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B2 OVERHEAD LINES
PS3 CLIMATE CHANGE AND EXTREME WEATHER EVENTS

High Voltage Suspension Insulator String Designs for Extreme Weather Events

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SUMMARY

As extreme weather events become more frequent with climate change, utilities are rethinking traditional transmission system design, which relied on historic data with n-1 reliability criterion—ensuring systems can withstand the limited unexpected failures. However, the growing impact of hurricanes, wildfires, ice storms, and other climate-driven events is prompting a shift toward n-x reliability, which address larger-scale, simultaneous failures through more resilient design approaches.

For high-voltage suspension insulators, traditional selection has focused on capital (CAPEX) and operating expenses (OPEX) to determine total cost (TOTEX) over the asset's lifespan. Today, many utilities are prioritizing performance under extreme conditions over cost alone. In-line with this, novel insulator string designs feature enhanced dielectric profiles, heat resistance, and modularity—enabling adaptability to evolving environmental and operational demands.

This paper examines design innovations addressing specific challenges like ice bridging, wildfires, and pollution. It advocates moving beyond traditional configurations toward more resilient designs and explores how certain insulator types can be used in emergency restoration, improving responsiveness to both n-1 [1] and n-x events [2]. Included are performance data from heat and pollution tests, and feedback from utilities. The aim is to help engineers and asset managers make informed choices to enhance the reliability, resilience, and adaptability of transmission systems in the face of a changing climate.

KEYWORDS

Resiliency, insulator, cap & pin, extreme weather, ice, birds, silicone coating, replacement

1 Introduction

Many utilities operate legacy high voltage transmission lines, handed down from previous generations who faced more predictable and less dynamic operating conditions. For those earlier generations, historic meteorological data proved invaluable in designing well-performing assets. But with time, our predecessors' assumptions and designs are challenged by less predictable and more extreme conditions [3]. To maintain the good performance of older transmission lines whose original insulator strings no longer provided adequate reliability, novel solutions have been developed addressing specific challenges. This paper presents a selection of cap & pin suspension string currently in-service and developed as replacements to original designs to address *in-situ* problems.

2 Ice-Bridging and Alternating Strings:

Typically associated with coastal environments with sea-spray or salt-fog, atomized salt in the air affects the performance of insulators as it accumulates into a conductive pollution layer. But a perfect storm of conditions has led to pollution-induced flashovers in North America's Great Lakes region on transmission lines running parallel to major highways. These occur predominantly in the spring during thawing and freezing periods. During the day, temperatures rise above freezing, melting ice and snow on the towers, crossarms, and insulator strings. With the fall back below freezing at night, dripping meltwater forms icicles bridging across the dielectric of one insulator to the adjoining unit below (Figure1). This is not an issue in clean environments [4], however, next to heavily salted highways where salt has been atomized into the air through the circulation of vehicles on the roadway, the mixture of salt and meltwater forms conductive paths across the insulator string.

Figure 1- Insulator string exhibiting ice bridging

2.1 Alternating Strings

Several utilities have developed a solution for ice bridging, one easily retrofitted onto existing structures or specified in the construction of new lines. Running counter to their intended use, insulators conceived for arid environments are being incorporated into I-strings of cap & pin insulators. These insulators, developed for use in areas without the benefit of the cleaning effects of rain, best take advantage of the wind to whisk away contamination. By flattening a 10-inch standard-profile insulator into a 15-inch flat disc (Figure 2), we eliminate the under-ribs which create areas sheltered from the wind where contamination can build up. But with a similar leakage distance, equivalent electromechanical performance is maintained.

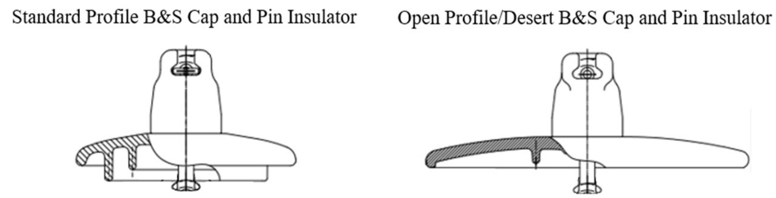

***Figure 2*- Standard (on the left) and open/desert (on the right) profile cap & pin insulators.**

The use of open profile insulators for their original purpose is rare in the Great Lakes region, but by alternating between open-profile and standard profile insulators in I-strings, a conductive icicle is forced to achieve twice the length it would if it were on an insulator string composed of a single profile type, see Figure 3.

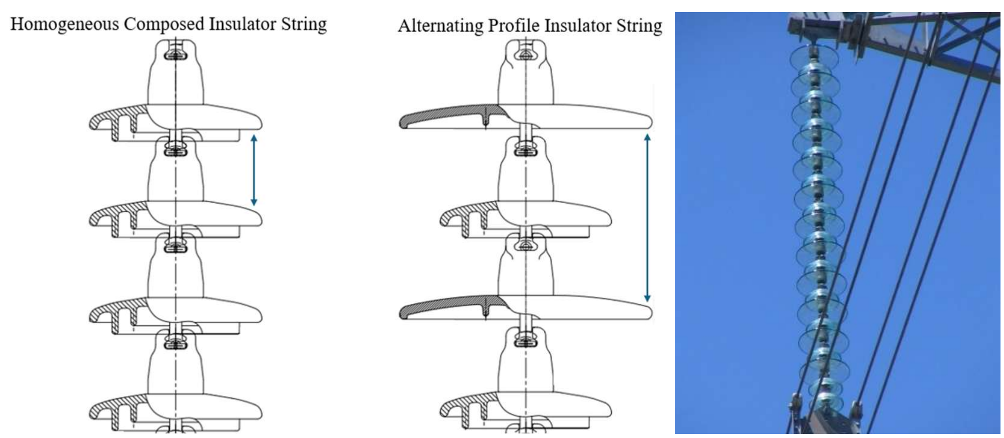

***Figure 3*- On the left, a classic design with only standard profile insulators. In the centre, an alternating string design with open and standard profile insulators. The blue arrows in both drawings represent icicle growth. On the right, a photo of an alternating string installation.**

With an installation base spanning over a decade, the thousands of insulators in alternating strings prove a good solution to a very specific issue, often unforeseen in the conception and design of transmission lines. Nonetheless, in cases where changing climatic conditions lead to ice bridging, their use can improve a line's reliability.

3 Bird Guards:

On certain transmission lines, birds, or more specifically their droppings, known as mute, are the leading cause of outages, surpassing those caused by vegetation or inclement weather [5]. Western North America faces a seasonal problem linked to the migratory patterns of ravens. Much has been written on solutions keyed at deterring their perching above insulator, as well as the use of hydrophobic coatings on toughened glass insulators to mitigate the risk of a bird mute related flashovers on V-strings [6]. Bird mute aside, in clean environments, there exists a more cost-effective solution, easily retrofitted onto cap & pin I-strings: the use of open-profile insulators on the cold/tower side of the string serving to shield 10-inch standard profile or 11-inch fog-types below (Figure 4). Climate change effects migration patterns. For any utility facing an increased threat to their assets' reliability due to bird mute, bird guards are a proven solution.

Figure 4- Open profile insulator installed as a bird guard above standard profile insulators.

Found primarily on tangent structures, this configuration has now also found its way onto deadend structures with crossarm-installed jumpers, replacing the originally installed 2-piece porcelain post type insulators after water shedding issues were noticed leading to ice bridging, see Figure 5.

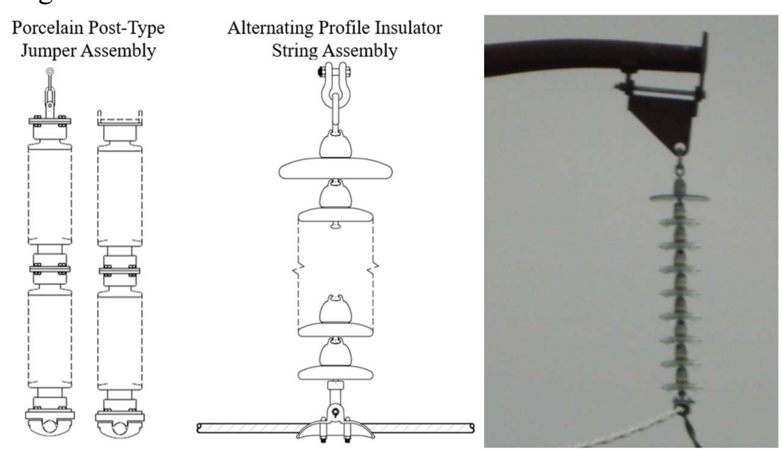

Figure 5- On the left, the original porcelain post-type jumper assemblies while in the center, the I-string now specified as the preferred option. On the right, a ComEd jumper assembly

4 Resistance to Extreme Heat (Wildfires):

Climate change has resulted in new weather patterns where extremes, such as droughts, predominate, increasing in intensity and frequency. Wildfire frequency has also risen along with the risk of exposing transmission lines to their extreme heat. And whereas sections of transmission lines directly in the path of a fire may require replacement, studies conducted to better understand the behaviour of insulators when exposed to extreme heat allow utilities to understand if assets can be salvaged, as some insulator types have been proven to handle well extreme heat. But this is not the case for all dielectric materials [7]. Figure 6 shows the relatively low temperature that composite/polymer insulators begin to lose mechanical strength.

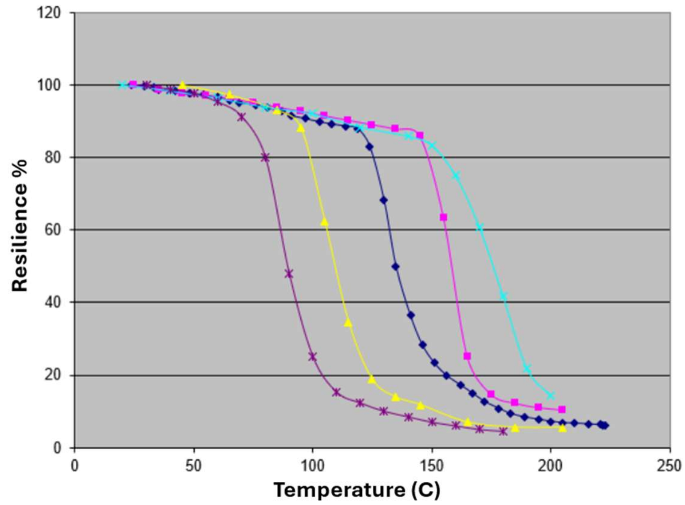

Figure 6- Tg set point loss of resilience of composite insulators during Torsional strength test

The studies also reveal how porcelain dielectrics exposed to high temperatures undergo accelerated aging. Figure 7 shows the results of electromechanical failing load tests after thermal preconditioning. Their performance loss is due to the difference in coefficient of thermal expansion of the porcelain and those of the cast iron cap, steel pin, and cement used in the complete insulator. Comparing this in Figure 8 with toughened glass, we see that glass' expansion rate aligns more closely with that of other components. But the composition of porcelain, with its micro structuring, is inherently prone to the propagation of miniscule fissures (Figure 9) in the dielectric material when introduced to thermal stress [8]. However, as seen in Figures 10 & 11, toughened glass' homogeneous composition and thermal expansion rate results in a unique ability to withstand high temperatures.

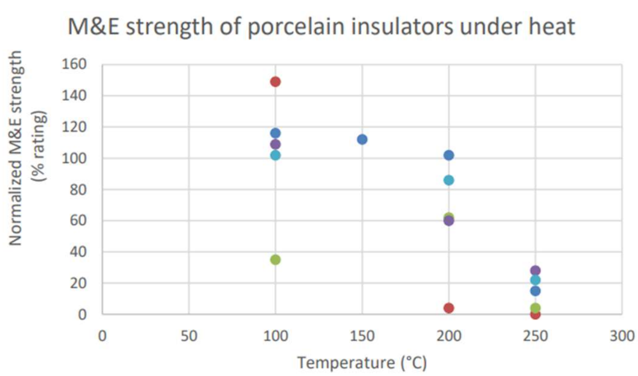

Figure 7- Results of electromechanical failing load testing of porcelain cap & pin insulators subjected to a thermal preconditioning in which they were subjected to high temperatures.

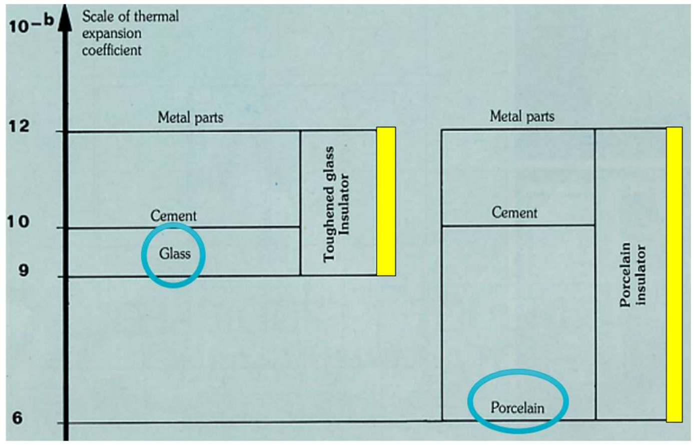

***Figure 8*- Thermal expansion rates of the components of ceramic cap & pin insulators**

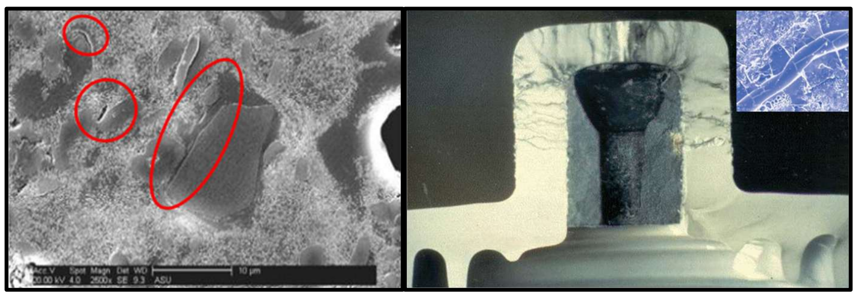

***Figure 9*- Porcelain magnification revealing micro voids on the left. On right, a cutaway of a punctured porcelain cap & pin insulator displaying evidence of an internal puncture. The inset photo is a magnification of the puncture channel.**

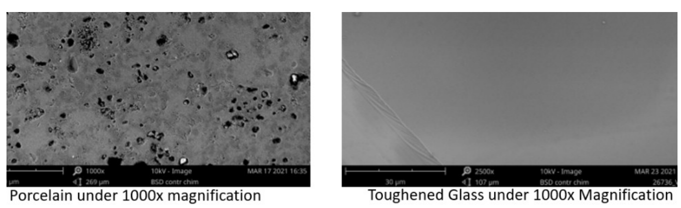

***Figure 10*- Porcelain (left) and toughened glass (right) under 1000x magnification**

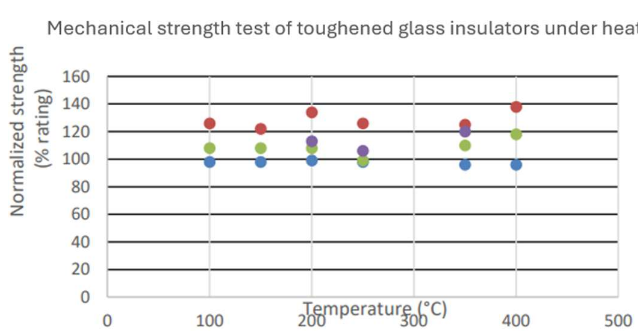

***Figure 11*- Results of electromechanical failing load tests on toughened glass insulators subjected to a thermal preconditioning.**

5 Emergency Storm Restoration:

Ice bridging, bird mute, and wildfires can all be considered localised issues which do not affect all utilities equally. Regardless of the threats a utility faces, one commonality is the need for robust and responsive emergency storm restoration plans. The increase in extreme weather events resulting in widespread outages push legacy assets beyond their designed capabilities. Whether facing increased ice loading, stronger winds, hurricanes, etc. unplanned failures present obvious challenges. But along with these challenges arise opportunities to strengthen assets as they are restored, making them less susceptible to the next storm.

5.1 2024 Illinois Tornados

2024 was unlike any other year in Illinois's recorded history [9]. Though not unfamiliar with tornados, the year was exceptional with a record 142 tornados confirmed across the state. In July, severe weather spawned over 40 tornadoes in Northern Illinois [10]. Unprecedented for Commonwealth Edison (ComEd), these storms resulted in widespread outages and damage to important assets, including a 765kV transmission line (Figure 12). Despite nearly half a million customers in the dark, power was restored impressively fast, in part due to a high degree of standardization of the insulators utilized in their designs.

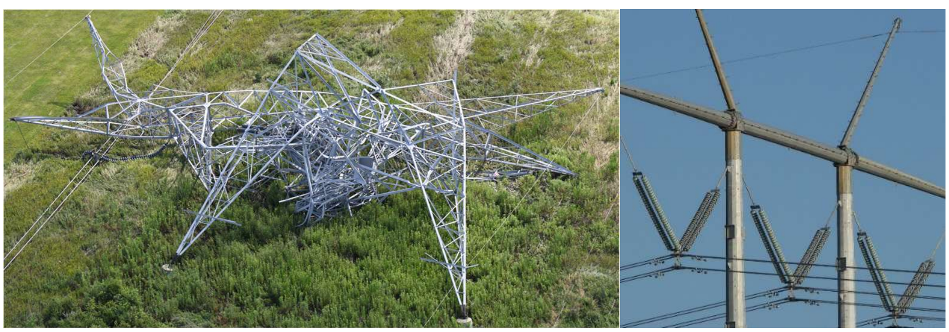

Figure 12- 765kV structure located in Illinois destroyed by tornado in 2024 (left).On the right, replacement structure with silicone coated toughened glass insulators

Another factor contributing to the recovery speed was the use of toughened glass insulators with an inherent binary nature where the dielectric can only exist in one of two well-defined states; fully intact or completely shattered. This differs from porcelain or composite insulators capable of hiding internal defects without any visual evidence of a fault, and in ComEd's case, would require electrical testing, especially in the case of live-line work. But a visual inspection provides infallible data on the conditional performance of a toughened glass insulators, and as such, additional testing or inspections were not required.

Also helping the recovery was the insulator of choice's reduced weight compared to the storm-damaged porcelain insulators. Weighing 20% less, they were more easily handled by recovery crews while their superior impact resistance permitted their rough handling in the crews' haste to restore power, all without risk of unknowingly installing a damaged dielectric.

Finally, a safety factor came to play in speeding up the recovery. While crews removing the old broken porcelain insulators had to act with caution to avoid injury due to the razor-sharp edges prevalent with failed porcelain dielectrics, those handling glass, had no such concerns as even a failed glass dielectric breaks apart into small fragments or kernels with a low probability of causing harm.

It should be noted that ComEd received two awards from the Edison Electrical Institute (EEI) recognizing their exemplary recovery efforts.

There were additional considerations made in the selection of the insulators used in the recovery efforts. With a forethought into future resilience against the next series of storms, toughened glass was selected in part due to its high residual strength. Going above and beyond ANSI C29.2B-2013, CSA C411.1-16, and IEC 60383 requirements of 65% of the insulator mechanical rating, ComEd requires an 80% residual strength. In this test, the dielectric shell of porcelain and glass insulators (both classified as ceramic) is completely broken from the cap and what remains is subjected to a mechanical strength test. The properties of stubs (the toughened glass insulator after the dielectric has been broken away) are such that not only is the residual strength high compared to other dielectric materials, but they remain electrically safe as well, without a risk of an internal flashover. The reason simply is because the path of least resistance for current is the air gap between the conductive cast iron cap and the steel pin of a stub.

These inherent benefits permitted ComEd to respond quickly and restore the functionality of assets all while increasing their resiliency.

6 Polymer Replacement with Coated Toughened Glass:

With its first use as an insulating material for high voltage applications sometime in the late 1800s, porcelain's the oldest dielectric material used in HV insulation. Toughened glass was introduced in 1947. A couple decades later, composite insulators were developed. Though all three materials have evolved since their inceptions, the introduction of a novel insulator type seems overdue. But there exists an insulator today which embraces the benefits of the various technologies; the longevity, reliability, and ease of inspection of toughened glass insulators, with the pollution performance of polymer insulators: silicone coated toughened glass.

With decades of in-service experience, factory-coated toughened glass insulators have long been understood to provide good performance in polluted environments while offering incomparable resilience. But in the past, these were primarily used to address *in-situ* performance issues as a retrofitted solution replacing uncoated porcelain or glass. Or, in new construction, specified as necessary due to contamination levels. But recently, coated glass has found a new use- the replacement of aged polymer insulators.

It is well understood ceramic insulators, including both porcelain and toughened glass, provide good in-service performance generally lasting several decades longer than polymer/composite insulators, especially in suspension applications [11]. Projects aiming to replaced aging polymer insulators are not uncommon. Utilities facing the inevitable replacement of their aged composite insulators now often select coated glass to attain a higher degree of reliability while still achieving good performance in contaminated environments. All while also enhancing the line's resilience because of the new insulator's superior ability to withstand line drops. It is precisely for these reasons ComEd elected to use coated glass to replace polymer insulators (Figure 13) on certain 138kV applications. Now, these assets benefit from a hardened resilience, longer anticipated service life, and are easier to inspect. And like non-coated toughened glass insulators, coated units retain their binary nature and ease of inspection.

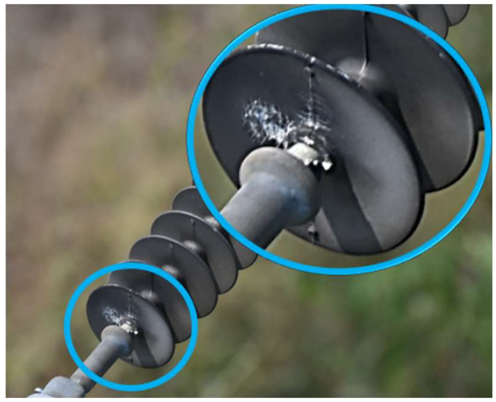

Figure 13- ***138kV polymer insulator exhibiting erosion and replaced with toughened glass.***

7 Discussion

Many of the solutions discussed above were not part of the original insulator string designs. They are retrofitted based on operating conditions and performance. In the case of older legacy transmission lines, even if the solutions had existed back during their conception, and considered, the capital expenditure into their acquisition could not be justified given the design philosophy at the time. With the insight possible after absorbing ballooning total expenditures on transmission lines with ever increasing operational costs, in hindsight, should different choices have been made? On the Pacific Coast where wildfires have wreaked havoc unforeseen decades ago, many utilities have now standardized to the use of insulator types, which among other benefits, provide better performance to extreme heat, have a higher residual strength, and offer a higher degree of security with their lower risk of line drop. Around the Great Lakes, the TOTEX of certain lines could have been reduced with the installation of insulator string assemblies better suited in a more dynamic operating environment during the initial construction, rather than decades later. Similarly, insulators with anticipated service lives shorter than that of the transmission line itself will require replacement. It comes as no surprise that ComEd elected to replace their aging polymer insulators with coated toughened glass, even at the relatively low voltage of 138kV. The cost of replacing the polymers a 2nd time couldn't be justified in consideration of the required dependability of the line and the cost difference with that of the coated glass, a logic that can be applied across a broad spectrum of applications.

8 Conclusion

An environment where high wind loads, exposure to extreme heat, ice-bridging, and tornados would seem an improbable area in which a utility would build and operate transmission lines. And yet, with assets inherited from past generations of engineers who weren't considering today's probabilities of extreme weather, we find ourselves very much operating such lines. But novel and relatively simple solutions exist for those facing the very specific challenges highlighted in this paper; ice-bridging, bird mute, polymer insulator replacement, storm restoration, and wildfires. In place for many years and across several utilities, these solutions offer resilience in the face of increasing uncertainty and *n-x* event probability.

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