Asset Management: Evaluation of Old Insulators

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Summary

This article presents a technical approach to asset management in transmission lines, focusing on the evaluation of the longevity of toughened glass insulators withdrawn from service after more than 40 years of operation in humid tropical environments in Brazil.

This publication complements several previous studies conducted in non-tropical regions [1]. As is well known, tropical regions, characterized by high humidity and elevated temperatures, are particularly aggressive toward materials, especially when these are subjected to high electrical stress.

All insulators tested had been in service for more than 40. Among them 75% were installed in 500kV systems.

The document also includes results from analysis reports on porcelain and composite insulators.

Due to the specific characteristics of Brazil's transmission network, the document focuses on the SIN (National Interconnected System), which is the system adopted throughout the country.

1. Introduction

The global energy sector has been undergoing several changes aimed at reducing carbon emissions and the need for a more sustainable energy transition, as well as the growing demand for electricity in terms of electricity supply for large consumer centers and future datacenters.

This has led to new challenges for utilities striving to balance the development of new transmission lines with the enhancement of existing infrastructure. It makes the topic of transmission line asset management crucial for companies, which involves the coordination and control of all components (including the insulators that are essential to maintain the integrity of transmission lines) with a focus on optimizing performance, minimizing risks, maximizing return on investments, not forgetting the commitment to the guidelines of the global compact focused on ESG (Environmental, Social and Governance).

This paper proposes an asset management approach focused on the longevity of toughened glass insulators in transmission lines.

Characteristics of the Tropical climate

- High relative humidity.
- Heavy and frequent rains.
- High temperatures and thermal variations.
- Increased risk of wet pollution and biological growth.

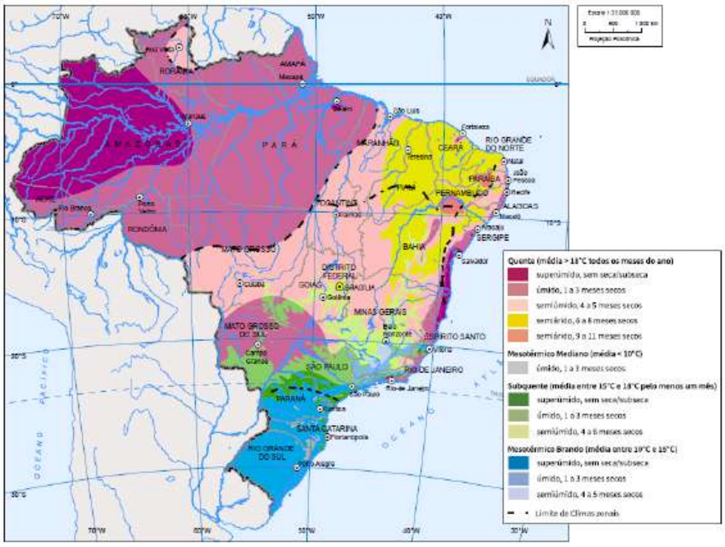


Fig. 1 - Map of types of climates in Brazil (Predominantly Tropical)
Source : https://www.ibge.gov.br

2. Insulators for Transmission Lines

Insulators are essential elements in transmission lines, responsible for supporting conductors and isolating them from support structures (towers).

Photo 1 – Example of 500kV cross rope structure (SIL high – 1860MW)
with suspension string toughened glass insulators

Although the insulator represents a small portion of the total cost of a transmission line (on average < 3%), their role is critical to the reliability of the transmission system. They are key components for the insulation of a transmission line and contribute to the resilience of the infrastructure in the face of maintenance challenges. Among the challenges we can mention degradation, aging, technology-related failures, improper sizing for pollution levels, manufacturing defects, vandalism (especially at voltages below 230 kV), wildfires, and climate-related phenomena such as strong winds and downbursts.

The aging of insulators is a continuous and cumulative process that leads to the deterioration of dielectric, mechanical, and surface properties. It is influenced by multiple factors, such as material composition, exposure to harsh environmental conditions, insulator design, manufacturing quality, electric field intensity, corona, electric arcs, leakage current, corrosion, etc.
The main technologies of insulators are ceramic (glass or porcelain) and polymeric exhibit distinct characteristics, degradation mechanism and risks in the application due to their different material structures and designs.
Table 1 below presents a comparative overview of the key characteristics between dielectric materials: porcelain, glass and polymeric.

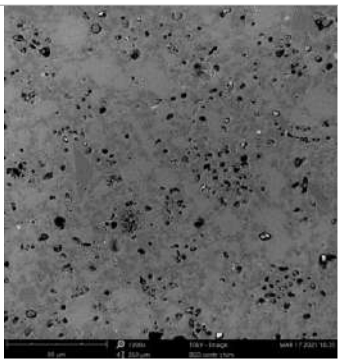
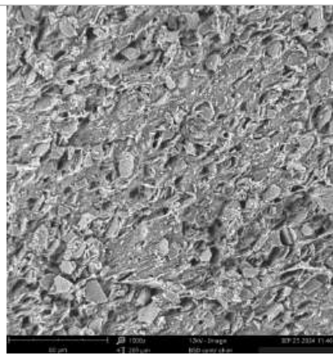
Characteristic	Ceramic Insulators		Non-Ceramic Insulators
	Porcelain	Toughened Glass	Polymeric
Atomic organization	Ordinate (crystalline)	Disordered (amorphous)	Ordinate (crystalline) + mineral filler
Microscopic surface	Rough, with visible grains	Smooth, no defined grains	Rough or smooth dependent on the mold used to make the insulator, with visible grains
Mechanical strength	High, but may have micro-defects	High, with good impact resistance	Low (rubber)
Images	 Porcelain under 1000x magnification	 Toughened Glass under 1000x magnification	 Composite under 1000x magnification

Table 1 - Comparison between dielectric materials

Porcelain insulators feature a microstructure that includes inherent porosity, which can lead to the development of intergranular cracks. These cracks may progress to internal punctures, as illustrated in Photo 2. When a punctured porcelain insulator is submitted to a power arc, it can result in severe mechanical failure, such as a pin pull out. This phenomenon is illustrated in Photo 3.

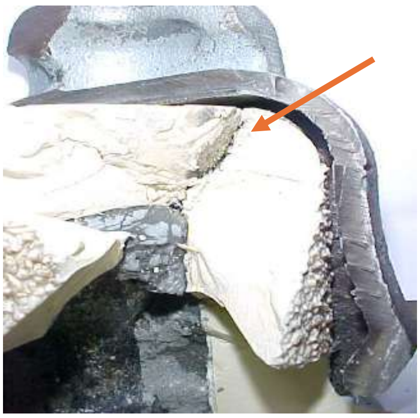


Photo 2 - Example of punctured porcelain insulator

Photo 3- Example of pin pull out after power arc

To illustrate what's happen when a porcelain insulator is punctured, a lightning impulse test was carried out on a short string consisting of 3 intact units at both ends and a punctured unit positioned in the middle. Photo 4 clearly illustrates that, in the case of a punctured porcelain insulator, the electrical discharge propagates internally.

Photo 4 - Atmospheric Impulse Test

Toughened glass insulators cannot puncture due to their amorphous structure and the toughening process. This process results in a binary failure mode: the insulator remains either fully intact or completely shattered [14]. Consequently, this technology as a major advantage over porcelain or composite: the ease of detecting damage. Maintenance and operations teams can reliably identify failed units through simple visual inspections, whether conducted from the ground, via drone or helicopter.

A study on a 500kV string was carried out to verify the influence of shattered TG insulators demonstrated that there is no risk with two shattered dielectric insulators in the string [2]

Polymeric insulators inherently undergo degradation over time while in service, due to the nature of the materials used in their production. The rate of aging is influenced by several factors, including design, manufacturing processes, production controls, material selection, and service conditions. Given the wide variability among these parameters, it remains challenging to establish a standardized specification that reliably ensures product quality and long-term performance in transmission line applications, particularly when aiming for a service life exceeding 30 years.

As an example, SEDIVER's research center carried out an analysis of polymeric insulators withdrawn from service after 12 years of operation (2011 to 2023), in a tropical environment. Cracks in the housing were identified during a detailed visual inspection of the transmission line, highlighting the effects of long-term exposure under such climatic conditions.

A cross-section of the insulators revealed that the cracks were nearing exposure of the core, as shown in Photo 5.

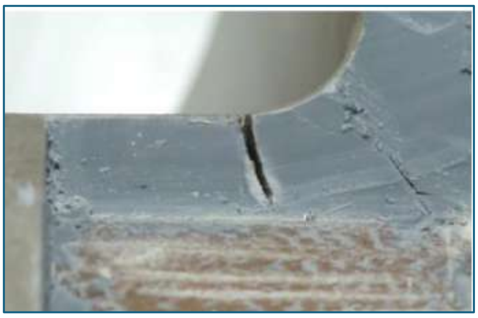
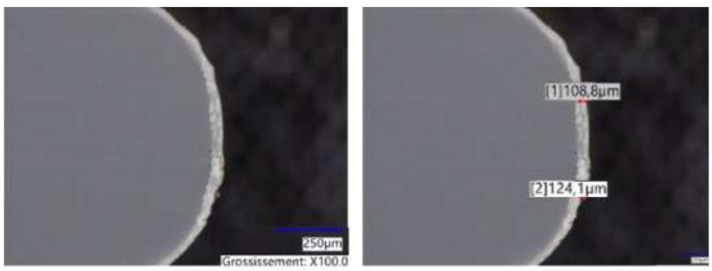


Photo 5 – Crack identified during detailed visual inspection



Transversal cut of a shed showing the mineral layer in surface

Photo 6 - White layer with thickness between 60 µm and 100 µm under magnification 100x

A microscopic analysis of the same insulator revealed the presence of a white surface layer on the housing, with a thickness ranging from 60 µm to 100 µm (Photo 6). This phenomenon results from the aging of silicone. The white layer corresponds to the formation of silicon dioxide on the surface, caused by a process known as silicification. This degradation reduces the elasticity of the material and may lead to cracks [11].

It is important to note that continuous exposure to environmental and electrical stresses progressively alters the physicochemical properties of polymeric materials. These changes include the loss of hydrophobicity, and reduced ability of silicone to recover its surface properties.

3. The Evaluation of Aged High Voltage Suspension Insulator

The results presented in this paper are part of a broader investigation into the aging and long-term reliability of the three existing transmission line insulator technologies.

In 2024, A.Matte and JMGeorge [1] conducted a comprehensive analysis of more than 2.000 ceramic insulators (porcelain and toughened glass) withdrawn from service, with the aim of evaluating the long-term reliability of these technologies. The survey covers more than 60 distinct populations, with service time ranging from 1 to 100 years, and includes data from more than a dozen manufacturers.

All insulators were subjected to electromechanical load failure tests, according to CSA C411.1-16, ANSI C29.2B-2013 and IEC 60383-1 standards, where the evaluation considered the dielectric and mechanical performance, excluding samples with severe corrosion or visual damage to the metal components.

Figure 2 shows an analysis of the samples according to the number of years of service. Differences in performance are observed, highlighting that toughened glass insulators present, proportionally, fewer results below the classification compared to porcelain populations.

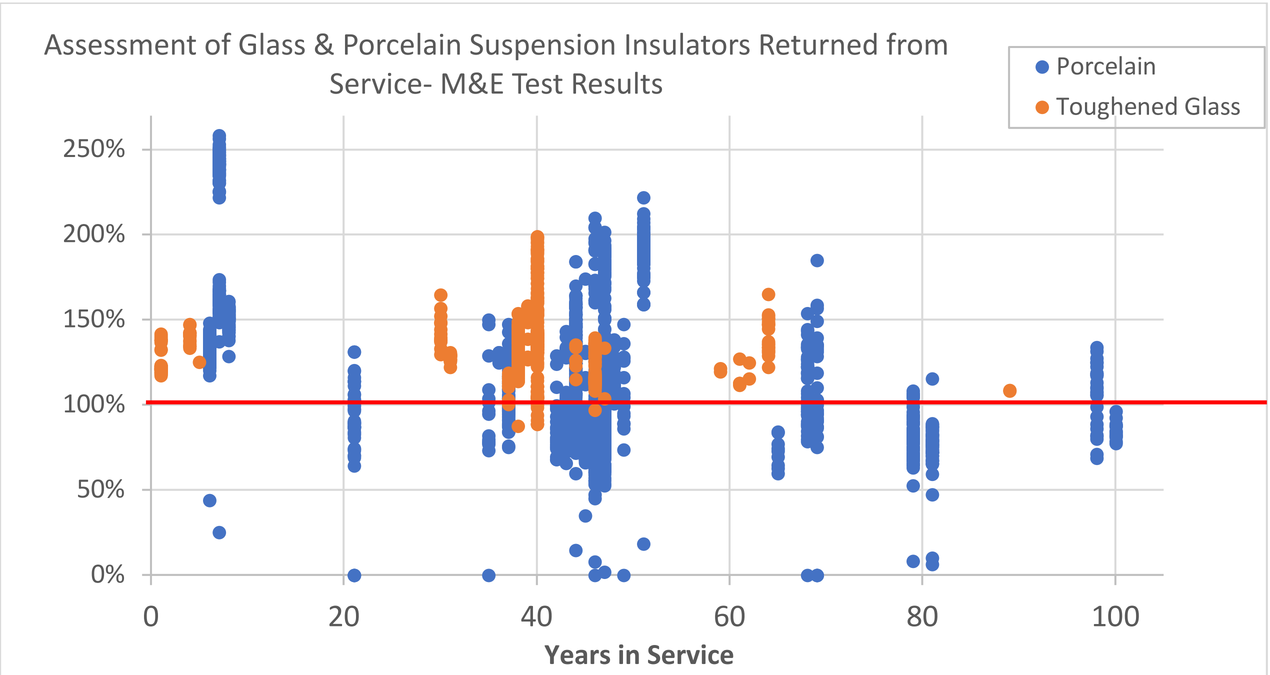


Fig 2 – M&E test results as a function of age for both porcelain and glass insulators. Porcelain units are represented in blue while toughened glass insulators are shown in orange.

Porcelain insulators exhibit dielectric aging, with less than 1% failure up to 20 years and about 50% after 45 years, due to the propagation of microcracks caused by thermal stresses.

Toughened glass insulators showed no signs of dielectric aging.

In conclusion, the article recommends that porcelain insulators older than 20 years be subjected to periodic inspections using laboratory methods or field-specific equipment. For toughened glass insulators, the text considers that visual inspections remain adequate, even for older models.

Regarding the Non-Ceramic Insulators (composite polymeric) it was not possible to perform a similar analysis due to the lack of data, since the available records usually involve investigations related to problems such as ruptures, silicon degradation and manufacturing defects in samples with significantly shorter use time than the one analyzed in the study [12 & 13].

4. Evaluation of Insulators with More than 40 years in Service in Tropical Climate in Brazil

4.1. Brazil's National Interconnected System (SIN)

Brazil's National Interconnected System (SIN) has approximately 171,640 km of transmission lines, according to data from the National Electric System Operator (ONS). Of this total, about 63% correspond to lines with voltages higher than 230 kV, where the insulators used are subject to high levels of electrical stress, resulting not only from high voltage levels but also from climatic variations typical of the tropical environment, such as temperature and humidity. These conditions require robust and reliable solutions to ensure the performance and durability of insulation systems over time.

kV	2023 km	%	2028 km	%
230	64.265	37%	69.070	35%
345	10.597	6%	10.744	5%
440	7.061	4%	7.072	4%
500	69.247	40%	91.192	46%
600	9.544	6%	9.544	5%
750	1.722	1%	1.722	1%
800	9.204	5%	10.671	5%
	171.640	100%	200.015	100%

Source: ONS

Figure 3 shows the historical development of transmission lines in Brazil. In the 1970s, toughened glass insulators predominated in a national interconnected system still in its initial phase, with transmission lines concentrated in the states of Minas Gerais, Rio de Janeiro and Paraná, far today's transmission corridors located in the northeastern region. At that time, quartz porcelain insulators were also commonly used as well as aluminous porcelain insulators for some lines above 230kV.

Note: *In Brazil, porcelain insulators from the ´60s and ´70s presented failure rates well above expected behavior standards (70/10,000 versus 10/10,000 year). Many of these insulators had radial fissures that in some cases extended from the pin to the skirt. [16] Insulators Training - Cigre Brasil GT B2.03. The photo on the side presents an example of a radial fissure detected at the time.*

In the 1980s, the use of polymeric insulators emerged as a response to pollution-related challenges. However, subsequent incidents involving insulator failures and conductor detachment, often resulting in penalty payments, were reported. These failures were attributed to material degradation or inadequate design, with affected insulators having been in service for periods between 6 to 18 years.

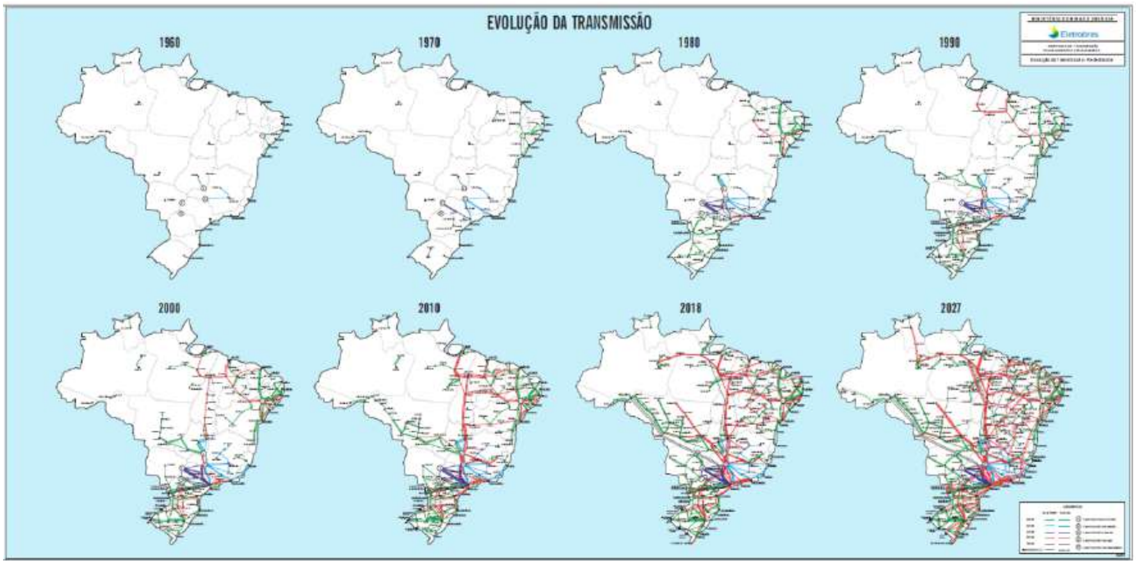


Fig. 3 - Historical evolution of the interconnected transmission system in Brazil. Source: Eletrobras

5. Description of the Tested Samples

A sample of 114 toughened glass insulators withdrawn from service after 40 years in operation was collected, located as shown in table 3 below.
These insulators were categorized into groups A, L and G.

State	Insulators quantity	Climate	Medium Humidity Annual	Temperature Average Annual	Specific Features
Rio de Janeiro (A)	52	Atlantic Tropical	60% - 80%	14°C - 36°C	• High humidity, well-distributed rainfall, rainier summer
Paraná (L)	12	Humid subtropical	70% - 80%	10°C - 30°C	• Hot summers, cold winters, well-distributed rainfall • Northwest with dry season in winter
Minas Gerais (G)	50	Tropical and semi-arid (northern)	55% - 70%	12°C - 35°C	• Dry (winter) and rainy (summer) season • North with semi-arid climate, scarce rainfall and intense heat

Table 3 – Specifications regarding the type of climate in force at the insulator installation sites

5.1.1. Tests

Based on the sample collected, a test program was defined for each group, following the procedures and criteria defined in IEC 60383-1:2023 and IEC 60815-1:2008, as detailed below.

- ❖ Visual inspection.
- ❖ Mechanical failing load test.
- ❖ Residual strength test.
- ❖ Pollution Measurement.
- ❖ Wet power frequency withstands voltage test.
- ❖ Dry lightning impulse voltage test.

5.1.2. Visual Inspection

During the visual inspection, the year of manufacture of the insulator, the visual aspect of the assembly and corrosion of the metal parts were verified.

The following years of manufacturing have been identified:

State (Group)	Insulators quantity	Year of manufacture
Rio de Janeiro (A)	52	1975
Paraná (L)	12	1975
Minas Gerais (G)	50	1975/1976/1977/1978/1988

Table 4 – Year of manufacture of the insulators

A gap of approximately 3 mm was observed at the cap-to-glass interface in all insulators manufactured prior to 1988.

Note: In Brazil, until late 70's, Toughened glass insulators were produced with a gap at the base of the cap, as shown in photo 7 below, to prevent contact between the glass and the dielectric. Starting in the 1980s, a new product was developed in collaboration with R&D in France without gap.

Photo 7 – Insulator with gap (1975) and without gap (1988)

The corrosion assessment was classified using table 3 based on the document CIGRE Brazil TB B2.03 002 « Insulators in Service Evaluation Criteria », where only 3 corrosion levels F1, F3 and F5 were considered. Table 5 below presents the results obtained.

Corrosion Classification	Description	Cap %	PIN %
F1	Galvanization protects always the metal, but some little superficial traces of oxidation are visible (modification of the visual aspect)	69	59
F3	Complete attack of the galvanization which is destroyed totally. A rust deposit covers the metal.	31	41
F5	Heavy corrosion with a significant reduction of the metal thickness.	0	0

Table 5 – Result of the corrosion assessment

Photo 8 – Example of cap corrosion:
(F1#17) and (F3 #42)

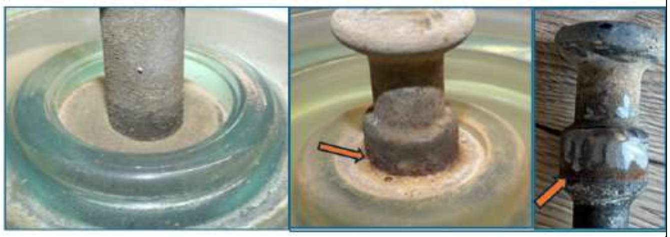


Photo 9- Example of a standard pin without corrosion (group L)
and a “pregnant” type pin with some corrosion of level F3 (group A)

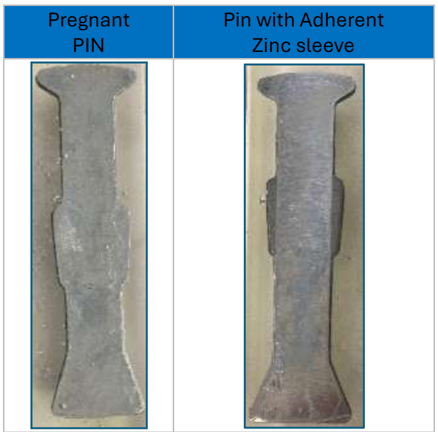


Photo 10 – pin Cross-section

During visual inspection, Group A and Group G insulators were identified featuring a “pregnant pin” design. As illustrated in Photo 10, this pin looks like a conventional pin type with zinc sleeve; however, instead of the sleeve, the pin features a steel overthickness.

This design was specifically developed to improve the mechanical resilience of the insulator in the event of a power arc, situation that can be particularly critical for 500 kV insulator sets, which were historically installed without adequate arcing protection.

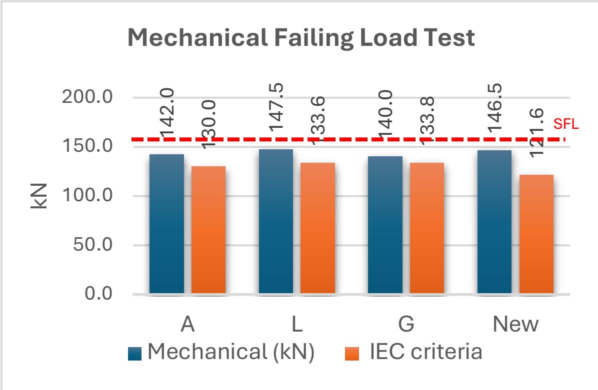
Mechanical Failing Load Test and Residual Strength Test

The mechanical results obtained on samples from groups A, L and G are detailed in table 5, figure 4 and photos 11 and 12 below. In the mechanical failing load test graph, there is a comparison between mechanical results and IEC criteria. For information, in figure 4 where there is a comparative result between mechanical failing load test and residual strength test, the maximum mechanical stress expected in service is indicated (40% of the SFL).

Note: [17] In the Brazilian standard ABNT NBR 5422/2024 14.2.2 Under working conditions without wind action, insulators and hardware cannot be subjected to a load exceeding 40% of their nominal breaking loads. 14.2.3 In the case of 10-minute wind for design, 3-s wind for design, and construction and maintenance of supports, insulators and hardware cannot be subjected to a load exceeding 60% of their nominal breaking loads.

State (group)	**Mechanical failing load test**			**Residual Strength test**		
	Qty	Result	Average mechanical failure value	Qty	Result	Average mechanical failure value
Rio de Janeiro (A)	10	9 pins broken/1 glass shell + pin pulled out	142,0 kN (118 % SFL)	10	10 pins pull out	118,9 kN (99 % SFL)
Paraná (L)	5	3 pins broken / 1 cap broken / 1 glass shell + pin pulled out	147,5 kN (123 % SFL)	5	1 pin broken/ 1 cap broken / 3 pull out	140,6 kN (117 % SFL)
Minas Gerais (G)	10	7 pins broken/2 caps broken/1 glass shell + pin pulled out	140,0 kN (117 % SFL)	12	1 pin broken/1 cap broken/10 pin pull out	113,4 kN (94 % SFL)

Table 5 – Mechanical failure types



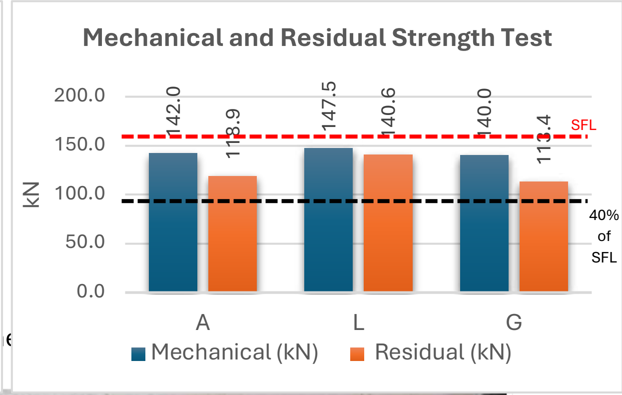


Photo 11 – Illustration of the result of the mechanical failing load test

Photo 12 – Illustration of the result of the residual strength test

5.2. Electrical tests – 1SS (Short Standard String) - IEC 60383-1/2023

One reduced string of 5 units was tested for each group.
After more than 40 years in service the results on unwashed samples still met the values specified in the manufacturer's catalog.

Test	Guaranteed value (kV)	Results
Dry Lightning Impulse Voltage Withstand	430	SATISFACTORY
Wet Power Frequency Withstand	195	

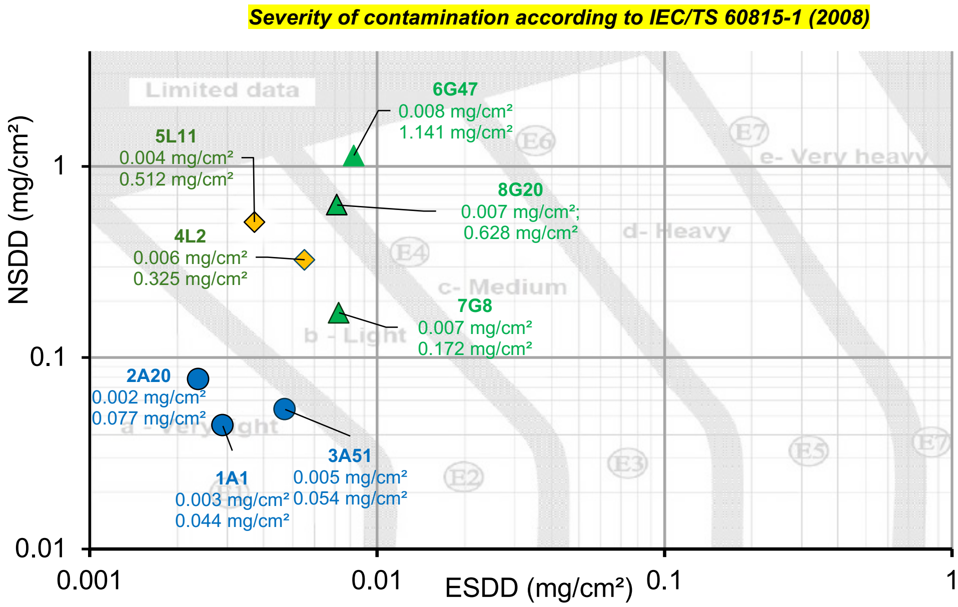
Photo 13 – Dry lightning impulse voltage test and one of the short strings during the wet power frequency test

5.3. Pollution measurements - IEC/TS 60815/2008

The severity of the pollution at the site (SPS), also referred to as the pollution level, was determined with the ESDD (Equivalent Salt Deposit Density) and NSDD (Non Soluble Deposit Density) method following the guidelines outlined in Appendix C of IEC/TS 60815/2008. The pollutants from the top and bottom were removed separately from the insulator surfaces to calculate CUR and the ESDD and NSDD values and classify the pollution severity level.

Photo 14 – Samples used for the evaluation of the pollution levels

The insulator strings were dimensioned for the b-Light pollution level (USCD 27.8mm/kVphase-ground).



Group	N/º	Surface	ESDD (mg/cm^2)	NSDD (mg/cm^2)	CUR	ESDD (mg/cm^2)	NSDD (mg/cm^2)	Pollution Class
A	1	TOP 1A1	0,003	0,033	0,9	0,003	0,044	Very Light
		BOT 1A1	0,003	0,050				
	20	TOP 2A20	0,003	0,035	0,6	0,002	0,077	Very Light
		BOT 2A20	0,002	0,100				
	51	TOP 3A51	0,008	0,033	0,4	0,005	0,054	Very Light
		BOT 3A51	0,003	0,065				
L	2	TOP 4L2	0,007	0,107	0,8	0,006	0,325	Light
		BOT 4L2	0,005	0,445				
	11	TOP 5L11	0,004	0,179	0,9	0,004	0,512	Light
		BOT 5L11	0,004	0,695				
G	47	TOP 6G47	0,005	0,462	2,0	0,008	1,141	Medium
		BOT 6G47	0,010	1,543				
	8	TOP 7G8	0,008	0,104	0,9	0,007	0,172	Light
		BOT 7G8	0,007	0,212				
	20	TOP 8G20	0,006	0,057	1,3	0,007	0,628	Light/Medium
		BOT 8G20	0,008	0,966				

Fig. 5 – Severity chart and table with ESDD/NSDD measurements

CUR = ESDD Bot/ ESDD Top (CUR ≈ 1: uniform contamination between the top and bottom surfaces. CUR > 1: Increased accumulation of contamination at the bottom. CUR < 1: Highest accumulation at the top.

Photo 15 – Sample 4L2 (CUR=0.8) and 5L11 (CUR=0.9) with heterogeneous pollution

Photo 16 – Sample 8G20 (CUR=1.3) and 6G47 (CUR=2.0)

6. Comments

6.1. Corrosion

It is possible to distinguish two main corrosion mechanisms specific to transmission line insulator [16]:

- Electrolytic corrosion: due to the passage of a frequent leakage current on each insulator of a string.

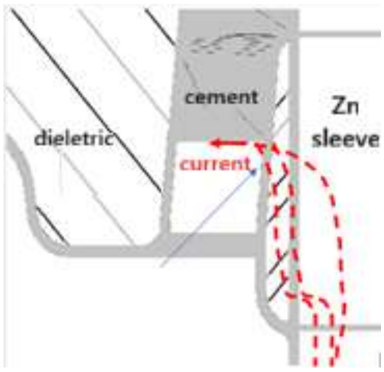


Fig 6 – Diagram of electrolytic corrosion in the zinc sleeve

- Corrosion due to electrical activity/arcs: phenomenon which concerns all the insulators of a string when the humidification of their surfaces is maximal, but also which increases the corrosion of the bottom units subjected to more arc activity duration than the other insulators during the pre-period of humidification and drying of the surface.

  These arcs are more intense/frequent in areas of greater electrical stress, such as the glass/cement/pin interface.

  The glass/cement/cap interface has a low incidence of activity/corrosion when there is no gap between them.

  Insulator strings that experience an intense electric field generating a high positive corona (+) index can also exhibit the same corrosion effect mentioned above.

  Transmission lines ≥ 345kV have the most intense electric field, therefore, a greater likelihood of this type of corrosion occurring.

6.1.1. Observation on the Caps of the Evaluated Samples

Corrosion at the cap/dielectric interface is mainly related to corrosion due to electrical activity/arcs because of existing GAP at the interface.

Photo 17 – Example of the cap machined to simulate a reduction of the metal thickness due to corrosion effect.

It should be noted that, from a mechanical standpoint, the insulator is not at risk, as the lower part of the cap in contact with the dielectric shell does not serve any mechanical function.

This conclusion is supported by tests simulating degradation in this region through machining for which the mechanical test results were equivalent to those obtained on new insulators.

6.1.2. Pin

The loss of galvanization in the pin region on the samples does not compromise the mechanical integrity of the insulator.

The observed corrosion is superficial and located linked at the over thickness section of the pin, specifically at the interface with the cement. No signs of electrical activity or leakage current were detected. ESDD measurements confirmed low pollution conductivity, and both the insulator design and string dimensioning were adapted to the environmental conditions of the transmission lines.

Photo 18 – Example of the corrosion observed in the over thickness of pregnant pin.

6.2. Mechanical

6.2.1. Mechanical failing load test

The mechanical results of the tested insulators of groups: A, L and G, met the evaluation criterion indicated in the IEC 60383-1/2023 standard.

The ANOVA method (Fig 7) was applied to determine whether the differences observed between groups are statistically significant or simply due to natural variability. The objective was to assess whether the insulator samples which were installed varying service conditions exhibit significantly different mechanical strength compared to each other and to new insulators.

Note: ANOVA (analysis of variance) is a statistical method for comparing the averages of three or more groups to see if any differences are significant. It uses the F-value to determine if the results are meaningful, helping researchers in fields like engineering and medicine assess the performance or differences among various groups or materials.

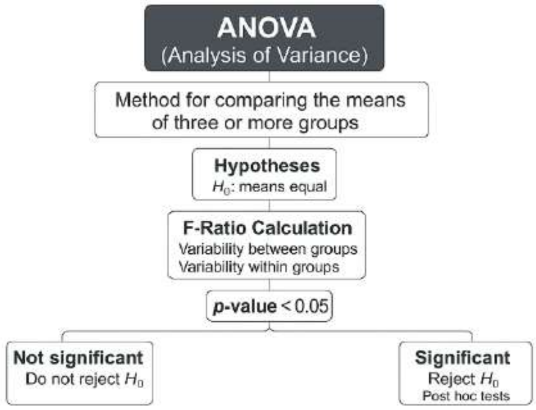


Fig 7 – Flowchart of ANOVA method

The results are the following:

Anova: single factor

SUMMARY

Group	*Count*	*Sum(kN)*	*Average(kN)*	*Variance*
G	10	1400,1	140,01	368,2832
A	10	1420,2	142,02	115,3729
L	5	737,6	147,52	13,352
New 2024	10	1464,5	146,45	4,800556

ANOVA

Source of variation	***SQ*** Sum of Squares (Crude Variance)	***Gl*** degrees of freedom	***MQ*** mean of squares = SS / df	***F*** statistic F = MQ between groups / MQ within groups	***p-value*** (3) probability of getting the data if H_0 is true	***Critical F*** (3) threshold value for rejecting H_0
Between Groups (1)	311,5317	3	103,8439	0,723485	0,545658	2,911334
Inside groups (2)	4449,518	31	143,5328			
Total	4761,05	34				

(1) Between-group variation: Measures the variance between group means. If this variation is large in relation to the internal variation, it may indicate a significant difference.

(2) Variation within groups: Measures the variation within each group (data dispersion). The lower it is, the more consistent the data.

(3) Statistical decision:
If p-value < 0.05 → Rejects H_0 → There is a significant difference between the means.
If F > F critical → also indicates significant difference.

The ANOVA results indicate that there are no statistically significant differences between the groups. When comparing the mechanical performance of aged insulators with that of a new insulator the results show no meaningful variation also. The insulators removed from service did not exhibit any signs of mechanical degradation or ageing.

6.2.2. Residual strength test

Residual mechanical strength refers to the maximum mechanical load reached by a cap and pin insulator having a damaged dielectric part.

In this test, the evaluation criterion of the IEC 60383-1/2023 standard was not adopted due to the number of samples for each group being tested. However, all the results were far above the normal working conditions and the maximum load during, and construction and maintenance defined in the Brazilian standard ABNT NBR 5422/2024 [15] (respectively 40% and 60 % of the specified failing load guarantee of the insulator)

6.3. Pollution

All the insulators evaluated presented an ESDD value lower than 0.01 m/cm^2, indicating low deposition of conductive contaminants. This feature significantly reduces the risk of high leakage currents and discharges from pollution.

The measured values of group A (Rio de Janeiro) and group L (Paraná) indicate that the design of the insulator string is in accordance with the pollution class found.

Group G (Minas Gerais) recorded one insulator with a pollution level classified as medium, which corresponds to a level above that foreseen in the string project.

7. Conclusion

Based on the evaluation of the toughened glass insulators removed from service after more than 40 years in a tropical, high-severity climate and in comparison, with the mechanical results of type tests conducted in 2024 with new toughened glass insulators as indicated as New 2024 in the section 6.2.1, no evidence of electromechanical degradation or ageing was identified. This performance is linked both to the quality of the toughened glass products and the design of the strings, which were appropriately dimensioned according to the pollution levels measured during testing (section 5.4).

According to the analysis, all three insulator populations were deemed suitable for continued service without replacement. However, particular attention should be given to monitoring pin corrosion during the visual transmission line inspections. The classification outlined in section 5.1.2 can be applied for this purpose.

In the context of asset management, which seeks to maximize the useful life of equipment, the use of drones integrated with artificial intelligence (AI) (photo 19) for diagnostic imaging in the inspection of TGI contributes to the efficiency of the process. The combination of the binary characteristic of these insulators [section 2] with the classification of the corrosion level [section 5.1.2] makes it possible to carry out inspections and the detection of defects in an accurate, agile way and with reduced operating costs (OPEX) throughout the life cycle of the component, indicating that it is a technology with the lowest Total Cost of Ownership during its useful life.

Photo 19 – Example of visual inspection with a drone string with glass insulator

Glass insulators are designed to be resilient, with long durability, low carbon emission and high strength.

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