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Aging Infrastructure Evaluation
The Evaluation of Aged High Voltage Ceramic Suspension Insulators- A Synthesized Analysis of In-Service Insulator Aging Assessments

A. MATTE **J.M. George**
Sediver **Sediver**
Canada **France**

SUMMARY

The conditional assessment of high voltage ceramic insulators is well understood to provide insight into the continued performance of a given population [1]. The more commonality across the population (manufacturer, class, year produced, factory of origin, and even batch), the more we can infer from the analysis of a small sample. In contrast, this paper reviews the results of a large volume of assessments revealing generalities useful to asset managers, design engineers, and standards committees as inferences can be made regarding the expected long-term performance of the different insulating technologies and the risk of failure of these assets as they age.

The criticality of this information only increases as utilities face the dual challenge associated with electrification: working to meet increased demand while simultaneously managing millions of aging insulators [2], many requiring replacement in order to maintain the dependability and reliability of their network. Utilities contend with the decision making required to appropriately balance the construction of new lines while also increasing the reliability of existing lines through rehabilitation projects targeting underperforming insulator populations.

As it is well established that a decrease in performance can be expected with certain ceramic insulators [3] (with porcelain and toughened glass inclusively defined as ceramic) [4], our study focuses strictly on units returned from service. Collected from utilities around the world, our analysis is based on well over two-thousand individual samples across more than 60 separate populations. Our synthesis includes populations with years in service spanning from a handful of years to an impressive one-hundred years in service. It includes a multitude of manufacturers without prejudice as it does not delve into any individual-level performance but rather investigates the generalized performance attributes that can be applied more broadly to any in-service ceramic insulator population.

KEYWORDS

Overhead line - Old insulator – Porcelain – Glass – Assessment - Aging - End of life – Reliability – Asset management

BACKGROUND

Insulator aging assessments are generally conducted in order to understand the continued performance of in-service populations of high voltage transmission line insulators [5]. Alternatively, they're also performed as part of a root cause investigation after a utility has encountered an issue such as a flashover across an insulator string, string failure resulting in a line drop, or higher than anticipated self-shattering rates. Despite conducting countless insulator aging assessments over the years across Sediver's network of labs, not until now was this data compiled and analysed collectively.

Past studies similarly encompassing large volumes of data endeavoured to allow asset managers the ability to make broad assumptions regarding an insulator population's continued *in situ* performance depending on the manufacturer, years in service, and other determinants. In contrast, herein we posit that by ignoring brand, mechanical rating, years in service or manufactured, operational voltage, etc… allows for a review of the industry's collective performance. Furthermore, delving into the aforementioned details reveals performance trends which may be of interest to both asset managers as well as standards committees.

By combing through Sediver's archives, we compiled data from any ceramic suspension insulator population where, at a minimum, the following data was available:

- Manufacturer
- Insulating material (porcelain or toughened glass)
- Year manufactured
- Years in service
- Mechanical rating & Class
- Dielectric profile
- Coupling type i.e. ball & socket or clevis tongue

Additionally, in order to include any population into this synthesis, it must have been subjected to an electromechanical failing load test where insulators were a tensile load was applied until the point of failure (either mechanical, electrical, or both) while simultaneously applying a minimum power frequency voltage of 75% of the insulator's dry power frequency voltage.

It must be noted that, as required by national standards such as CSA C411.1-16 and ANSI C29.2B-2013 as well as international standards, for example IEC 60383-1, do not require the electrical portion of the electromechanical failing load test on toughened glass insulators due to their binary nature; where the glass shell can only exist in either a fully intact state, or completely shattered, without the possibility of a partially punctured dielectric. This property results in an inability to hide internal punctures. This is in contrast to porcelain units which must undergo electrical testing during tensile testing to ensure the internal integrity of the dielectric.

The quantification of results was then possible in terms of a percentage of a sample's original M&E (Mechanical & Electrical) rating. This permitted us to analyze multiple populations across a wide range of electromechanical classes. As this analysis focuses on the aging of the dielectric materials, samples with severe corrosion of the metal components, or exhibiting visual evidence of possible compromised integrity of either the cap or pin, were omitted from the synthesized data.

In all, over a dozen manufacturers are represented (six glass manufacturers and seven porcelain manufacturers). The oldest insulators were manufactured in the closing days of the First World War in 1918, while in comparison, the youngest population spent only a single year in service and was manufactured over a hundred years later. With samples from all decades in between, this study's data represents much of the high voltage transmission insulator industry's very existence. All samples included in our synthesis are represented in Figures 1A & 1B where the red horizontal line represents the normalized rating at 100% of an insulator's M&E rating with any datapoints falling below failing to meet their rating. All points above the red line exceeded their M&E rating during testing. Figures 1A & 1B do not take into account years in service. Porcelain samples are represented in blue while toughened glass units are shown in orange in Figure 1A while in Figure 1B individual manufacturers are represented through unique colorization of datapoints attributed to each manufacturer's insulators included in the study.

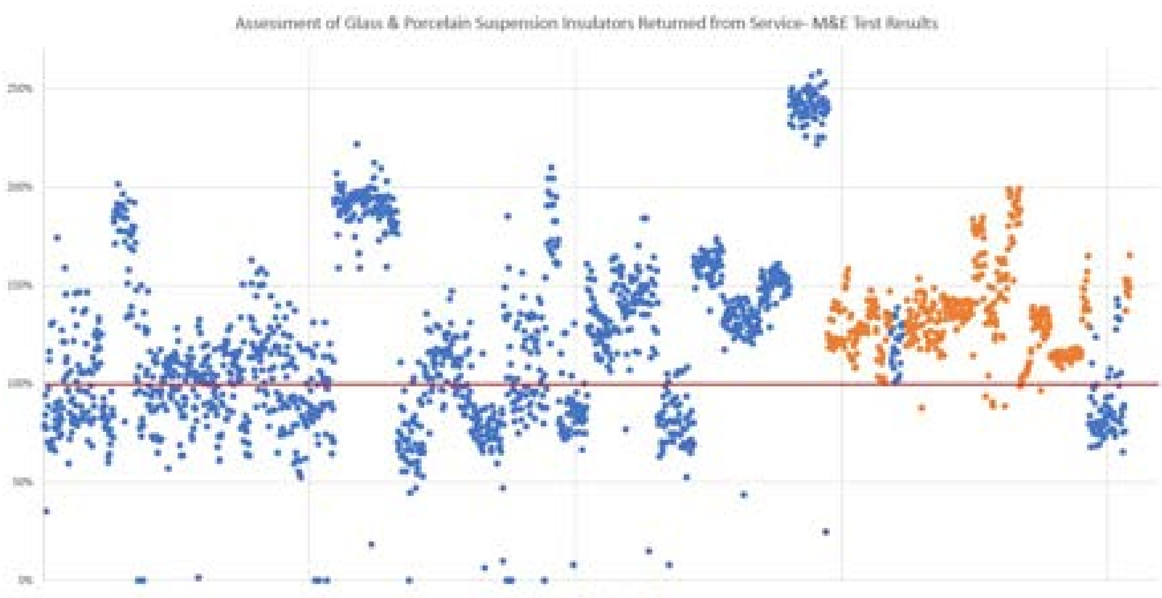


Figure 1A- Porcelain & toughened glass insulator M&E test results. Blue datapoints represent porcelain samples while toughened glass insulators are shown in orange. The horizontal axis represents individual sample number, not timeline.

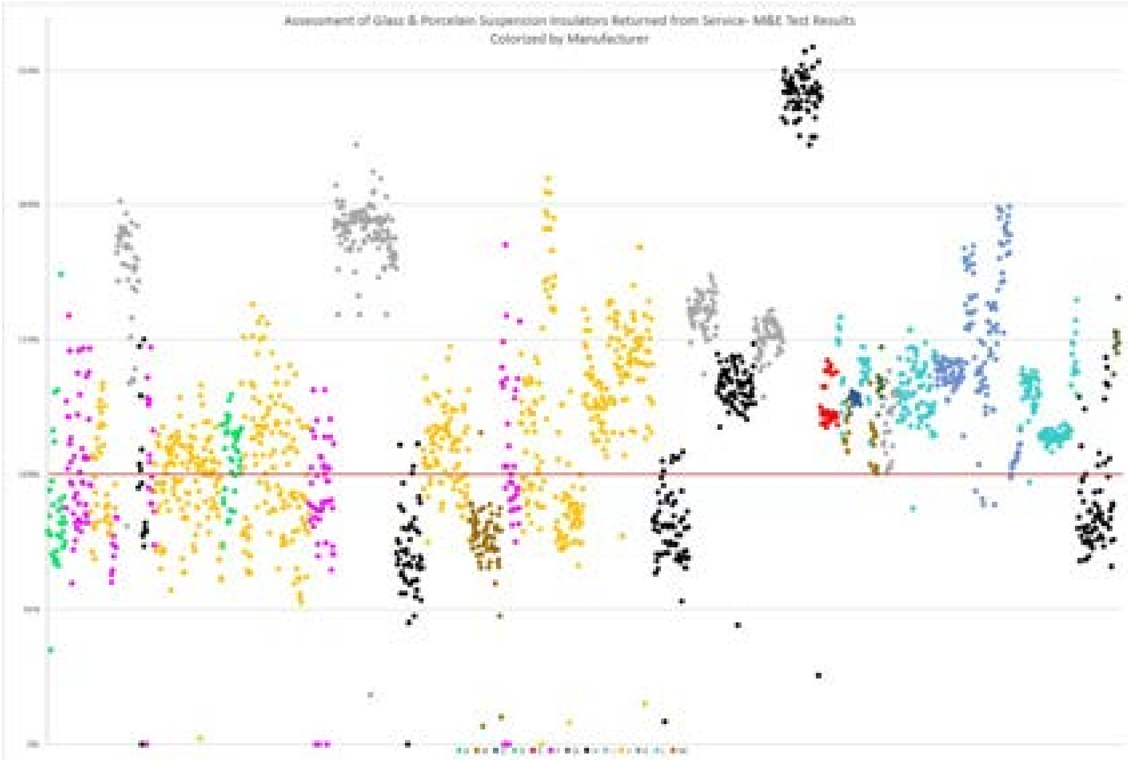


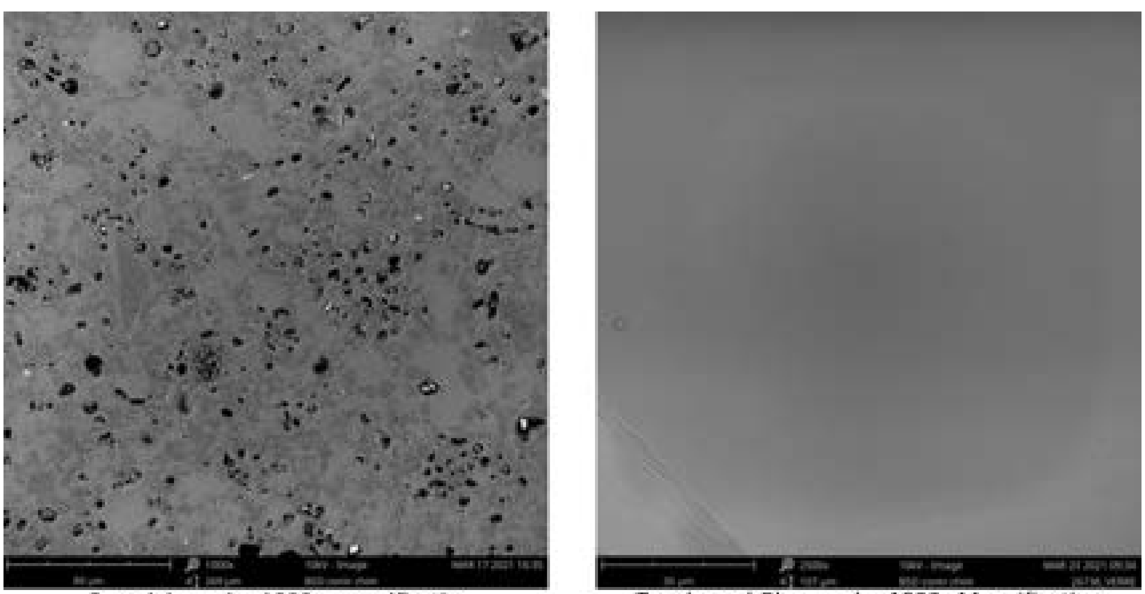
Figure 1B- Porcelain & toughened glass insulator M&E test results with unique colorization for each manufacturer included in the study. The horizontal axis represents individual sample number, not timeline.

Though they share some commonality with regard to their components, and despite the fact both porcelain and toughened glass insulators are classified as ceramic, fundamental differences exist in the dielectric materials [6]. It is well understood that porcelain dielectrics age through the propagation of microcracks resulting from the service-induced stresses; a consequence of the difference in the coefficient of thermal expansion of the porcelain dielectric compared to the cast iron cap, steel pin, and cement from which an insulator is assembled.

Figure 2 displays the result of an aging assessment conducted on 45-year-old 120kN porcelain insulators which were leftover construction spares. Never installed and stored outdoors, these insulators were subjected only to the thermal stresses associated with weathering Canadian summers and winters. An assessment of these units was requested upon the utility's initiation of the transmission line's insulator string rehabilitation as it was hoped they could be used in the replacement project. But as can be seen in the graph, nearly half the population failed to meet the insulator model's electromechanical rating during testing, resulting in the disposal of the inventoried units. Testing was conducted following CSA C411.1-16's electromechanical failing load test in-line with all other populations included in this study.

Figure 2 – M&E test results on unused porcelain insulators after 45 years in outdoor storage. The horizontal axis represents individual sample number, not timeline.

Toughened glass insulators, as a consequence of the amorphous, non-crystalline structure of the material from which the dielectric is manufactured, does not age similarly to porcelain when subjected to thermal stresses incurred through thermal expansion and contraction. This is the result, in part, of a closer alignment between the glass' coefficient of thermal expansion and those of the cap, pin, and cement. Also, properly toughened glass insulators are inherently binary in behavior, existing only in two well-defined states: with the dielectric fully intact or completely shattered. Consequently, any faulty toughened glass dielectric exhibits a self-identifying behavior by completely shattering, leaving a mechanically and electrically safe stub [7].



Porcelain under 1000x magnification

Toughened Glass under 1000x Magnification

Figure 3 – Porcelain and toughened glass under 1000x magnification

ANALYSIS

Previously conducted studies on aging ceramic insulators reveal significant differences in performance when comparing one homogenous population of insulators to another, and between the two types of ceramic insulators, porcelain and glass. In consideration of this, our analysis looks at the two distinct ceramic dielectric materials separately.

Figures 1A & 4 distinguish the datapoints between glass and porcelain with the Figure 1A displaying the disparity of results across all individual samples while Figure 4 focuses on the samples based on the number of years in service, though again here disparities in performance are noticed with far fewer toughened glass insulators proportionately failing to meet their rating than the porcelain populations. All toughened glass insulator failures below rating were attributed to failures of the metal components and not the dielectric. Additionally, virtually all failures were from a single manufacturer, proving, as with porcelain, variances exist in terms of quality between the various glass insulator manufacturers.

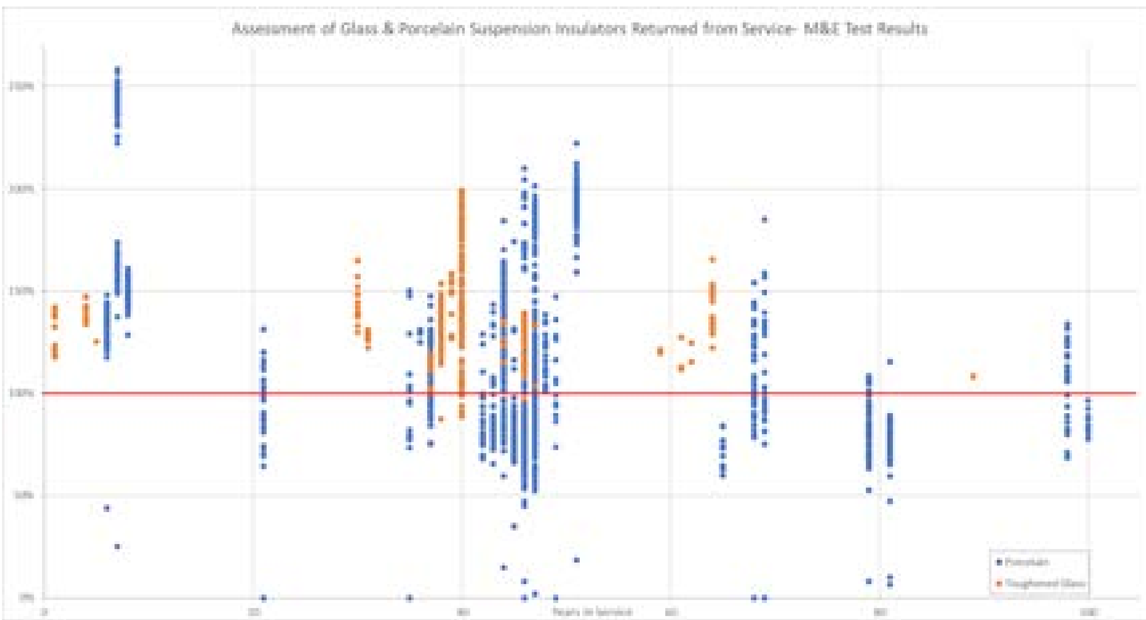


Figure 4- M&E test results as a function of age for both porcelain and glass insulators. Porcelain units are represented in blue while toughened glass insulators are shown in orange.

Since not all porcelain ages similalry and can vary considerably in terms of its expected service life [8], an attempt was made to produce the classic Weibull density bathtub curb with little success, suspected to be caused by the inconsistency in results from one homogeneous population of porcelain insulators from another. This aligns with Cigre's guide on the assessment of porcelain and glass insulators whose efforts also proved fruitless in this regard. Nonetheless, others have gone ahead with conducting Mean Time to Failure calculations for given populations. Herein, no such attempt is made, rather, by quantifying the failure rates across all populations included in this study, we hope to provide useful insight into how best to manage insulators still in service.

Interestingly, across the over 1,500 porcelain samples included in our study and depicted in Figure 5 below, we note a total failure rate of approximately 1% for insulators with less than 20 years in service. Looking beyond that, however, it's noted insulator populations remaining in service beyond 45 years have an approximate 50% chance of not meeting their M&E ratings with significant proportions of the populations exhibiting punctured dielectrics during M&E failing load testing and a failure rate which increases with time.

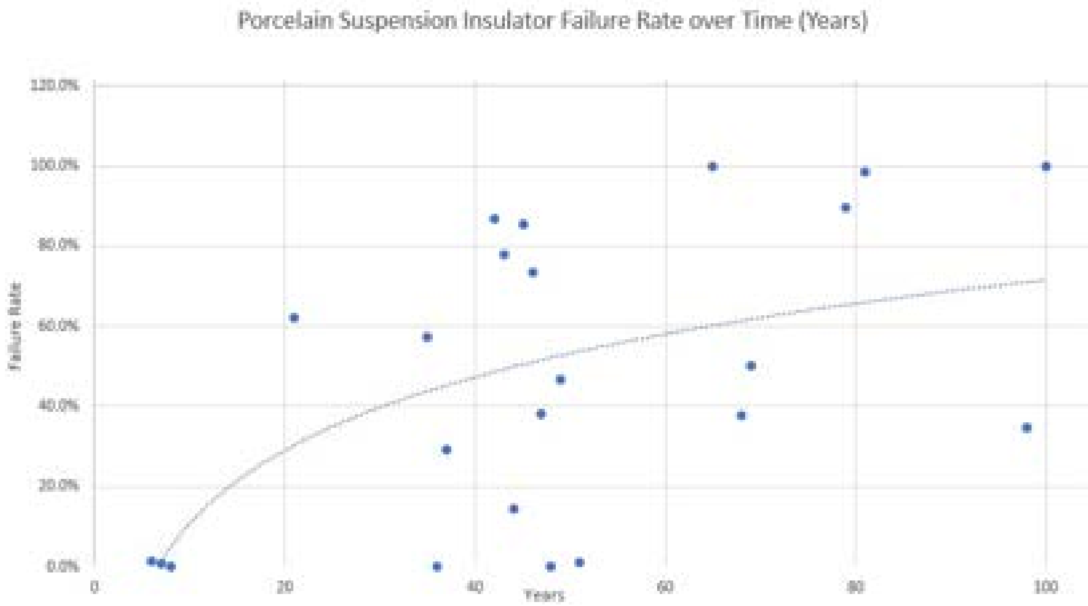


Figure 5- Porcelain insulator failure rate over time (approx. 1500 samples included in analysis)

Comparatively, the data from toughened glass insulator population assessments are shown in Figure 6. Though, similar to porcelain, a few failures were noted for units beginning at approximately 40 years in service, all failures were associated with the metal components. This contrasts with porcelain where most failures were attributed to the dielectrics. Still, this represents little in statistical terms. The result is a nearly flat projected failure rate of approximately 1% across the nearly 90 years analyzed. No exponential increase was noted for glass insulator failure rates confirming the absence of aging of the glass dielectric itself.

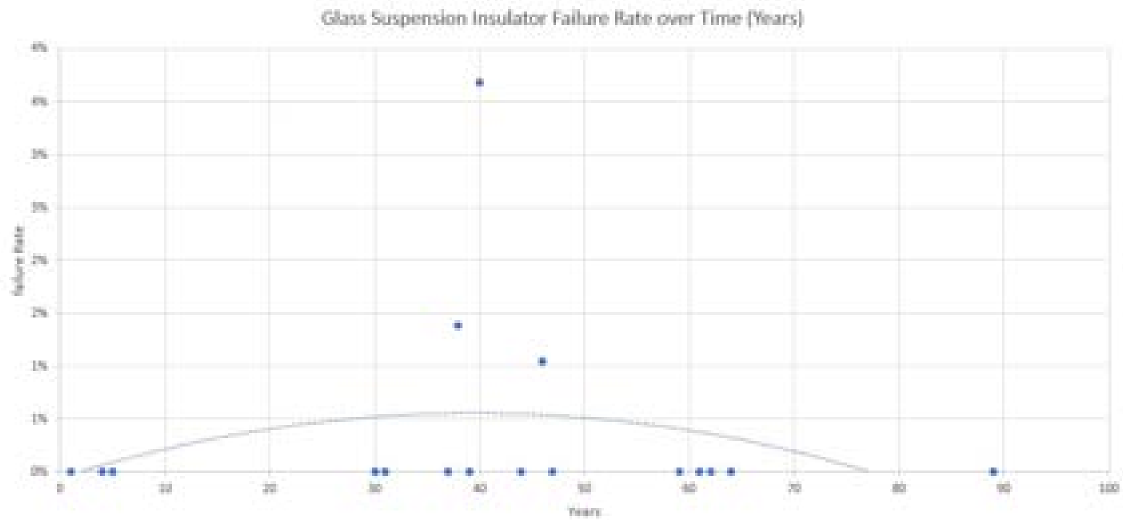


Figure 6 – Toughened glass insulator failure rates over time (approx. 500 samples included in analysis)

DISCUSSION

As utilities content with the historic challenge of maintaining existing assets, current and forecasted labor shortages [9] limit the capacity to simultaneously develop new lines that are required as a result of increases in demand due to electrification, or to connect new sources of clean energy as part of decarbonization efforts. Not to mention the organic development of lines due to population growth. And, whereas in the past, little attention may have been given to "middle-aged" insulators (20-45 years in service), consumers' tolerances for outages has decreased [10], requiring utilities to increase reliability of their assets. A review of synthesized porcelain insulator populations' M&E test results could justify the dedication of additional resources to monitor the continued in-service performance for any units exceeding 20 years in service in order to maximize reliability.

Insulators represent approximately 5% to 7% of the total expenditure of building a new transmission line. With utilities publishing data on maintenance costs and reporting 1 of every 2 dollars spent is attributed to insulator failures [11], the question arises if the significant failure rate of 20+ year old (and especially 40+ year old) porcelain is directly correlated to the expense of maintaining these assests. So long as correlations also exist between pricing and quality of insulators [12], the old addage stating "you get what you pay for" very well may prove of use to standards groups, design engineers, and asset managers when considering a project's TOTEX (comprised of both the capital expenditure -CAPEX, of a project as well as the operational expenditures -OPEX, required to maintain an asset over its anticipated service life).

This determination will become critical over the next few years as our industry enters an unprecedented period of development. With tens of millions of kilometers of new transmission lines needed globally by 2040 [13], demand for many components will dwarf existing supply. Understanding if the selection of one insulating material over another will result in the necessary and increasing allocation of resources as time progresses, will only escalate in importance in a larger and more complex network. A network managed by an increasingly strained workforces covering more and more kilometers of lines. Will utilities have the same ability to replace failed or failing insulators tomorrow the same as they do today? Will replacement insulators be as readily available in the future as they are now?

Another observation derived from the synthesis; as a result of the significant failure rate of the porcelain insulators, only approximately 1% failed below 50% which is interesting given the fact that all ceramic suspension insulators have to undergo a systematic routine test load of 50% of their M&E rating at the end of manufacturing. This corresponds to CSA design critieria as well but if designing per NESC which permits 65% loading, the failure rate increases to 4%. It should be noted that across the nearly 500 glass insulator samples from a half-dozen manufacturers, and despite the inconsitancies in performance between manufacturers, no insulator failed below 88% of its electromechanical rating.

RECOMMENDATIONS

Given the results of this analysis, it seems reasonable to recommend that utilities increase the inspection rate of porcelain insulators upon attaining 20 years in service. Whereas visual inspections give little information on the actual condition of porcelain discs, more sophisticated methodologies, including the use of in-field test equipement may be more appropriate for these older populations. Utilities should consider conducting regular sampling of these populations, removing a statistically representational selection of units for laboratory testing.

For glass insulators, the flat failure rate observed raises little doubt that a continuation of the visual inspections typical for this dielectric material is well suited for these populations, even as they age, as its binary nature allows for infallible conditional asssesments at a glance. No change in frequency or modality is necessary over time since the dieleectric does not age.

CONCLUSION

Utilities face an era of unprecedented development where they are expected to build, operate, and maintain transmission lines with increasing reliliability. Gaining a deeper understanding of the continued in-service conditional performance of their ceramic suspension insulators allows them to develop efficient maintenance and inspection plans and permits for the implementation of proactive and cost effective asset management strategies. Knowing when and what resouces to appropriately dedicate to a given insulator population will only increase in importance as our grid evolves in both size and complexity. That said, the empirical evidence gathered across a large volume of ceramic suspension insulators reveals performance trends for each of the dielectric materials. A comprehension of these trends allows for the appropriate allocation of resources for each insulator type as these asssets age. Furthermore, design engineers and standards groups within utilities may find the performance trends usefull in determining what qualifies for in-service use as well as how best to equip transmission lines with the most reliable insulation materials. When considering TOTEX, the information contained herein hopefully allows utilities to more accurately quantify the projected costs of maintaining transmission lines given the insulator type across its service life.

Lastly, now armed with a deeper understanding of the long-term performance of *in situ* insulator populations, utilities may reevaluate the most appropriate use of newly sourced insulators during this period of unprecedented forecasted network expansion. With the anticipated growth of world's tranmission networks, a time may soon come where the common practice of removing and replacing entire strings of ceramic insulators during planned rehabilitation work or during emergency remediation changes to take into account the age and anticipated continued performance of the insulators in question.

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