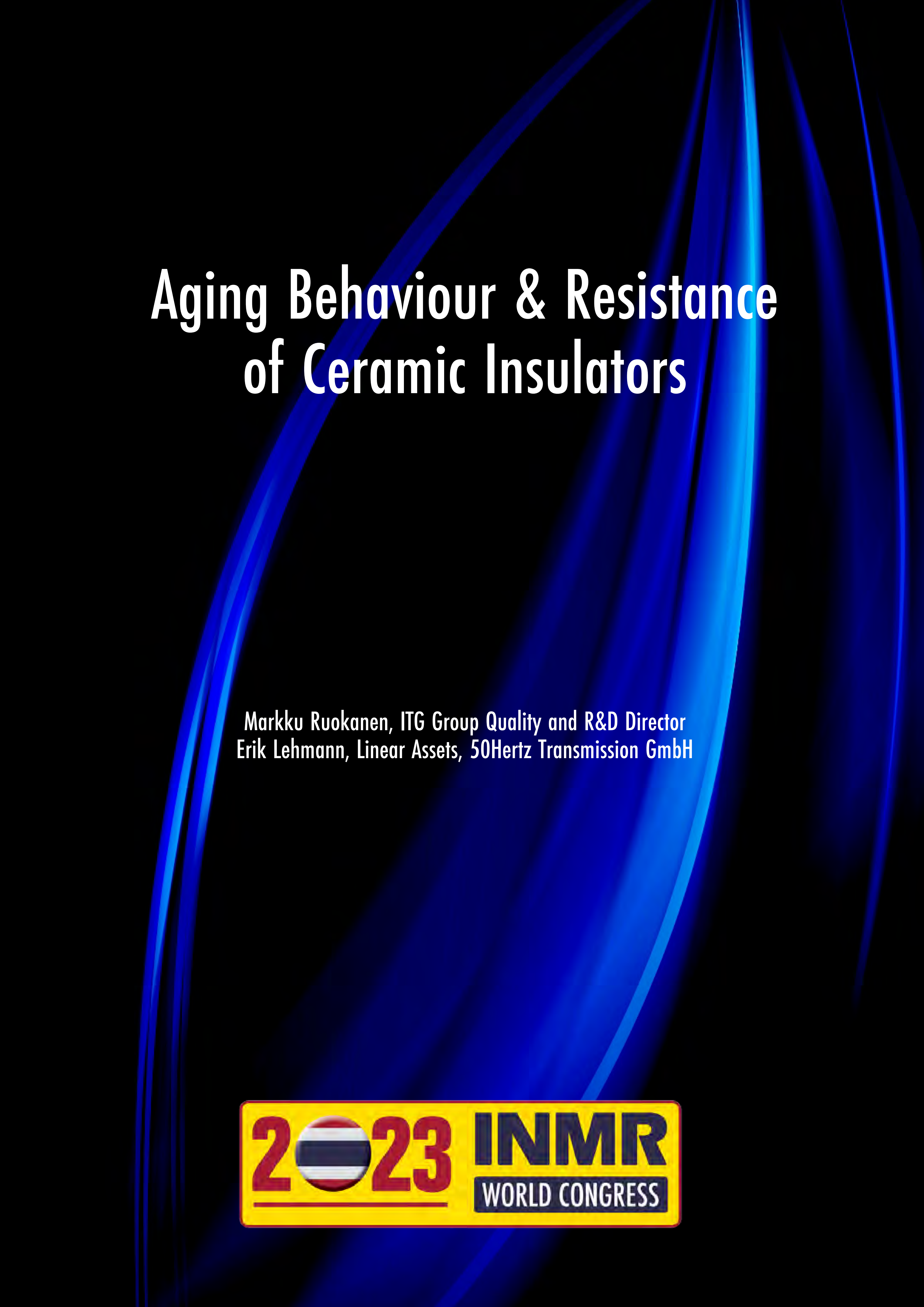

Aging Behaviour & Resistance of Ceramic Insulators

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Abstract

The remaining life-time of the aging grid is an important question anywhere in the world, the Transmission Systems Operators (TSO) must anticipate end-of-life and refurbish the on right moments, not too early and not too late.

Cigré guides TB 306 (1) and TB 481 (2) are widely used to make assessment of aging glass, ceramic and composite insulators. Both guides are based on statistical analysis of a population of aged insulators, the aging mechanism and following failure mode are not the purpose of these guides and were let without deeper analysis as there were too many degradation modes and variables. Anyhow when making conclusion of the results after an aging study it is important to understand the aging mechanisms of the insulator.

The ceramic insulators are having are having only three components: the ceramic insulator body, the cast iron fitting or cap and the assembly material, which is mostly either a Portland cement or lean-antimony alloy.

On a recent long rod assessment of 33 years old C-120 insulators with 50 Hertz it was observed that the porcelain didn't show absolutely no aging. Anyhow the failure modes and mineralogical analysis were giving important information of the remaining life-time and the quality of the alumina porcelain in the 80's. The data is suggesting that the properly manufactured C-120 and C-130 Long Rods from 80's are resisting aging much longer than anticipated.

KEYWORDS: Ceramic Aging, Long Rod Insulators, Overhead-line insulators, Failure Modes

1. Introduction

Electric energy supply security and availability is a strategic topic for all Transmission Systems Operators (TSO): our society support less and less blackouts and the potential consequences are more and more serious and expensive than ever.

The potential risks for energy supply disruption are permanently analysed and actions are taken either to mitigate the risk, build systematically redundancy to the grid and prepare quick recovery plans to limit the damage. The risk which are present in media and publicly debated are mostly related to storms and floodings caused by the climate change, earthquakes terrorist attacks, hybrid warfare and other unforeseen events which are hard to anticipate. There is another creeping risk-factor, which is less discussed publicly: the aging.

This is a known risk by the professionals, but it is getting less public attention. Aging is extremely difficult to quantify as multiple factors are having an impact: insulator and installation design, external service conditions, material selection and operations. Those who are familiar with reliability engineering know that aging follows the bathtub curb when the end-of-life approaches the induvial failures starts to increase exponentially and then it is already too late to react. On the other hand, refurbishing installations and transmission lines too early is economically sustainable.

The hot topic is therefore how to estimate the remaining useful lifetime of the installed systems and transmission lines. There is no “silver-bullet” which solves this question: one aging model might work perfectly somewhere and give completely wrong estimation elsewhere. Therefore, Cigré Working Group B2.03 has published the technical brochure 306(1) with multiple reference cases to estimate the remaining life-time of ceramic and glass insulators. WG B2.21 has created similar guide TB 481(2) for composite insulators.

The difference between the two brochures is mainly that TB 306 focuses on mechanical aging and statistical probability of the failures. The collected samples of insulators are divided in two groups, where the 1st group of insulators is mechanically testes as arrived and the 2nd group is artificially aged by Thermo-Mechanical Performance Test (TMP), then the results are plotted in a probability diagram as we can see below an example.

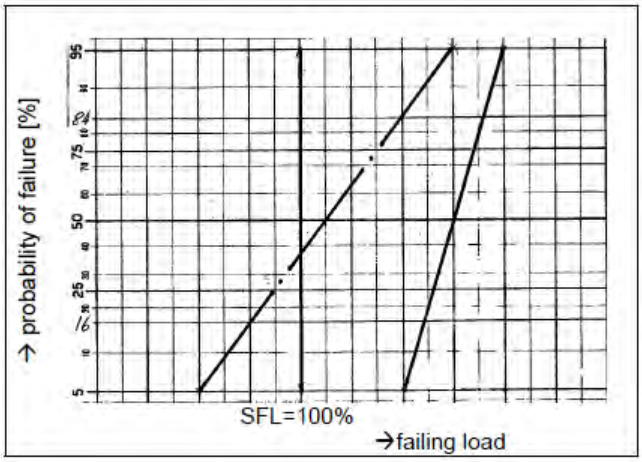

Diagram 1: Scenario F3 from Cigré TB 306(1), where the solid line presents failing as arrived and the dashed/dotted line after the TMP testing.

We can see on the diagram how the artificial aging has moved the failing load on left and it is crossing the Specific Failing Load at 35 % probability. The demonstrates advanced aging even when the insulators were good as received. In such case the recommendation would be to repeat the test in couple of years and see if the as arrived have been further deteriorated.

The Cigré TB 481 for composite insulators is more focused on different laboratory test and evaluate different aging mechanisms more in detail. This is a logical solution as composite insulators are having more different components and material interphases (Caps, silicon, epoxy, glass fibres) and therefore multiple failure modes.

In this paper we are focusing on ceramic aging and Cigré TB 306 based assessment with 50 Herz of long Rods.

2. What is Aging?

All materials are aging. Aging of the materials refers to the gradual process in which the material properties, structure or systems, changes, normally degrades, over time and/or use. The aging mechanism can by physical, biological, chemical, or mechanical.

The physical aging means material degradation by physical phenomes like radiation, mainly UV, but any energetic radiation (α-, β-, γ- radiations, etc) is aging materials. Temperature alone causes aging just by increasing the internal atom-diffusion speed or it can accelerate the chemical aging process.

Biological aging is caused by living organisms capable to use the material as source of nutrition by a decomposition process. Mainly it is fungus, moose or bacteria which are in this category. The biological aging can happen as well on extreme conditions, there are bacteria's living in high pressure and temperature gladly eating the polymers or even metals around a prospering in these conditions.

When are looking closer the aging of a ceramic insulators, we can limit the normal aging mechanism to chemical and mechanical degradation over time.

Chemical aging is mainly observed on the galvanised metallic caps or fittings and on the Portland cement. The ceramic itself, silica-porcelains according to IEC 60672 $_{(3)}$ are not corroding on the normal outdoor service conditions. When lead-antimony alloy is used in long rod assembly, there is no observed corrosion mechanism during the designed life-time. The corrosion is strongly dependent of the climatic condition, mainly air humidity, salt content and pollution levels.

Mechanical aging can be observed on all the three components, metal fittings, Portland cement and porcelain when external stresses are present permanently or periodically. In a simplified way it can be said that mechanical aging is principally crack nucleation and propagation. The crack initiation and growth needs energy, which is coming from the mechanical stresses. The initiation of cracks happens close to any type of material impurity or non-homogeneity where the stresses are cumulating, and the crack intensity factor (K_I) threshold is locally passed. The geometry of non-homogeneity and eventual orientation against the stress are having an impact to the threshold.

This paper will be focusing to the mechanical aging of the C-120 and C-130 ceramic core.

3. Aging Mechanism of Ceramic Materials

What are the typical material defects and condition which are causing alumina porcelain aging?

3.1 When the "activation energy" is coming from physical stresses

The known fact is that ceramic materials are having excellent resistance against the compression stresses. But they are more sensitive in-service conditions where tensile forces are dominating stress-mode, like in long rods.

When the application includes bending forces, like in post insulators, we have a situation where there is compression on other sides and traction on the opposite side. In such case the position of a material defect is determinant: when it is close to the surface on the traction side it is always a potential place for a crack nucleation. It should be noted that in bending there is a neutral axe where there is neither compressive nor tensile forces and the potential defect, even quite big, has absolutely no impact. The impact of a defect increases in square when approaching the surface.

Therefore, when we suppose that the quantity of impurities is constant and normally distributed in batch of ceramic body, the same body will always be more sensitive in a long rod application then in post insulator application.

3.2 When the "activation energy" is coming from other sources

Alumina based ceramic materials are generally speaking extremely resistant against chemicals, different radiations, and temperature. So, it can be stated that in normal service conditions there is no corrosion, degradation by UV-radiation or high temperature service conditions.

The porcelain microstructure which is composed mainly of corundum and mullite crystals on a glass-matrix are having almost identical thermal expansion coefficients so even quite high temperature gradient are not enough to start crack propagation in C-120 and C-130 porcelains. The thermal expansion can be an issue with a Portland cement assembly but in long rods application this is eliminated by the Lead-Antimony assembly which makes a flexible joint between the cap and the ceramic core.

In some service condition the combination of wind and airborne particles (sand) can cause erosion, which can as well be considered an aging mechanism. Such conditions do affect all materials on the substations or over-head-lines, but ceramic insulators, because the hardness of alumina, will be in any conditions the last survived structure.

All the high voltage applications are operating in a strong electromagnetic field. The dielectric stability of ceramic materials is very high, so this doesn't act as activation energy for crack propagation. When it comes then to partial discharges or even flashovers caused by pollution the ceramic remains unsensitive and doesn't show any aging. These phenomes are then accelerating the corrosion of the metallic structures, insulator caps, cross arms, cables, and Portland cement when used as assembly material.

3.3 What are the typical material defects causing the crack nucleation and growth in ceramic materials?

Quartz

The structure C-130 consist of Corundum (35 – 40%), Mullite (10 – 15 %), Quartz (< 2 %) and the rest is glass phase (SiO_2). The presence of Quartz should be avoided (7), but recent studies have shown that size of quartz particles is more critical than the quantity (4;5).

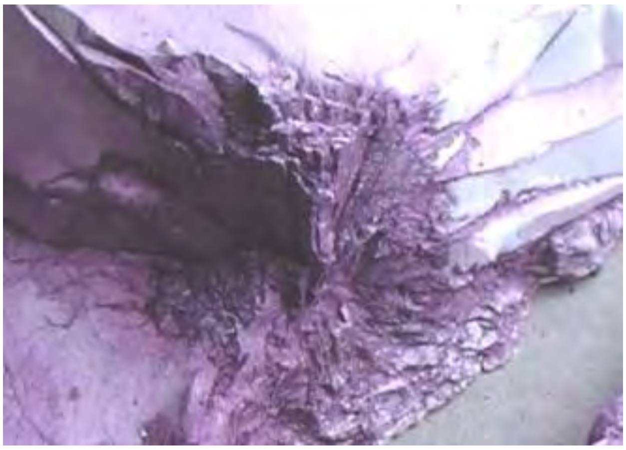

Photo 1: Quartz initiated crack growth in a long rod. Quartz content > 2%

Anyhow high residual quartz content increase the probability that of bigger particles and bigger initial cracks on the cooling. There are different values for the critical quartz size threshold: 10 µm (5) 20 µm(6) and 50 µm(7), the reality is probably around 20 µm depending of the microstructure.

Porosity

There is always some porosity on ceramic materials, C-120 and C-130 are tight fired, developed for this propose, which means that there is no open porosity which would allow moisture absorption and crack propagation in low temperatures(8). Normally the porosity density is about 10-15 % and the pore sizes being about 5 µm - 10 µm, which is not causing significant sub-critical crack propagation (9). When the pore-size is higher than 20 µm it can be considered as material defect, but these are nowadays extremely rare.

Photo 2: C-130 body pieces on the porosity test samples according to IEC 60383-1 § 26 (10), no porosity.

"Hard particles"

"Hard particle" is a material defect from manufacturing process. It is a hard agglomeration of particles from body preparation. When raw material particles are under pressure with presence of moisture, it can cause chemical reactions between particles with are then agglomerating bigger particle. This can happen in silo-storage with any powder type material when the storage time becomes too long. Normally these are still dissolved in the slurry at body preparation process, but agglomerated particles at the bottom of silo, which were same time under pressure might go through the process.

Another source of “hard particles” is from the extrusion. On extrusion counter pressure at nozzle is applied to compress the blank. Material which can cumulate on the angles and nozzle joints over longer periods becomes hard like stone and can be break when it is big enough. Then it can find itself to the ceramic body and cause the failure already in the routine test and when they particles are smaller can initiate sub-critical crack growth. These defects are avoided by regular preventive maintenance where the extruder is fully cleaned inside.

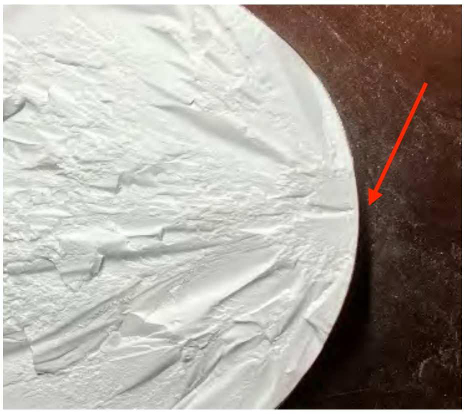

Photo 3: So called “hard particle”, very small, but critically positioned just under the glazing.

Iron Particle

This is called “iron particle” or “black dot”. The particle can be iron, or it can be any other metal, which is a foreign particle. Thes particles can come from raw-material or from contamination on the logistic chain. One root cause is that the truck has been used to transport other materials or even waste, which contaminates the delivered raw material. Another root cause can the recycling of big bags, without proper cleaning.

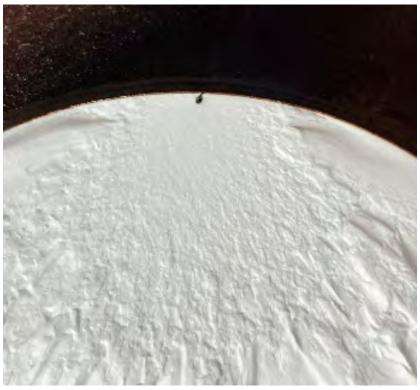

Photo 4: An iron particle on breakage surface on a tensile test, clearly visible and can be identified as a place to the critical crack propagation.

The iron contamination can as well happen in manufacturers own warehouse, especially if that happens outdoor. Normally a proper silo-warehousing protects the raw material quite well.

To eliminate the iron particles, manufacturers have installed strong magnets and sieves on the pipes on which the slurry is pumped to the filter presses.

Core & Surface Cracks

Core and Surface cracks are manufacturing defects which are typical in all ceramic industry.

The first category is drying cracks: at shaping the insulators are still having c. 20 % moisture, this needs to reduce below 1 % before firing, otherwise the insulator is literally exploding in the kiln. The material is shrinking in the drying, which causes internal stresses, which can cause cracks. The drying process is delicate and normally takes from days to couple of weeks for big insulators.

Another category of cracks are the firing cracks. These are as well coming from the material shrinkage (10 – 20%) during the firing, casing tension and then cracks which can open to the surface or hidden in the core. The firing curb is important and to high temperature gradient inside the body must be avoided. Small quantity moisture can as well be the reason for the cracks when the water becomes vapor above 100 °C.

Manufacturers are eliminating the visual cracks by inspection after firing. The non-visible core cracks are eliminated by the 100 % routine tensile test and bending tests with 50 % or 70 % of the nominal load. Thermal shock test eliminates as well efficiently hidden cracks.

4. Assessment of 33-year-old C-120 Porcelain Long Rods

72 long rod insulators from the grid of the 50 Hertz were analysed according to Cigré TB 306(1). The insulators were types 75/21/105 TB and 75/25/105 TB

from 1989, so 33 years field service. The material grade used was marked as C-120.

TB 306 is referring to TMP testing according to IEC 60383-1(10), which requires 4 x 24-hour cycles. The TMP equipment allows testing long rods only one by one and would take too long time, it was agreed with 50 Hertz that the thermal shock test was used as accelerated aging.

All insulators passed the routine tensile test of 70 % of the test of Specified Failing Load 105 kN. After the routine test the batch was dived in two lots of 36 insulators, the first lot being broken on tensile test as they were and the 2nd after thermal cycling. The Temperature cycling test according to IEC 60383 was used as the TMP-teats requires a 96-h cycle (means a week) and must be done one by one. The state of art was, that thermal cycling was expected to be as efficient for the aging. The results are plotted on the Diagram 2.

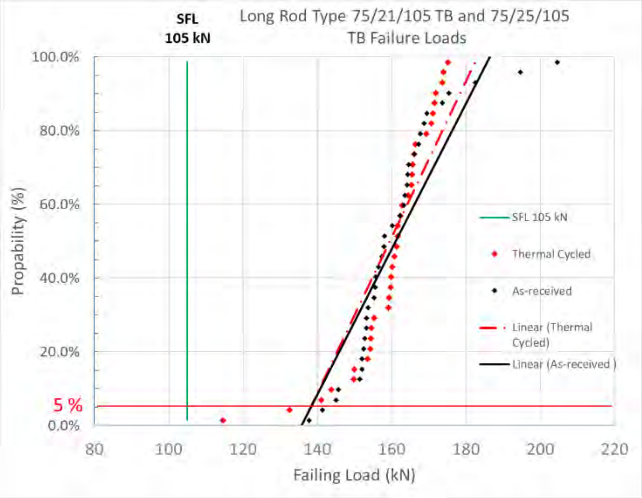

Diagram 2: Long rods 75/21/105 TB and 75/25/105 TB plot as defined by TB 306.

The first observation is that the failing load was normally distributed.

The failure load values were 161 kN for the as-received lot and 150 kN for the thermally cycled, both groups were having good standard deviation of 12 kN. The SFL at 5 % probability was 31 %. The scatter for both groups was 8% and considered as normal.

The 1st conclusion is that there is no field aging causing sub-critical crack grown, which would be visible on laboratory artificial aging with thermal cycling.

When analysing the failure modes, it was first observed that majority of the failures were on cast iron CAP, 60 insulators of 72, presenting 83 % of the failures. The failure was always in same place and the broken cap didn’t show any specific material defects: like porosity, casting inclusion, big grains, or corrosion damages. The average failure force was 162 kN with 11 kN Standard deviation. The 2nd conclusion was that the caps didn’t show any aging but were just design point of view the weakest point.

Photo 5: Typical Long Rod 75/21/105 TB Cap failure.

The remaining 12 (17%) failures at ceramic presented the following failure modes:

Failure Mode	**Qty**
Quartz	0
Porosity	0
Hard Particles	1
Iron Particle	1
Surface Cracks	4
Core Cracks	3
Not identified	3

Table 1: Observed Ceramic Failure modes.

The non-identified failure modes could potentially be related to quartz particles, but the mineralogical analysis showed residual quartz content below < 2%, this is not very probable. It is possible that it could have been an iron particle or hard particle which disappeared at the break.

Totally four surface cracks were observed as starting point of the failure. Anyway, these were not open cracks: they appeared before the firing on drying, so the glaze penetrated to the crack and sealed it. Ceramic glaze itself is very solid, and it is also used to join big hollows of multiple segments.

When the crack allows the glaze to penetrate, it is kind of healing the surface crack. On the Photo 6 we can see how the glaze has penetrated the core and sealing it. The insulator didn’t show after 33 years’ service any aging, but this small hidden and sealed surface crack was the weakest point.

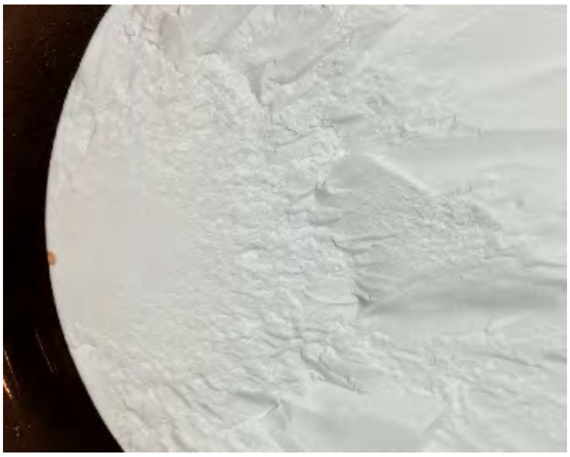

Photo 6: Small drying crack which was penetrated by glaze before firing.

It was a hazard that of the 12 insulators failing on ceramic body, 7 were broken as received and 5 were thermally cycled before the testing. This allowed us to arrange the data as in TB 306.

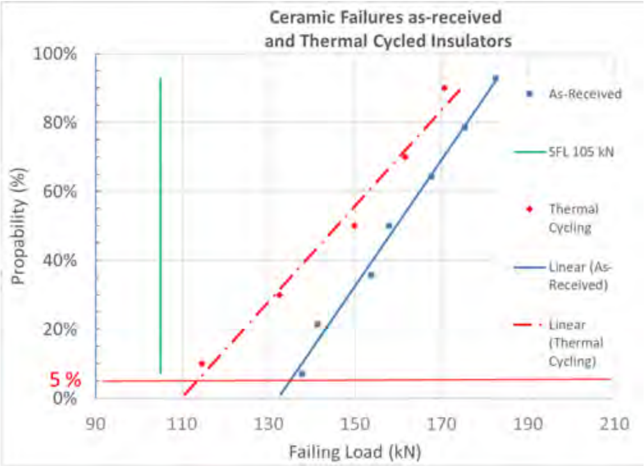

Diagram 3: Failures on ceramic body of long rods 75/21/105 TB and 75/25/105 TB plotted as received and thermally cycled.

It is obvious that 7 and 5 samples are statistically not enough to make any kind of conclusion and statements. Anyhow this plot, which looks 100 % identical to scenario F5 of the TB 306, raises more questions than is giving answer and does merit a discussion.

The mineralogical analysis was completed and was giving as well surprising results of the two concerned suppliers:

Suppl.	Quartz	Corundum	Cristobalite	Mullit	Rest.
A	< 2%	39 %	< 2%	12	49
B	< 2%	50 %	< 2%	7	43

The two suppliers, both had a high Corundum content for a C-120 grade. Lieberman proposed in 2001 for an optimised C-130 a phase relation Corundum > 40 %, Mullit < 15 %, Quartz < 1% and the rest glass phase (11). This shows that the alumina content is higher the 50 % and performance point of view the material is rather C-130 then C-120.

The high alumina and corundum content are explaining as well why no field aging after 33 service years was not observed.

The 6 samples which were passed both thermal shock and TMP-test broke all in the caps, not in the porcelain.

5. Discussion

On the diagram 3 we can see how the 12 porcelain failures are plotted in the probability diagram and looks like the scenario 5 on the TB 306. But using the scenario 5 for conclusion would be misleading. We have here a situation where a population 12 pieces of 72 failed on porcelain and it was possible in 9 to identify a material defect where the critical crack propagation started.

Anyhow 7 of these insulators tested as-received were having an average failure load of 159 kN which is same to the average of all the 60 Cast Iron Cap failure loads 161 kN. This is suggesting that there has not been statistically significant aging of the long rods after 33 years in the service.

Then the 5 of the 12, which passed the thermal cycling test according to IEC 60383-1 § 23 had 146 kN average failure load so lost about 9 % of the mechanical strength when compared to the 7 tested as-received. This is quite brutal aging with only 3 thermal cycles of 70 K delta. Couple cycles more and the line would move left-hand side of the SFL 5%.

The accelerated aging by thermal cycles works well, when there is a latent material defect allowing sub-critical crack growth. On the population of 60 insulators the ceramic material defects where too small to cause any measurable aging at TMP-test or thermal test. So, from the aging point of view, it is important to minimize the material defect and keep them small enough to avoid the crack initiation, on the crack is there it will grow anyway.

The mineralogical analysis was quite surprising with high Corundum content, which is explaining the very good performance of these insulators. This has been demonstrated in multiple papers since C-120 and C-130 were introduced to the market. These C-120 insulators from 1989 have been performing as the best quality C-130 insulators today.

The If we now look again at Freese & Pohlman graph(8), we see that in this project the mechanical performance after 33 years' service is much better then proposed in 1999.

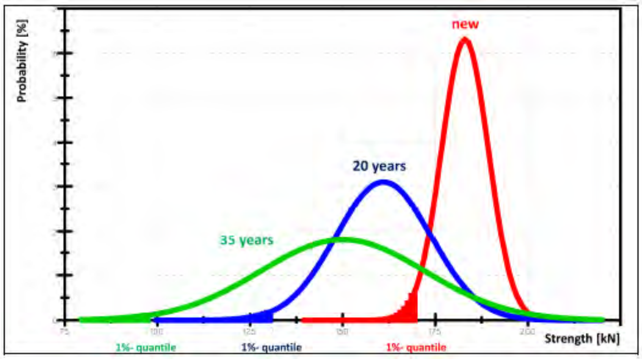

Diagram 4: Statistical long rod life-time assessment by Freese and Pohlman.

Anyhow it is evident that only one study is not statistically enough to confirm that these "20 years" and "35 years" gaussians could be moved more on right-hand side. But the topic is worth to be discussed and other studies should be launched.

On this project we have observed that accelerated aging was possible only with insulators already having material defect or non-homogeneity allowing the sub-critical crack propagation. This could be suggesting that manufacturing technology has been developing since 60's when the sample insulators for Freese & Pohlman were manufactured. The analysed samples were manufactured by two different suppliers, but were totally equivalent in performance, which support the thought that in late 80's the manufacturing technology was generally in a higher level. The improvements are mainly the reduction of the various material defects and better control of the critical parameters in body preparation. One part of the improvement is certainly coming the improved quality of the used raw materials. Anyhow the original Freese and Pohlman statement remins valid: longer cracks grow faster then small ones.

The Cigré TB 306 (1) was published in 2006 and the same observation applies to the data and insulators tested to create the guide. The long rod scenarios are presenting ceramic insulator manufacturing technology from the 60's and 70's. Now when utilities starts to test insulators installed in late 80's and early 90's they perform better.

The TB 36 is based on the MTP testing as accelerated aging in laboratory, but it seems that the thermal cycling alone, at least with long rods, would be enough. This is important when big quantities of insulators are tested. Thermal cycling according to IEC 60383 takes c. 3 hours and 6 long rods can be tested same time, so 12 insulators in one shift. The TMP-tests takes 96 hours per insulator. So, some 48 insulators can be thermally cycled when only one insulator is passing the IMP-test.

TB 306 doesn't include any closer failure analysis and mineralogical study in the assessment. This is strongly recommended: in this study the diagram 2 is proposing that that insulators are like new after 33 years' service. Only the failure mode analysis shows that there is a 17 % fraction of insulators which were sensitive to the accelerated aging due material defects. If the test is repeated in 10 years and the ratio 12 ceramic failures/60 cap failures moves, it would be an indication, that ceramic aging has been accelerating and more cracks was initiated between 33 and 43 years.

6. Conclusions

The study shows that an assessment of the old long rod insulators should always be accompanied by failure mode and mineralogical analysis; pure statistical approach could lead to wrong conclusions of the remaining life-time.

The results are suggesting that, when the ceramic is already having non-homogeneity and defects bigger than the critical threshold, the thermal cycling alone is enough causing the accelerated aging by crack propagation. This is interesting, as the thermal cycling testing is much faster and cheaper to organize as the TMP-test. This observation is statistically not significative, as it is based on seven and five samples only, but it is logical would merit more studies.

When non-homogeneity and defects (quartz, hard particles, voids, iron particles, cracks) are smaller than the critical threshold the alumina porcelain is neither showing measurable aging after 33 years field service nor in laboratory after thermal cycling or TMP-testing.

We can observe that this batch of C-120 long rod insulators manufactured in late 80’s are overperforming in aging resistance, when compared to field performance studies based on insulators manufactured 60’s and 70’s. This suggest has there has been significative improvements on the raw-material purity and manufacturing technologies in between, which have been reducing the quantity and size of the typical material defects.

To confirm this suggestion more lifetime estimations of insulators manufactured in late 80’s and early 90’s are needed.

ACKNOWLEDGMENTS

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