Field Ageing Behaviour of Long Rods Analysed According Cigré TB 306

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Abstract

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

Cigré guide TB 306 (1) is one of the tools widely used to make risk assessment for aging of glass and ceramic insulators. TB 306 is based statistical analysis of a population of aged insulators. A selected batch is divided to two groups, the 1st is tensile tested as arrived and the 2nd group will go a Thermo-Mechanical Performance (TMP) test according to IEC 60383 and are broken afterwards. The purpose of the TMP is to provoke crack growth on microcracks nucleated in the service and create an accelerated aging to estimate the remaining lifetime. In practice the TMP is often replaced by a routine thermal cycling test, as the laboratory TMP-test capacity is limited. The intention of this study was to analyse in laboratory how the routine thermal cycling test is creating a sub-critical crack growth on the ceramic body.

Two different ceramic recipes for C-120 and C-130 porcelains were evaluated with calibrated defects and their mechanical strength was measured and microstructure was analysed were. It was not possible to create confirmed crack growth on the samples, but the importance of the alumina content and the mineralogical structure to the mechanical performance was clearly proved. The best way to improve the crack growth resistance on the long rods was discussed as the field data is suggesting that insulators with higher alumina and optimised corundum/mullite ratio are not showing field aging.

KEYWORDS: Cigré TB 306, Long Rod Insulators, Overhead-line Insulators, Ceramic Failure modes, Lifetime, subcritical crack growth in ceramics.

1. Introduction

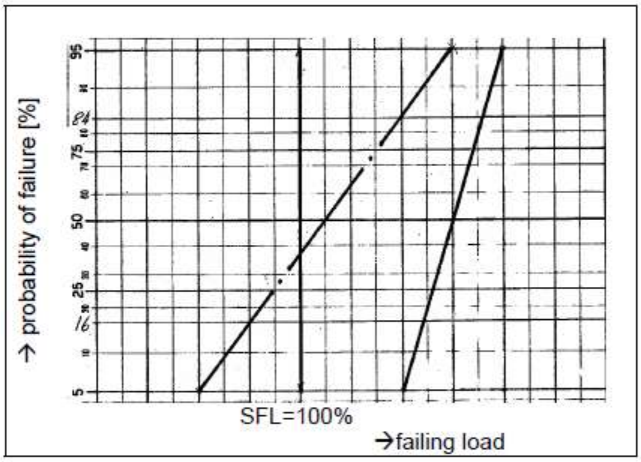
Electric energy supply security and availability is a strategic topic for all Transmission Systems Operators (TSO): our society support less and less blackouts and the potential consequences are increasingly serious and expensive than ever.

The potential risks for energy supply disruption are permanently evaluated 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 black-out risk which are present in media and publicly debated are mostly related to storms, voltage surge caused by cascading grid disconnections, hybrid warfare and other unforeseen reasons. There is another creeping risk-factor, which is less discussed publicly: the aging.

This is a known risk by the TSO's, 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 choice 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.

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 on the graphic 1.

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



***Graphic 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.*

In the real life when thousands of kilometres overhead lines and hundreds of ceramic long rods needs to be evaluated the MTP is not suitable because of the long cycle times. The TMP-tests takes 96 hours per insulator and on the test device there is room only for a single, eventually two long rods. This is the reason by TSO are often replacing the TPM by temperature cycle test according to IEC 60383 § 24.1, which takes about 3 hours for class A insulators (long rods) and 6 long rods can be tested same time. In one working week 60 long rods can be thermally cycled compared one single piece TMP-tested. [2]

The 70 K thermal shock is a routine test, with the purpose to eliminate pieces having potentially internal stresses or other material inhomogeneities, like pores, microcracks, residual quartz and foreign particles. The thermal shock can cause open cracks at the test or initiate crack propagation, which will reduce the mechanical strength in the following tensile test. What is then unknown how the thermal shock would affect the crack propagation and simulate accelerated aging.

In this study we have tried to quantify in laboratory scale how the thermal shock is causing crack propagation on a small ceramic laboratory bar with calibrated material defect.

2. The sample preparation and experimental method.

The goal of this experiment was to prepare "calibrated defects" in the test-bar to study their impact on crack propagation in laboratory conditions. Manufacturing "calibrated defects" is a classical Root Cause Analysis (RCA) method used in modern Quality Management. Based on the results from quartz impact study from 2022 (3), where the 64 µm quartz sand particles were used to contaminate the base body, the same method was selected to create non-homogeneities in the body.

The 64 µm fraction was sieved and selected because this fraction is close to the A. Rawat and R. S. Gorur findings: aged insulators samples with > 50 µm quartz failed on punctuation test (4). On the 2022 quartz study(3) it was shown that 1 % of this fraction of quartz particles reduced the mechanical strength of C-130 porcelain about 5% -6%.

Two types of porcelain body were selected as base material A) a recipe for an isostatic production, C-130 with high alumina content B) process and a C-120 recipe for plastic manufacturing process.

The quartz particles 1 wt.% were mixed into the base-body in the laboratory mill. For baseline test-bars with 0 wt.% quartz was made of the same batch of body.
The body was pressed in the laboratory (Fig. 1) and extruded with the laboratory extruder (Fig. 2) to 10 mm diameter and 150 mm long test-bars.

Fig 1. The laboratory filter-press

It was decided to make the test bars non-glazed. The glaze is increasing the mechanical strength of the body up to 30 % and that could potentially hide the small crack propagation, which we were looking for.

Fig 2. The laboratory extruder.

After extrusion, the test bars were fired in the production kiln (Fig. 3)

Fig 3. Samples ready on kiln for firing.

The fired samples where the put in thermal shoch test according to IEC 60672 § 11, Method A (5). 10 samples were heated in oven at 120 °C +/- 5 °C, over 2 hours and quickly immersed on water 20 °C staying there 5 minutes. (Fig. 4)

Fig 4. Test bars immersed on 20°C water.

The thermal shock was repeated on batch of 10 samples 3, 10, and 30 times. The standard defines only 3 shocks, but as it was not sure if 3 cycles was enough to create crack propagation, which would be visible on the 3-point bending test, the 10 cycles and 30 cycles were added to the Design of Experiment.

The 3 point-bending machine (Fig. 5) was used to break the test bars.

Fig. 5 The 3 point-bending machine.

After the breakage the sample, the breakage surfaces were inspected to be sure that the values were not affected by any material defect or impurity on the body.

3. Results

The 3-point bending results, average of 10 test bars, are presented on the table 1 and 2.

Table 1: Breakeage Value MPa		
Body A	No Quartz	1 % Quartz
Baseline	188	165
3 cycles	184	156
10 cycles	181	161
30 cycles	191	157

Table 2: Breakeage Value MPa		
Body B	No Quartz	1 % Quartz
Baseline	125	121
3 cycles	Fail	Fail
10 cycles	126	121
30 cycles	121	116

The chemical analysis was giving the following results on Table 3.

Element	Body A	Body B
SiO_2	39,0 %	45,5 %
Al_2O_3	55,3 %	47,5 %
Remaining	5,7 %	7,0 %

Table 3: Chemical analysis

The remaining oxides are typically Iron oxide Fe_2O_3, Titan oxide TiO_2, Calcium oxide CaO, Magnesium oxide MgO, Kalium oxide K_2O and Sodium oxide Na_2O.

IEC 60672(5) is not any specifying the chemical analysis or minimum aluminium content. Anyhow the Alumina content is typical for the C-120 and C-130 ceramic insulators manufactured today.

The mineralogical analysis results are below in Table 4.

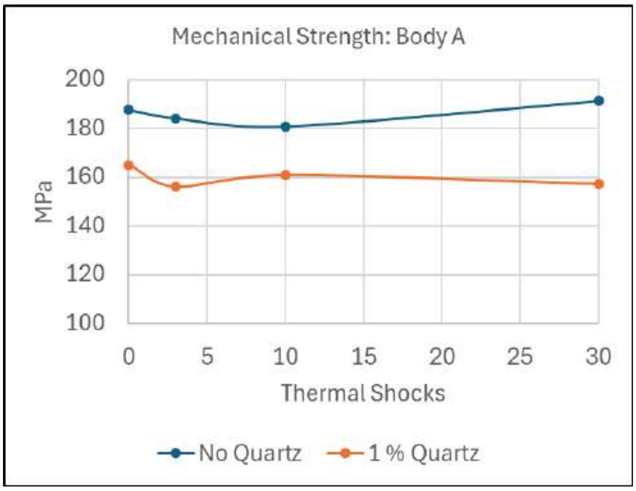
Microstructure (%)	Body A No Quartz	Body A with Quartz	Body B No Quartz	Body B with Quartz
Cristobalite	0,1	0,2	0,2	0,2
Quartz	1,0	1,0	2,6	2,5
Corundum	32,1	30,8	22,2	18,3
Mullite	19,4	19,5	8,7	7,4

Table 4: Mineralogical analysis

It should be noted that the accuracy of the XDR-analysis is at its best 0,5 % when analysing mineralogy structures, so values below 1 % are basically showing only a residual.

4. Discussion

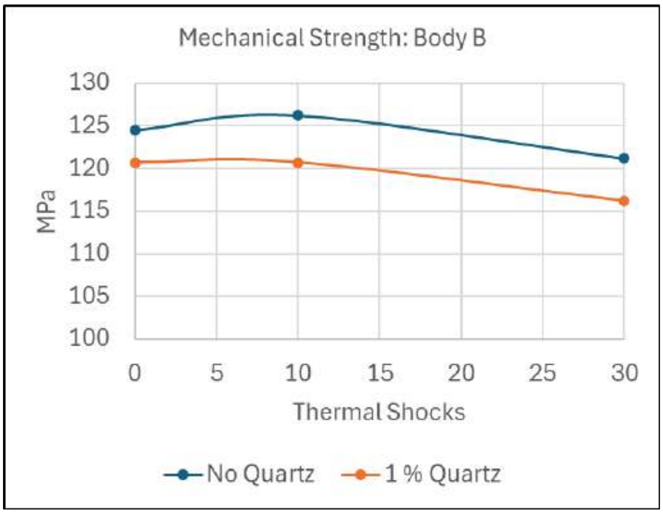
The results are plotted on the graphic 2 and 3:



Graphic 2: The change of 3-point breakage value of body A in function of thermal shocks.

The first observation was that the 1 % quartz as added impurity was decreasing the mechanical strength of the body A by 14 %.

The loss of strength is more important than it was on the 2022 study (3), but it is confirming the conclusion that the strength of reduction is related to the quartz particle size, not on quantity.



Graphic 3: The change of 3-point breakage value of body B in function of thermal shocks.

We see with a body B a smaller, just 4 % loss of mechanical strength with added quartz particles. The 3 thermal shock tests failed, but the 10 and 30 shock are confirming the same observation then with body A.

We can see as well that the strength of body B is 35 % lower than the body A. This can be explained by the chemical analysis and microstructure, it is well known that that the mechanical strength is related to the alumina content and the body A is having 8 % more alumina (6,7). Further Liebermann (6,7) has proposed that optimised C-130 a phase relation Corundum > 40 %, Mullit < 15 %, Quartz < 1% and the rest glass phase. The body A is not having an optimised structure, but it is close enough to give excellent results.

It can be supposed that the difference of loss of strength of body A between tests 2022 and this study is coming variations on the production firing curb. The Quartz is having a melting point of + 1713°C, but in the firing the fluxes in the body, feldspar, alkali oxides are melting around 1000°C – 1100°C and forms a liquid glassy phase, which can partially dissolve the quartz. The degree of the dissolution depends on the firing temperature, time and particle size. When the particle size was constant the quantity and size of residual quartz particles is therefore dependent of the firing cycle variations in sample preparation.

The low measured residual quartz, independently if there was added 1 % fraction or not, is as well coming from this mechanism. There are quartz particles on the raw material minerals like Feldspar, Kaolin's and Clays, but their particle size is too small to affect the strength. The impact on the strength is coming that the 64 µm.

The breakage surface was inspected by Electron microscope in the Department of Material and Ceramic Engineering at University of Aveiro in Portugal. The breakage surface molecules were analysed by Energy-Dispersive Spectrometry (ESD).

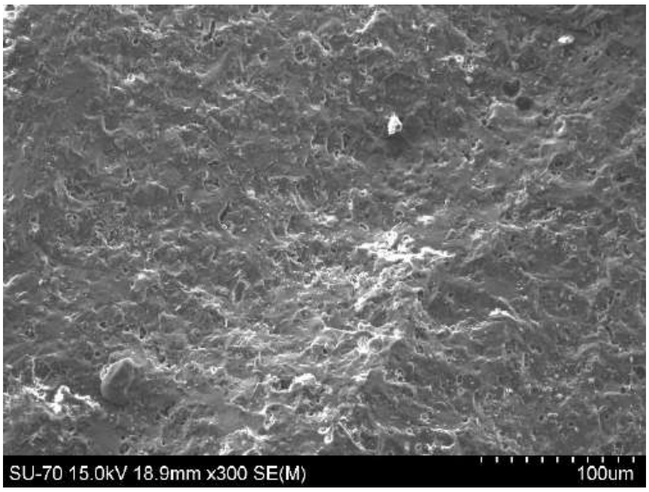


Fig. 6: Breakage surfaces of Body A, no added quartz, and no thermal shocks.

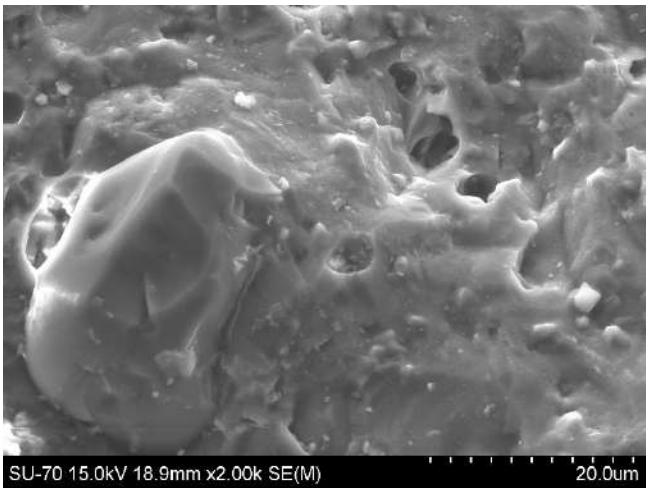


Fig. 7: Breakage surface of Body A, no added quartz, detail, where a small 20 µm x 30 µm quartz crystal is visible. No visible micro-cracks on s surface. Small 1 – 2 µm pores in the ceramic.

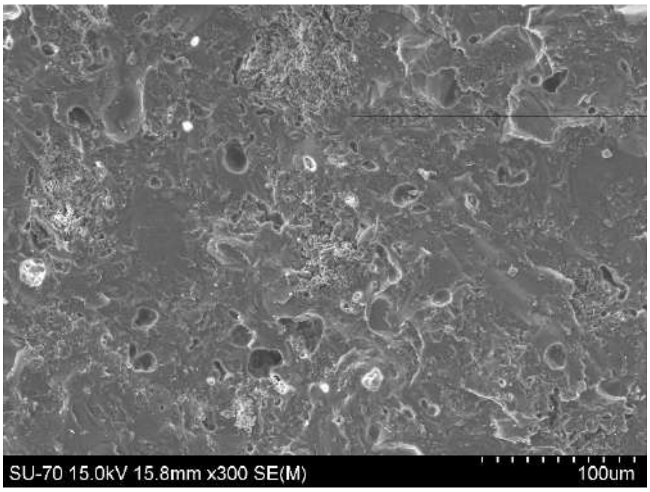


Fig. 8: Breakage surface of Body B, no added quartz, and no thermal shocks.

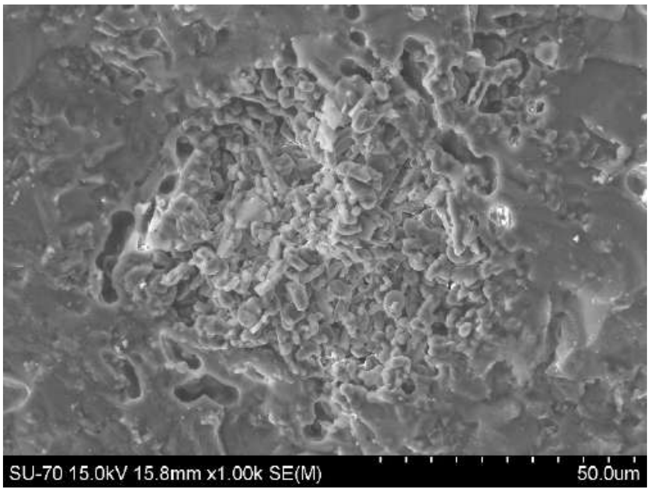


Fig. 9: Breakage surface of Body B, no added quartz, and no thermal shocks. Detail: of an alumina crystal cluster, confirmed by ESD.

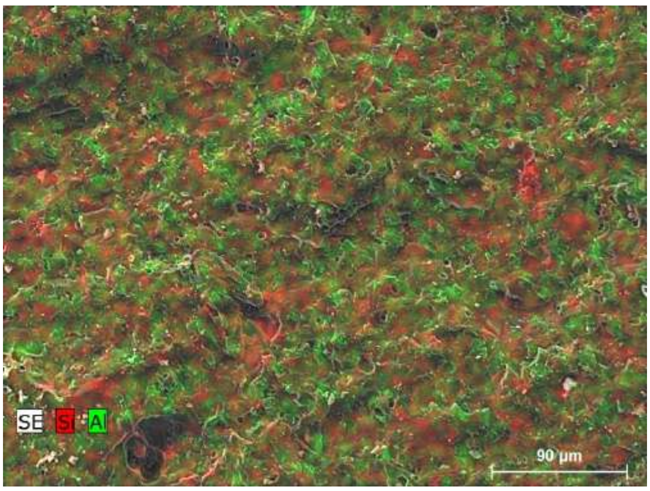


Fig. 10: Breakage surface of Body A, ESD analysis.

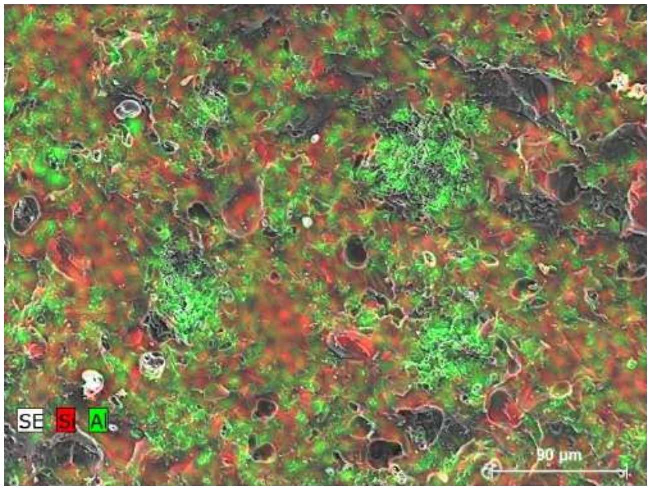


Fig. 11: Breakage surface of Body B, ESD analysis.

The ESD is showing another main difference between the bodies A and B. The alumina, green colour, is homogeneously dispersed on the body A, on body B the alumina crystals have tendency be agglomerated.

This difference is coming the body preparation process and recipe, body A is a recipe for Isostatic process and body B is a recipe for classical plastic process. The microporosity is as well bigger on the body B, as plastic body is having a lower density after firing.

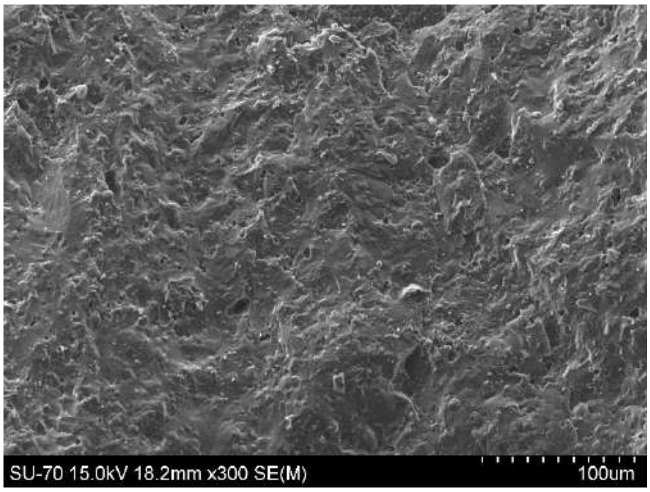


Fig. 12: Breakage surface of Body A added quartz and 30 thermal shocks.

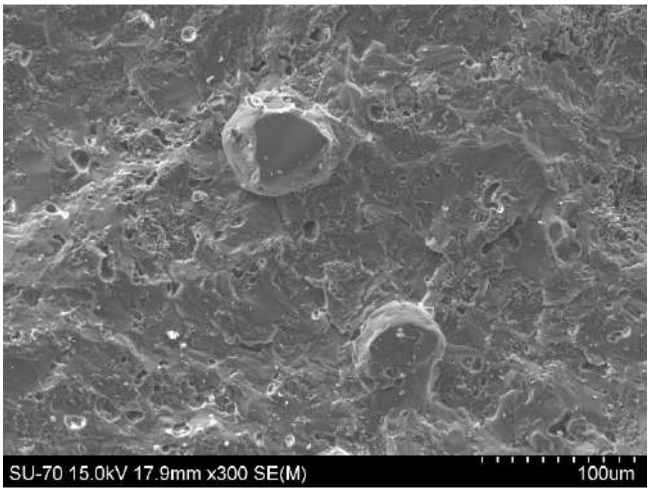


Fig. 13: Breakage surface of Body B added quartz and 30 thermal shocks.

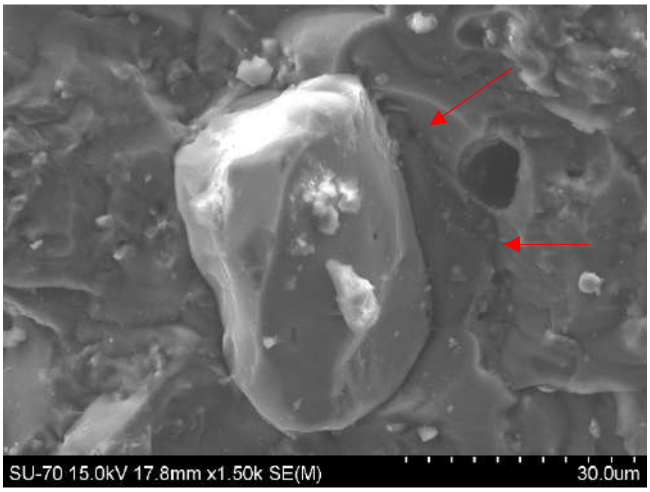


Fig. 14: Breakage surface of Body B added quartz and 30 thermal shocks. Detail: there seems to be a micro-crack on a 3 µm from the Quartz particle.

The thermal shocks were not affecting the mechanical strength, even when on the body B first cracks around the Quartz particles were observed. This suggesting that 30 cycles were not enough causing further crack propagation. The test bar 10 mm diameter is probably too small to cause big enough temperature gradient causing stresses for the sub-crack growth. The center and surface achieve the same temperature very quickly, almost same time.

When full-size insulators are cycled same way, the geometry is making the major difference: the sheds are cooling fast compared to the body. This will create bigger thermal stress in the body with high thermal inertia then we can ever have with a 10 mm test bar. In the routine thermal cycling test insulators breaking point is systematically between the shed and the core.

The joint Lapp Insulators and 50-Hertz Long Rod Aging Study in 2023(2) showed that insulators manufactured 33 years ago didn't show any aging. In case where a material defect was seen in the ceramic brakes surface the 3 thermal shocks according to IEC 60383-1 were causing a small loss of strength, which was statistically not significative and inside the standard deviation of the examinate batch of long rods. All the tested insulators were largely above the Specified Failing Load.

On other, non-disclosed, old-insulators analysis according to Cigré TB 306 it has become increasingly clear that porcelain Long Rods manufactured in early 90's. These insulators are having high alumina content and corundum is the dominating alumina crystal structure against the mullite. Both factors are efficient way to reduce sub-critical crack growth.

Difference studies (7,9,10,11) comparing porcelains, glass-ceramics, and alumina-rich composites suggest that raising the alumina fraction usually:

- Increases fracture toughness (KIc) and strength.
- Raises the threshold stress intensity (K_I0) below which sub-critical propagation is negligible.
- Lowers the stress-corrosion susceptibility coefficient.

Multiple reviews and experimental papers (3, 4, 6, 9, 12) emphasize that:

- alumina grain size
- porosity
- residual stresses
- the distribution/size of the glassy phase
- residual quartz, grain size and distribution
- corundum/mullite ratio

control sub-critical crack growth as much as nominal alumina percent. So limited quantity of large residual quartz grains; fine, well-bonded corundum grains plus limited, well-distributed mullite and low glass fraction give best slow-crack resistance.

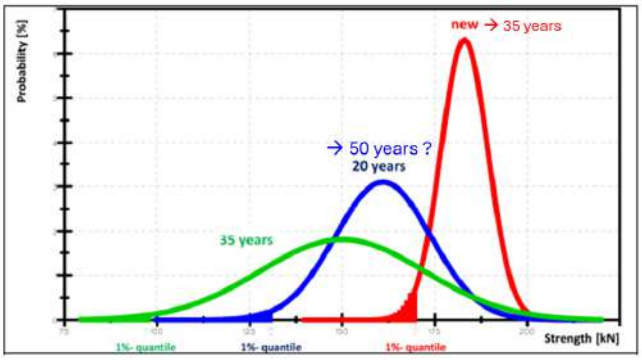
In the microscope and chemical analysis of the bodies A and B are confirming that statement. Body A was having high alumina content, small particle size, good corundum and mullite ratio with homogenous distribution, smaller and less microporosity, which gives 35 % higher mechanical strength, which is essential to reduce the sub-critical crack growth.

5. Conclusions

On this study it became clear, that using laboratory test-bars to simulate the impact of thermal shocks to the sub-critical crack growth on C-130 ceramic body is not efficient with 64 µm quartz particles. In full insulator scale, the thermal mass of the core and fast cooling of the sheds, will create high enough stresses at thermal shock to create crack propagation when the existing non-homogeneity is big enough.

Anyhow the field data and recent long old rod assessments according to the Cigré TB 306, suggest that the routine thermal cycling according to IEC 60383-1 is enough to create sub-critical crack growth if the original material defects were big enough.

The analysing the long rods manufactured after the 90's are strongly opposite what Freese and Pohlman were suggested for lifetime-assessment in 1999 (13). In cases where the ceramic body was having a high alumina content and optimised corundum/mullite ratio their mechanical strength was equivalent to new ones after 35 years in service.



Graphic 4: Statistical long rod life-time assessment by Freese and Pohlman, suggested new levels.

As there a is major structural difference between insulators manufactured before and after the 90's and between the manufacturers the Cigré TB 306 assessment, should always be completed with a failure and mineralogical analysis.

The IEC 60672-3:1997 doesn't specify anything about the alumina content or the microstructure of the C-120 or C-130.

C-120 is specified as:

"Feldspar fluxed porcelain in which quartz is partially replaced by alumina."

And C-130 is specified as:

"Non-refractory, feldspar fluxed porcelain in which alumina is the principal filler."

Perhaps, it is time to revise IEC 60672-3:1997 and specify these two critical characteristics for the insulator's lifetime: alumina content and microstructure.

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