing of aluminous cement in water can occur through two different crystallographic patterns. If cured in cold water (ambient temperature) the crystals will take a hexagonal shape which is unstable and will progressively convert into a stable cubical stage. This conversion process can take years unless the cement is cured in hot water (temperature around 70°C) in which case the conversion is immediate. Obviously, the process of hot curing will be more expensive but leads directly to a stable mechanical performance. It has been clearly demonstrated that when a cold cured aluminous cement is progressively converting from a hexagonal to a cubical shape there is a drop of strength (which eventually will be restored when the conversion comes to completion). Figure 2 describes this phenomenon.

The evolution of the strength of a cold cured cement cannot be predicted in time and value. To better determine such effects the residual strength test can be a good indicator.

To differentiate cold from hot cured, another approach is possible using thermo-gravimetric analyses (TGA) through the identification of hydrates present in the mortar.

CAH_{10} (CaO, Al_2O_3, $10H_2O$) and C_2AH_8 ($2CaO$, Al_2O_3, $8H_2O$) are the hexagonal unstable hydrates described previously. C_3AH_6 is the cubic stable hydrate. The cold cured process introduces temporarily hydrates such as CAH_{10} and C_2AH_8 which progressively react to become C_3AH_6 ($3CaO$, Al_2O_3, $6H_2O$).

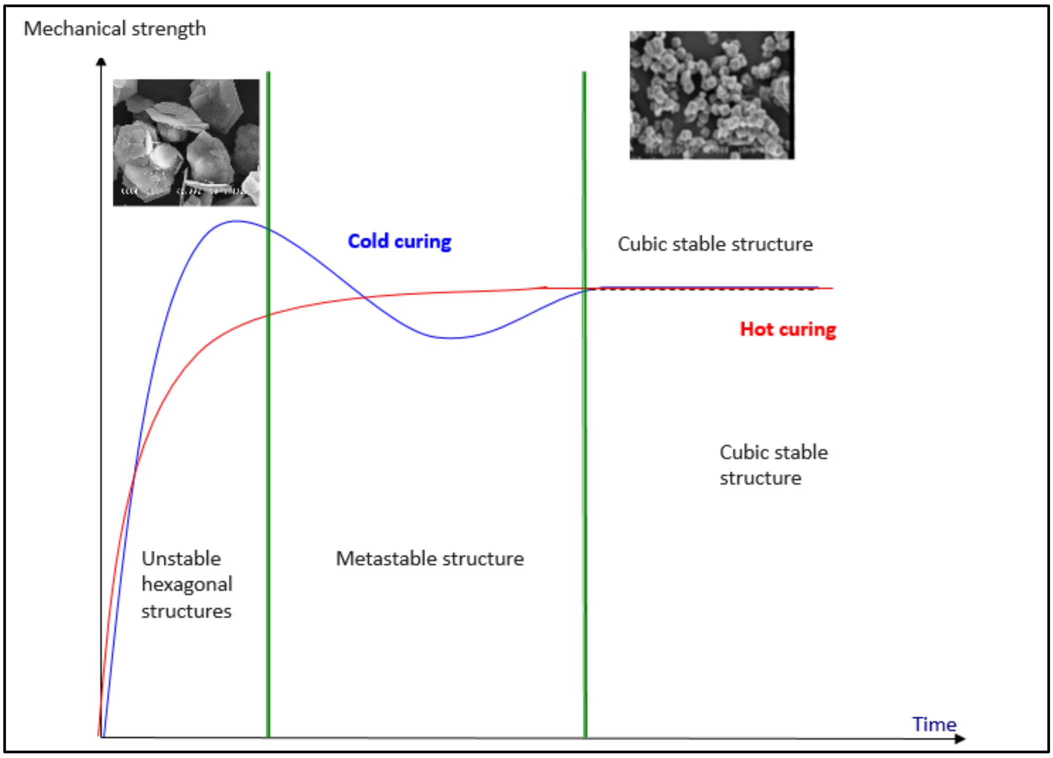


Figure 2: Curing and conversion process of aluminous cement

Among the reasons for the strength to be lower during this unstable phase, table 5 shows the difference in density of these hydrates, meaning higher porosity and therefore lower strength.

Hydrate	Volume (cm^3) (for 1CA)	Density
CAH_{10}	197	1,7
C_2AH_8	125	1,95
C_3AH_6	93	2,5

Table 5: Relative density of the various oxides involved in the curing of aluminous cement

The TGA spectrum shown in figure 3 compares a cold cured and hot cured aluminous cement. It is easy to discriminate which one is being used in an insulator if there was a doubt. Quite a number of utilities leaning towards aluminous cement specify today hot cured cement only. **So does CSA.**

The evaluation of the performance and type of curing can also be spotted through a residual strength test as described in section 3.1 below.

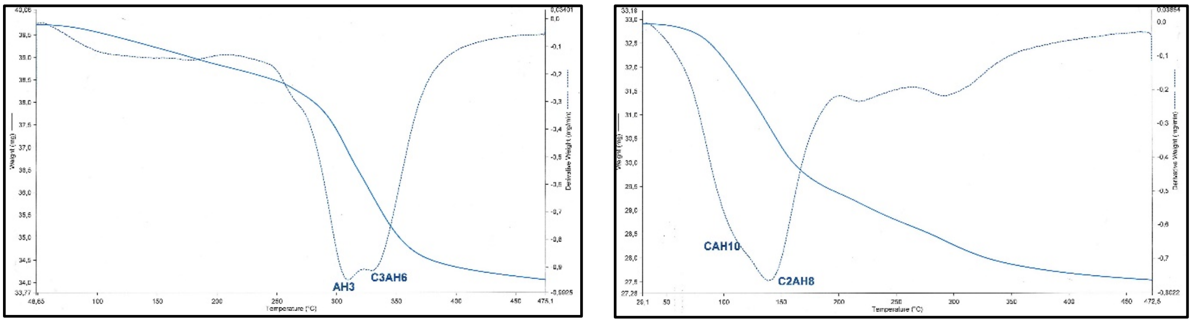


Figure 3: Left: TGA on hot cured cement with a completed conversion where only cubic structure is present (as per hot curing) Right: TGA with unstable hydrates as per cold cured aluminous cement.

2.3 Glass

a. Purity of glass

Unlike porcelain which by nature has a heterogeneous structure made of a variety of crystals, glass is amorphous and has no structure at all. This is one the main reason why glass makes a perfect dielectric material [5] which does not age. However, during the melting process of glass it is possible to have impurities in the glass melt. This (among other reasons) has a direct impact on quality regarding so called "self-shattering". These impurities are usually, but not only, coming from the wear and tear of the refractory walls (figure 4). In the mid 1980s Sediver has studied and identified the diverse root causes of these defects leading to new techniques and processes.

Figure 4: Typical aspect of the inner walls of a glass furnace after several years of service

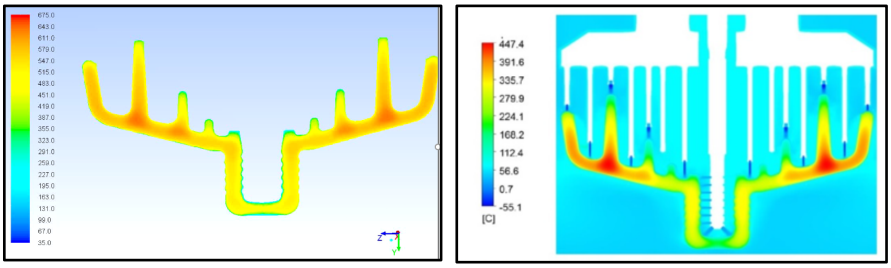
While a broken glass disc (also called “stub”) is not a problem for the performance and safety of a line (no need to replace a stub in a string [6]), excessive numbers of stubs could become a concern which requires maintenance. While there is no standard dealing with this question, utilities should systematically request performance certificates from other utilities where the self-shattering rate is clearly reported. To this effect such certificates should refer to large quantities supplied outside the manufacturers home country (to ensure full disconnection and independence of expression). At least 3 such certificates dealing with deliveries in quantities above 100000 pieces in service for 10 years should be requested. The benchmark for self-shattering is 1/10000 per year.

Table 3 in section 1 describes several thermal shocks intended to help weeding out glass shells containing impurities. Major manufacturers have implemented specific additional tests to further improve the quality of glass targeting some specific impurities. Technical specialized literature on glass purity refers to procedures used in the flat glass industry such as “soak test” or others, and some manufacturers advertise a full compliance to such treatments to explain their quality strategy. Reality is more complex since glass discs are not flat and do not have regular thicknesses across their volume. Based on the above-mentioned research in the early 1980s, Sediver has customized such processes to take into consideration these particularities demonstrating a consistent benchmark level with a shattering rate at or below 1/10000. The quality level reached today is a combination of the acquired knowledge from the factory quality indicators and line surveys where actual shattered discs are being counted. While there is no standard describing the optimum processes involved (this knowhow cannot be disclosed by manufacturers), there are still many ways to make the evaluation of the effectiveness of the glass manufacturing processes through actual performance certificates from the field as explained earlier.

b. Molding and toughening

Molding and toughening are important steps in the process and need to be considered carefully. The quality of the insulator could be compromised with glass shells containing defects from any of these operations. Section 3.2 will describe test procedures which can be helpful in the screening of these aspects, and it will appear very obviously that steep front test really makes sense in a sample test plan intended to check for consistency.

Toughening is what makes glass strong enough to be used for overhead transmission lines. Some will try to convince the market that “the more the best”. In fact, this process requires a careful approach and both product shape and tools have to be designed as a combination. Figure 5 shows a typical example of a digital simulation of the cooling process during toughening showing how intimately product and tools are connected to precisely match thermodynamic requirements.



<u>Figure 5 :</u> digital simulation of a toughening cooling process and relevant simulation of the tools producing this process.

Some utilities which have acquired insulators from various brands have reported some surprises when dealing with some breakage patterns questioning the quality of toughening such as those shown in figure 6. This is very different from what happens when small chips of flakes appear after a strong impact on the glass surface which is always possible and acceptable when the flake remains in the volume of glass under compression.

Figure 6: Improper toughening of the glass shell seen on an insulator from a manufacturer received by a utility.

Some engineers and experts recommend making the assessment of the quality of the toughening by breaking samples of glass based on size and distribution of the glass pieces. The impact strength test could be reviewed with a description of the typical breakage pattern expected.

3. Type tests and sample tests

3.1 Residual strength test

A residual strength test is performed to demonstrate the ability of an insulator to keep a minimum mechanical strength once it is damaged. This mechanical test is therefore performed on broken discs with the skirt removed if it is porcelain and a stub if it is glass. By design the mechanical load is transferred between cap and pin mostly through compression. Therefore, the design of the head of the insulator as well as the cement are critical components which performance can be assessed through this test.

In the case of cold cured aluminous cement new insulators would show very high values, but progressively, if tested while the conversion (section 2.2) is in progress the strength could drop close to half of their initial values. The phenomenon can be artificially accelerated if the samples are immersed for some time in hot water. Figure 7 shows test results on cold cured aluminous cement insulators which were immersed for various times in hot water. The dip is obvious and can reach 50% of the rating of the insulator when applying a 2σ standard deviation.

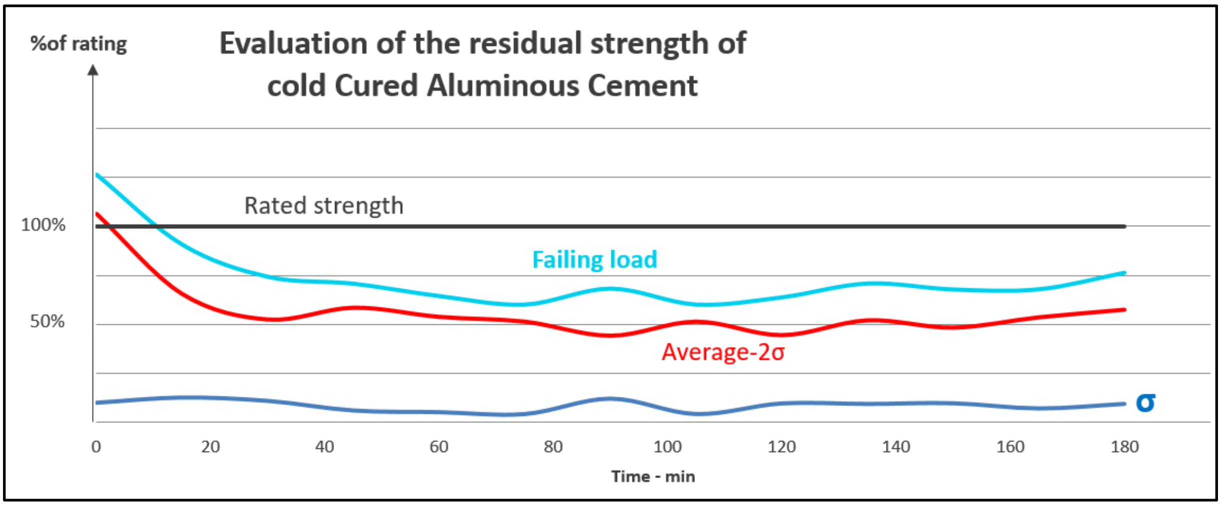


Figure 7: Variation of cold cured aluminous cement strength as a function of time left in hot water prior to be tested in residual strength test conditions.

Today ANSI does not specify any thermal preconditioning prior to the residual strength test. IEC and CSA call for a preconditioning at a temperature around 75°C max. which is just not enough to make this risk visible. We believe that all standards should include a preconditioning at hot temperature around 85°C or 90°C. For a hot cured cement, and since the conversion is completed during manufacturing such test would show no variation of strength.

Among the reasons for being careful with residual strength of insulators we can take the example, of the USA with the new NESC guide (rule 277) which allows now utilities to load their lines up to 65% of the rating of the insulators. The current standards, as shown in table 1, are not offering any buffer.
To this effect a value of residual strength after thermal preconditioning (as explained earlier) of 80% seems an adequate move for ensuring full reliability of insulators. This test needs to be a sample test, possibly in addition to chemical verifications of the cement itself.

3.2 Steep front test

IEC has developed a steep front testing standard (IEC 61211) to test dielectrics under severe overvoltage conditions (2.5 or 2.8pu see figure 8) without the need of oil like in the traditional oil puncture test where the dielectric is tested under power frequency conditions. Today there is sufficient data available to support the steep front test in replacement of the oil test. This test is pointing out insulators which contain defects generated during manufacturing, either porcelain microcracks and structural defects or molding and glass defects for toughened glass insulators.

It is also clearly established today that when doing a puncture test in oil the main parameter for making up the result is not the insulator but the oil. Very little is being said about oil characteristics in ANSI. CSA and IEC at least give a resistivity value to be set between $10^6\Omega m$ and $10^9\Omega.m$ but nothing about dielectric strength. Bad insulators can go through the oil test while good insulators could fail because of a thermal gradient in the oil if it is too resistive. Standards should all converge today towards steep front testing provided they follow IEC 61211. Since this test offers a good idea of the quality of the insulator, it should be recommended to be done not only as a type test but also as a sample test through a **random selection in a batch of insulators**.

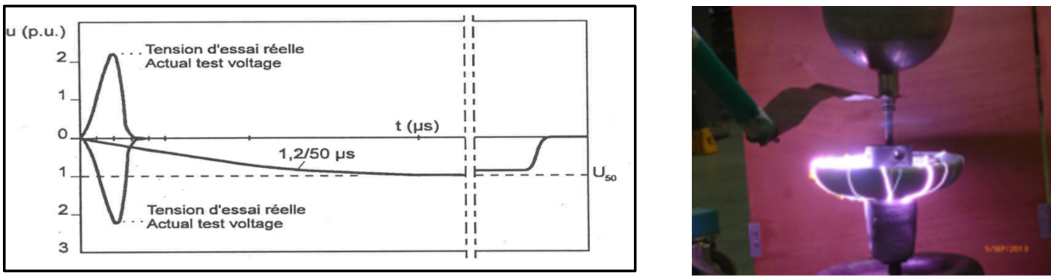


Figure 8: Steep front wave test and set up

CSA is calling for steep front test not only as a normal type test but also after a thermo-mechanical test (figure 9). By pre-stressing the insulator the test simulates the behavior of an insulator not when it is new but after several years of service going through a variety of environmental and service conditions.

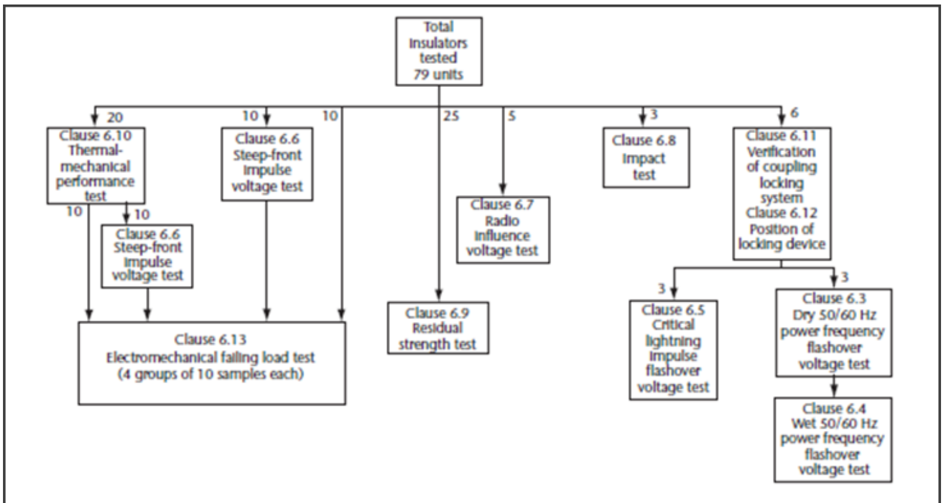


Figure 1
Schedule B type test program
(See Clause 6.2.4.2.)

<u>Figure 9:</u> Schedule B in CSA 411.1.16

Looking at various standards applicable to insulators there could be a real value in harmonizing all standards around the CSA parameters which are more stringent especially with a thermo-mechanical preconditioning. Insulator failures during various benchmark sessions have been recorded in CSA while nothing was visible with the other protocols. In each case either an assembly or glass quality problem could be traced back as a root cause.

3.3 <u>RIV</u>

There are no RIV values specified in the standards except for ANSI. At the same time, there is a debate around the possible introduction of an RIV test in IEC. RIV requirements can be a good indicator for the quality assessment of some of the aspects linked to the shape or the assembly of the insulator. The specified values should however take into consideration parameters such as size of the insulator and possibly maximum voltage seen by the most stressed unit in a string (meaning line end). This can be done by making either a voltage distribution evaluation in a laboratory or make assumption such as 10% or 15% in some cases of the phase to ground voltage of the line under consideration. Having a specification with low values will show little if anything, taking values that are too severe could lead to either overdesigning the insulator (cap size) or using artificial means to pass such values. An example of the latter is shown in figure 10 where a manufacturer was using some cement coverage coating which rapidly after several hours under a mild salt fog environment would disappear and subsequently lead to higher RIV values.

Figure 10: Unstable RIV performance based on non-permanent and artificial solution (left new insulator. Center: same insulator after 20h at 10g/l salt fog on a string of 6 units energized at 65kV. Right: RIV before and after the preconditioning).

RIV generated by bad cap to glass seal (or connection) is usually much more difficult to generate than from the pin side unless the gap under the cap is extremely poor. Figure 11 shows such an example where the gap is of the order of 2mm leading to corona but at a high voltage level (situation which can occur at a bottom of a string unshielded as shown in figure 11). Likewise, in some cases manufacturers may use a plastic ring under the cap often made with poor plastic degrading over time and temperature (figure 12a). RIV values would progressively increase over time and therefore such solution should be avoided to the benefit of a classical “flock” deposit at the base of the cap (figure 12b).

Figure 11: Large gap at the base of the cap leading to corona, corrosion of the cap base and high RIV

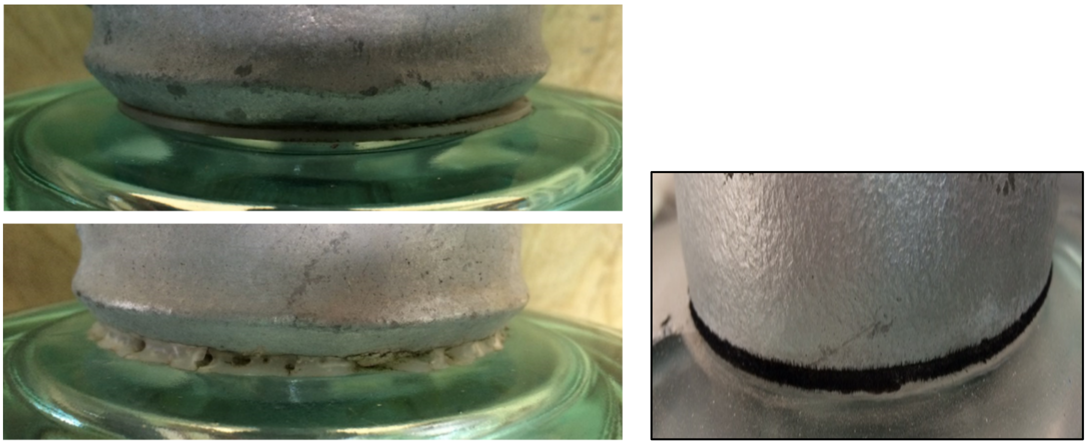


Figure 12: Left top new plastic ring. Left bottom: damaged ring from electric activity. Right: flock at the base of a cap

Other ideas such as a RIV test under wet conditions have been described [1] based on different behaviors through test observations. However, there is a necessary precaution here since it is important to understand if the differences can be correlated to weaknesses, defects, flaws or lower quality designs. This is not yet clearly established.

4. Recommendations

The following table can be a base for future upgrades or changes in standards or specifications. Beyond the tests themselves, it is key to understand that random sampling to perform tests so far only performed at the level of type tests can be extremely instrumental in the demonstration of consistency and quality.

Nature of the test	Type	Sample
M&E with 4s	x	x
Residual with k≥0,8 precondition. 85°C/15°C	x	x
Thermo-mechanical 70% -50°C/+50°C 4s	x	Periodic random
RIV dry (values to define)	x	x
Steep front impulse	x	x
Cement check (chemical composition and TGA)	x	x
Glass cullet distribution/ modified impact test		x

References:

[1]: STRI paper
[2]: IEC60383
[3]: ANSI C29 2B
[4]: CSA 411-1-16
[5]: Assessment of electrical and mechanical performance of toughened glass insulators removed from existing HV lines. CIGRE Canada Calgary 2007. George et al
[6]: ISH 2013 Electrical properties and characteristics of a stub. George et al
[7]: Condition assessment of porcelain and toughened glass insulators from residual strength test. CEIPD 2006. Gorur et al.