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PS 2 – Latest Techniques in Asset Management,
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Overhead line insulators in operating constraints under severely polluted conditions: the benefits of silicone coated glass insulators and their application at the PG&E Diablo Canyon Nuclear Power Plant

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SUMMARY

Over the years, power utilities have had three options to insulate their power lines: porcelain, glass, or polymer insulators. In heavily contaminated environments many utilities were and are still solving pollution related flashover issues by either washing, or by simply putting grease to their existing ceramic insulators, without a design change. Once polymer insulators were easily available, many utilities applied this technology in contaminated areas due to the hydrophobic nature of their silicone surface. The hydrophobicity of silicone defends against moisture which acts like a conductive catalyst to insulators that have a layer of pollution on the surface. However, a greater need for resiliency in the power grid brings a stronger focus on pollution mitigation methods using traditional insulators which is a key driver for using silicone coating on overhead line insulators. For decades, silicone coatings on high voltage ceramic (glass and porcelain) insulators have proven to perform well under severe pollution environments, and primarily in substations.

We now see coated ceramic overhead line insulators as a fourth option of choice from a design stage combining the benefits of greater resiliency with enhanced performance in high pollution environments without washing. This is especially true in remote areas that are difficult to access by maintenance crews. Often, pollution flashover issues are isolated to just a particular location on the overhead line where pollution exists more so than other locations. Other times, these areas are much larger in scale like transmission lines that run along the coast, or through the desert. In either case, the practicability of coating is an attractive alternative to regular insulator washing. Today it is not uncommon to see new transmission lines designed from the beginning with this combined feature. Today coatings are being more often applied in an industrial and controlled environment for performance and longevity considerations compared to on site application.

The rapid growth of silicone coatings has led several standardization bodies to start looking into this technology with the objective of setting guidelines in material selection, application methods, screening properties towards ageing, etc. Among the recent work CIGRE TB 837 constitutes a good reference document. A review of the key elements under consideration is given in this paper.

To illustrate the performance of silicone coated insulators, we look to the California coast where Pacific Gas & Electric shares their experience from their nuclear facility at the Diablo Canyon Power Plant (DCPP) located on the shore of Avila Beach, CA. Nuclear power generation requires cooling water, so it is common to position these plants on the coast where there is an abundance of sea water. However, the coastal environment requires the infrastructure to be more robust, and able to operate under corrosive and contaminated conditions. The same is true for the power lines connecting the generation station to the grid. The presence of coastal salt fog creates a major stress on the insulators. Surface pollution, such as salt deposits, together with periods of moist salt fog can lead to surface discharges and potentially flashovers.

KEYWORDS

Pollution – Glass insulator - Silicone coating – Maintenance - Resilience - Insulator washing - Asset management - Nuclear - Transmission

1. INTRODUCTION

Insulator selection criteria for overhead lines has evolved over the last decades. Pollution resulting either from airborne dust or coastal salt fog constitutes a major factor in this determination. In extreme conditions, ceramic insulators (glass or porcelain) often serve beyond their limits, forcing periodic insulator washing to clean off contaminants. Another option is to use polymer insulators in which the housing material is made of silicone rubber, thus providing the benefit of a water-repellent surface, the so-called hydrophobic property of silicone. This property results in a reduction of the leakage current on the surface of the insulator when moisture is absorbed by the surface deposits and subsequently reduces the risk of flashovers.

While this property is one of the key features of polymer insulators, the last decades have also shown the limitations and risks related to ageing of polymer insulators especially in these harsh conditions. An alternative common approach that sees extensive application is the use of silicone coating over either traditional glass or porcelain insulators. The selection of the appropriate silicone chemistry and the choice of the application process are being reviewed in this paper with a quick review of the key parameters to take into consideration for coatings.

A case study of the use of silicone coating over glass insulators is presented in this paper through the actual field experience of the Diablo Canyon Power Plant (DCPP) in California where porcelain insulators had to be washed frequently. The study performed to improve this situation involves considerations of leakage distance availability combined with the use of RTV (Room Temperature Vulcanizing) silicone coating.

2. HYDROPHOBICITY

The capability of silicone surfaces to shed water is largely known today and used in the electric sector mostly to prevent surface currents and subsequent surface arcing. A material is being classified as hydrophobic when the contact angle as shown in figure 1 is higher than 90°. A classification of the hydrophobic status of a surface was set up in IEC TS 62073 [1]. This property is transferred through the pollution deposit and is expected to survive over time even in very harsh conditions as shown in Figure 1. For overhead line insulators it offers a mean to reducing leakage currents, avoiding flashovers but this benefit should not be traded against risks of failure or line drops.

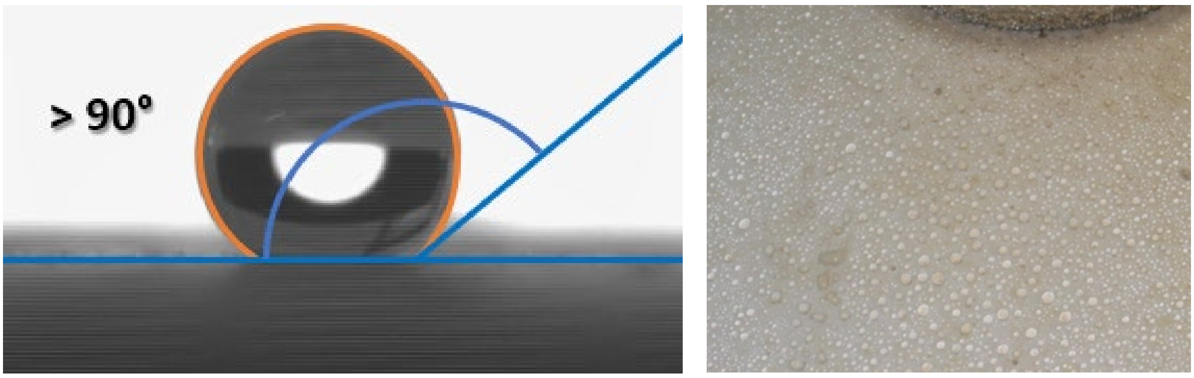

Figure 1 (Left): defines hydrophobicity, (Right): hydrophobicity maintained in the surface of a silicone coated glass insulators after approximately 20 years in harsh environment.

Originally silicone grease was applied on the surface of porcelain bushing and other apparatus in substations. This was not well adapted for overhead lines since the grease had to be removed and reapplied periodically thus not practically applicable to insulator strings hanging up in the air on towers and often disseminated in the wilderness.

The use of polymer insulators came in for the very reason that it offered the same benefit without the need of replacing the grease. Nevertheless, polymer insulators showed their limits in a number of locations and especially harsh environments. In fact, the silicone housing, while ensuring proper overall hydrophobicity to prevent flashovers, is stressed electrically through corona and dry band activity. These conditions often led to erosion of the silicone itself and expose the internal core of the insulator until a failure occurs as shown in Figure 2. Field experience has shown that hydrophobicity often survives the stage where a silicone polymer housing is eroded but the level of erosion is usually the limiting lifetime factor for polymer insulators. It is in this context that silicone coating gained popularity in the protection of overhead line insulators when exposed to harsh contamination conditions. For coated insulators erosion can also take place (Figure 2) but the risk of a catastrophic failure is eliminated by the fact that under the silicone housing the material is not an organic fiberglass core like for polymers.

Figure 2 (Left): Erosion of a polymer insulator which is still hydrophobic after approximately 15 years in service in harsh conditions. (Right): Comparative erosion of a silicone coated glass insulator.

3. SILICONE COATED INSULATORS

Silicone coated insulators have been used in a variety of conditions and environments with great success. A very interesting document published by CIGRE in 2021 bringing together most technical aspects related to silicone coating (CIGRE TB 837 [5]) describes the key physico-chemical, ageing considerations, pollution performance, application methods and examples of specifications. The most important elements to keep in mind can be summarized as follow:

- Fingerprinting of the material: many coatings exist, and various tests are suggested to verify that the coating supplied is in line with the one selected through type tests. Among those TGA testing (Thermo Gravimetric Analyses) will ensure the presence of ATH (Alumina Tri Hydrate) which is a very effective filler known for tracking and erosion resistance.
- Thickness consistency with appropriate check points.
- Adherence of the silicone to the surface: method for testing was discussed in the Technical Brochure TB837. Scratch test method using the tool from ISO2409 [3] standard is favoured. Discussions around the water boiling test as per IEEE 1523 [4] have shown that this test is relatively irrelevant and will be discussed further.

- Ageing testing of coated insulators can be evaluated through various test procedures, but one seems to stick out since it has already been adopted by many utilities. The test sequence is shown in Figure 3 and consist of a 2000h multi-stress test. It is an interesting test since it shows a clear ability to discriminate best performers (Figure 4).

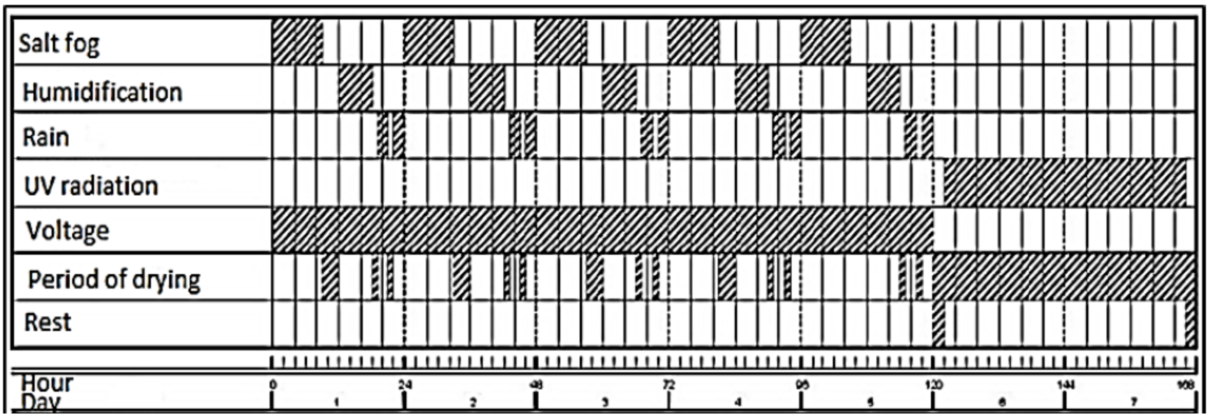

Figure 3: 2000h multi stress test cycle for ageing evaluation of silicone coated insulators

Figure 4: Examples of silicone coated glass insulators using different chemistries of coating after the 2000h test.

4. POLLUTION PERFORMANCE

Laboratory testing of silicone hydrophobic surfaces (also called HTM) can be tricky. Recent [5] and ongoing work is trying to establish the best test procedure for an insulator which exhibits dynamic properties such as the transfer of hydrophobicity through the contamination deposit and the recovery if disrupted by preliminary preconditioning during testing (as currently described in IEC 60507 [6]).

Nevertheless, either for salt fog conditions or with solid layer pollution an abundant set of test results is clearly showing the extremely interesting performance of silicone coated insulators. Figure 5 shows the performance of non-coated glass insulators relatively to fully coated and under coated glass insulators.

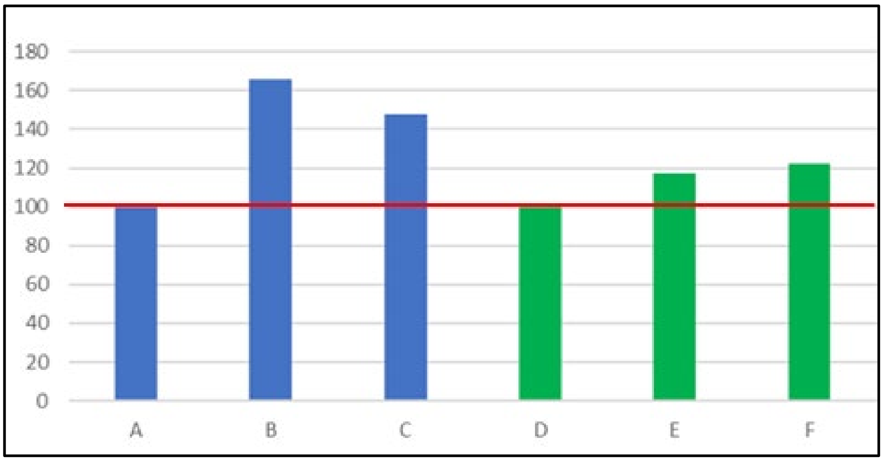

Figure 5: Relative pollution performance in % between non coated (A, D), fully coated (B, E) and under coated insulators (C, F). With reference on a base 100 for non-coated units. In green salt fog test at 40g/l. In blue clean fog test with ESDD=0.1mg/cm² and NSDD=0.2mg/cm².

As illustrated in Figure 5, silicone undercoating (Figure 6) is an option which is gaining popularity since it provides very good pollution performance, and is less likely to be damaged when shipping, handling and installation. Unlike the top surface of the insulator, the underside is rarely in contact with packaging crates, or the ground when the insulator strings are being assembled for installation. Another benefit of undercoating is the visual confirmation that the dialectic shell is glass, and not porcelain. Because porcelain and glass behave differently, this is an important factor. Pacific Gas & Electric is using undercoated glass insulators as a standard feature today for their polluted areas across the grid (Figure 7).

Figure 6: Under coated glass insulators

Figure 7: Example of under coated glass insulators installation at PG&E

In the end, the best laboratory test is the actual field performance, and in this respect, the following experience at DCPP is very interesting.

5. DIABLO CANYON NUCLEAR POWER PLANT

DCPP (Figure 8) was commissioned by PG&E in the mid 1980's with two 500kV overhead lines extending out from the generators and turbine building to deliver power. Since the plant's inception, DCPP would wash insulators and other equipment regularly, and as a result, had not experienced a pollution related flashover for nearly 3 decades. However, in the years of 2012 to 2014 DCPP saw an elevated number of flashover incidents at the station which resulted in loss of generation. Identified causes included insulator contamination, inadequate insulator leakage distance, and equipment not designed to withstand the harsh coastal environment. It is noteworthy that this period was documented as the 3rd driest period on record in San Luis Obispo County going back to 1870. This extremely dry period deprived the station of several inches of rain which would have had a cleaning effect on the insulators as well as other equipment. At that time, Equivalent Salt Deposit Density (ESDD) were reported at very high levels sometimes beyond 1 mg/cm² which is largely above the "very heavy" classification of IEC 61815 [7]. A risk mitigation plan was needed.

Figure 8: DCPP nuclear generation station is located directly on the Pacific coast

A preventive maintenance program was implemented which included an escalated insulator washing schedule. With an 8-man crew, DCPP was washing insulators 4-6 times per year. Due to the frequency of washing and given the particular aspects of a nuclear generation where both outage costs and reconnection complexity to the grid are major issues, there was not the luxury of planned outages. Therefore, the insulators were washed while the line was energized, known as hot wash where deionized water spray was applied at high pressure. Hot washes are considered high risk activities as they expose the energized lines to a potential flashover that can lead to a unit trip and jeopardize crew safety. Insulator washing needed to be planned, coordinated and scheduled carefully with many departments to avoid conflict with other maintenance activities, grid configuration and plant operations. The water spray from insulator washing was also affecting other energized equipment causing further disruption.

Alternative insulator options were considered to improve performance. It was discovered that toughened glass insulators can have a much higher leakage distance than porcelain units due to the geometric strength of toughened glass. The inner ribs of glass insulators can be longer, thinner, and deeper than porcelain which results into higher leakage distance. Another consideration was silicone coating to defend against pollution which could eliminate the need to wash altogether. The added leakage distance with a hydrophobic surface, on a material that does not age, was considered a "belt and suspenders" solution that could drastically reduce the amount of time, cost and resources to keep the 500kV lines safe and operational.

The 500kV lines connecting to the turbines were originally insulated with 58 porcelain insulators in a double bundle dead end configuration (Figure 9). The replacement of porcelain insulators to fully coated toughened glass was evaluated and compared in the table below. Without any change to the existing hardware, the fully coated glass units could be installed "like for like" and provide 68% more leakage distance than the porcelain. No adjustment of conductor sag was necessary.

This final choice resulted in the combination of higher leakage distance and a hydrophobic surface (Table I). The additional leakage distance would have improved the situation, but the extreme contamination encountered would still be considered as a potential threat. Likewise, using silicone coating without changing the leakage distance could have resulted in a possible ageing of the coating. Today experts recognize that even when HTM (hydrophobic surface) can avoid flashovers, leakage distance should not be sacrificed to ensure a better longevity of the material. The decision to act on both parameters appeared to be the way to go.

Table I: summary of insulator string designs and characteristics before and after

Insulator Type	M&E Rating (lbs)	Leakage Distance per Unit (in)	Insulator Spacing per Unit (in)	Number of Insulators per String	Total Leakage Distance (in)	Total Insulator Spacing (in)
Porcelain Fog Type	36,000	12.81	5.75	58	743.13	333.50
Coated Glass Fog Type	36,000	21.50	5.75	58	1,247.00	333.50

Figure 9: String arrangement

In October 2015, DCPP replaced three dead end strings on Turbine Unit 2 with fully RTV coated glass insulators as a pilot project (Figure 10). Immediately, there was a noticeable reduction in audible noise and RF noise from the insulator strings. Thermography photos also indicated a lower operating temperature compared to the adjacent porcelain insulator strings. The dead-end insulator strings on Unit 1 were replaced the following year. Since the successful installments on Unit 1 and 2, there has been no degradation of the insulators, nor has there been pollution related flashovers. The plant no longer hot washes. To quantify, 6 years without washing is a savings of approximately 55 washes and counting. In addition to a large cost savings, it has allowed the maintenance crews to concentrate on other projects which keep the plant safe and reliable. DCPP still performs cold washes since it is mandated as per maintenance procedures every 18 months during the refueling outage. Cold wash is the application of deionized water spray at low pressure when the line is not energized (rain resemblance). It was clearly noticed that the strings remain silent for their entire service time up to each one of these maintenance operations.

From a practical point of view, the insulators being fully coated (Figure 11) required special care to avoid surface damages. Nevertheless, some units were damaged and therefore were repaired using silicone repair kits prior to installation (Figure 11). This point has since been fixed by the manufacturer who offers today to PG&E a proprietary coating chemistry which is more robust to handling and installation.

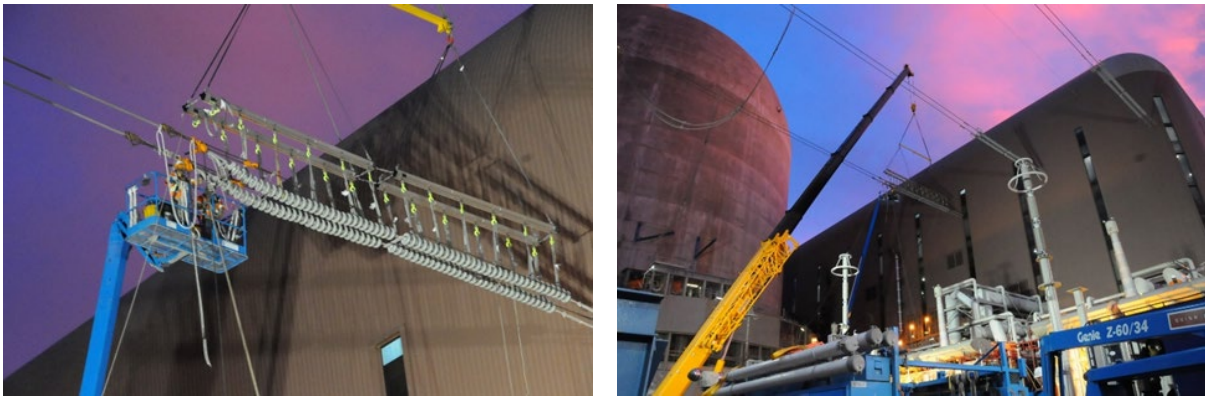

Figure 10: Installation of the coated strings

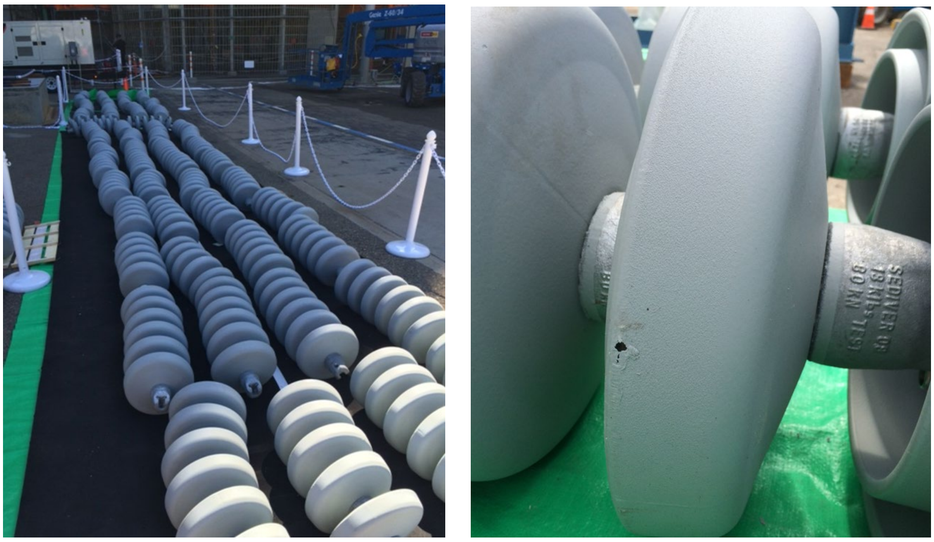

Figure 11: Fully coated glass insulators prepared on the ground for installation. Some small damages were identified and repaired on site prior to installation.

Overall, the experience gathered since 2015 is showing benefits as summarized in Table II below.

Table II: Summary of benefits with the silicone coated glass solution

Before	After	Primary Benefit
Hot washing 4-6 times per year	No hot washing	Less cost
Wash planning & scheduling conflicts	Less maintenance conflicts	Improved efficiency
High operational risk	No risk	Plant/equipment safety
Personal safety risk	No risk	Crew safety
Generation loss	No generation loss	Reliable power delivery
Water consumption	Less water consumption	Sustainability
Audible RF noise from corona discharge	Audible / RF noise reduction	Less impact on RF sensitive instrumentation

6. CONCLUSION

The experience at DCPP has shown that contamination can be controlled by the use of silicone coated glass insulators. This technology provides the resiliency of toughened glass with a hydrophobic surface to fight against major pollution related flashover problems that can cause sustained outages. The elimination of hot washing is a substantial cost savings, reduces the risk of equipment failure and improves personal safety. Water preservation is also an important concern as we see our climate change in the images of draught and forest fires. Water spray can also have a negative impact on energized equipment causing trips or even flashovers. Grid hardening and the greater need for long lasting resiliency has driven insulator technology to be more robust and to reduce maintenance cost.

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