SILICONE COMPOUNDS FOR HIGH-VOLTAGE INSULATORS: HPS TESTING OF SILICONE COMPOUNDS

PART 2 OF 2 (SERIES)

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INTRODUCTION TO DESIGN TESTING

This paper is part two of a two-part series. Part one provided an overview of the manufacturing of silicone and the ingredients used to make the silicone rubber compound. This paper will discuss the testing used by Hubbell Power Systems (HPS) to verify that a silicone rubber compound is suitable for use in the high-voltage insulator market.

Polymer insulating materials are typically formulated to provide critical performance characteristics equivalent to, or better than, that of porcelain. Due to the different physical properties of porcelain and polymers, a comparison is usually made on short term electrical characteristics of complete insulators (e.g., wet and dry 60 Hz flashover or critical impulse flashover). However, many physical properties of a polymer material must be understood and properly controlled to give the material the characteristics necessary to serve as a high-voltage insulating polymer.

During the 1960s, the Ohio Brass division of HPS performed pioneering work to evaluate polymer material for use in high-voltage insulators. Original design tests measured the material properties that make a good insulator — dielectric strength, environmental stability, tracking and erosion resistance, ultra-violet resistance, and thermal stability. During the 1980s, HPS introduced more tests to better predict the field performance of polymer insulators. Factors tested included corona cutting resistance, hydrophobicity and flammability. In the 1990s, HPS built upon the accumulated results of years of testing to develop a silicone rubber compound suitable for high-voltage insulators.

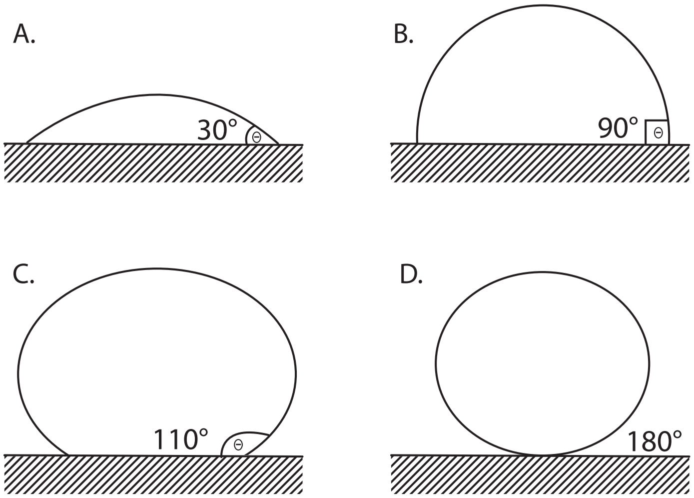
HYDROPHOBICITY

Hydrophobicity is the property that prevents water from forming a sheet on the surface of a polymer. When water cannot form a solid conducting layer, leakage currents are reduced. Hydrophobicity also aids in cleaning polymer surfaces. When water readily beads and runs off a hydrophobic surface, it can remove loose contamination from the insulator surface. Removing contamination can result in lower leakage currents. **Silicone rubber insulators are preferred in highly contaminated areas due to their lower leakage currents and self-cleaning characteristic. With the self-cleaning feature of silicone rubber, the interval between cleanings may be extended.**

Hydrophobicity can be measured using Swedish Transmission Research Institute (STRI) Guide 1, 92/1 that rates hydrophobicity by comparison to standard images or by using a contact angle measurement. The STRI method has seven levels of hydrophobicity from 1 to 7, most to least hydrophobic. A more sensitive method is the contact angle measurement, because it allows one to measure accurately in small increments. For laboratory testing, the contact angle measurement is better. For field use, or when the sample is large or contoured, the STRI method is better.

The contact angle is measured between a water drop and the sample surface. The angle on the inside of the drop is measured (Figure 1). An idealized surface with perfect hydrophobicity will have an angle of 180 degrees. A sample that is completely hydrophilic will have a contact angle of 0 degrees. To be considered hydrophobic, the contact angle must be at least 90 degrees; to be considered superhydrophobic, the contact angle must be more than 150 degrees.

HPS' silicone compound is typical of all silicone compounds, with a contact angle measurement of approximately 110 degrees. All silicone compounds tested for this paper had similar results.



[Figure 1] Contact Angle Measurements - (A) hydrophilic surface, (B) minimum hydrophobic surface, (C) typical hydrophobicity for silicone rubber, (D) ideal superhydrophobic surface.

TRACKING AND EROSION RESISTANCE

A result of HPS' pioneering work was the development of the erosion test (now called tracking and erosion resistance test) to test glazes on porcelain insulators. As HPS started researching polymer compounds for high-voltage insulators, having a well established erosion test proved invaluable in the development of a suitable formulation, and particularly in the development of our silicone rubber compound.

Moisture and contamination on all insulators can result in leakage currents. The reduced diameter of polymer insulators at the shank, as compared to porcelain, causes higher leakage current densities, as well as a greater level of Ohmic heating. Since the film dries first on the shank, arcing occurs first there. Electrical arcing across a dry gap, called "dry band arcing," generates ozone, high temperatures and UV radiation exposure on the polymer surface. The tracking and erosion resistance of a compound is a measure of its ability to withstand intense leakage currents combined with dry band arcing. This test specifically mimics these service conditions.

Silicone rubber compounds go through four stages of degradation in response to electrical activity — loss of hydrophobicity, dry band arcing, formation of silica layer, and erosion. Silicone rubber may fail as an insulator due to the formation of a thick silica layer which could lead to trapped moisture and high leakage currents. A silicone rubber insulator may also fail due to material erosion exposing the fiberglass rod.

The tracking and erosion test specifically measures the response of the silicone rubber through all four stages of degradation, focusing on the final stage. Materials without an inherent resistance to tracking and erosion do not perform well in this test because the formation of the silica layer occurs very early in the test.

The tracking and erosion test is an accelerated test because the hydrophobicity is removed in the first few cycles, and the test sample is not given an opportunity to recover the hydrophobicity. Recovery takes days to weeks, depending first on the absence of electrical activity, and then on the silicone compound, environmental conditions, thickness of the silica layer, and the presence of cracks in the silica layer. The lack of recovery time is the reason silicone rubber compounds were not originally expected to perform as well as porcelain glaze on the tracking and erosion test.

Tracking and erosion test samples are mounted on a 15-degree incline with electrodes attached on either side. The electrodes are positioned 35 mm apart. With an applied voltage of 10 kV, the samples are cyclically sprayed with a conductive solution while being continuously energized. Each cycle lasts 90 seconds. The conductive liquid has a nominal resistivity of 400 Ωcm and is formulated to leave no residue on the sample surface. The leakage current and subsequent dry band arcing degrade the surface of the sample. Test results obtained from the tracking and erosion test provide a means of comparatively ranking the tracking resistance of materials (as seen in Table 1).

Failure is judged by one of the following three criteria:

- Carbonization or tracking on sample surface
- Sample remains conductive at the end of the 90-second cycle
- Erosion penetrates the sample

ULTRAVIOLET

Polymer insulating compounds are exposed to ultraviolet (UV) radiation not only from sunlight, but also from corona and dry band arcing. Resistance to degradation resulting from ultraviolet exposure is an important factor in determining the service life of a polymer.

MATERIAL	CYCLES
Porcelain	50,000
HPS Silicone	72,000
Silicone Rubber$_1$	16,000
Silicone Rubber$_2$	60,000
Liquid Silicone$_1$	12,000
Liquid Silicone$_2$	120

[Table 1] Tracking and Erosion Test Results — Current minimum requirements are 20,000 for silicone rubber. Silicone Rubber 1, Silicone Rubber 2, Liquid Silicone 1 and Liquid Silicone 2 are commercially available insulating compounds. Cycles listed are the average results of samples tested to failure.

The energy from sunlight that is most destructive to polymers has a wavelength between 320 and 290 nanometers, classified as UVB. Shorter UVB wavelengths have a larger effect on polymer degradation than longer UVA (400-320 nanometers) wavelengths. Wavelengths shorter than 270 nanometers, classified as UVC (290-100 nanometers) and generated by the sun, do not reach the planet's surface, but can be generated by electrical activity. UVB constitutes less than five percent of the total radiation reaching the surface of the planet. The absorption of this UV radiation results in mechanical and chemical degradation of the polymer structure that can affect the dielectric, physical and weathering properties. The rate at which the degradation occurs is dependent upon the intensity and wavelength of the radiation. These factors vary with season, time of day, elevation and latitude. Acceleration of the effects occurs in the presence of moisture on the polymer surface. Polymer compounds for use in outdoor environments should, therefore, be evaluated in the combined presence of UV radiation and high humidity.

The QUV test is an accelerated weathering test performed in conformance to ASTM G53. The QUV test alternates UV radiation exposure and condensation during each cycle. A cycle consists of 8 hours of condensation and 16 hours of UV exposure. The QUV test simulates the effects of sunlight by means of fluorescent UV lamps positioned within inches of the test specimen. A water reservoir at the bottom of the test chamber is heated to produce vapor. The hot vapor keeps the chamber at 100-percent relative humidity. During the condensation phase, water vapor condenses on the cooler surfaces of the test specimens. The combination of condensation with high-intensity UV radiation results in an accelerated exposure test.

Through comparisons with tests performed at the Desert Sunshine Exposure Test (DSET) site in Arizona, the aging acceleration of the QUV test has been assessed as 8:1; that is, one hour of QUV test is equivalent to eight hours of exposure in the Arizona desert, which is considered one of the most severe natural UV environments in

North America. Negative effects of UV radiation for a polymer may include the following:

- Crazing, checking or cracking of the surface
- Loss of hydrophobicity
- Discoloration

Under accelerated testing methods, such as ASTM G53 (QUV), a good polymer compound should be capable of sustaining 10,000 hours of exposure without crazing, cracking or displaying any loss of hydrophobicity. The test results obtained from the QUV test provide a means of comparatively ranking the UV resistance of materials. Such results are listed in Table 2. The times listed are for ongoing testing.

MATERIAL	TIME, HRS	COMMENTS
HPS Silicone Rubber	86,000	Still Hydrophobic
Silicone Rubber$_1$	39,000	Still Hydrophobic
Silicone Rubber$_2$	12,000	Still Hydrophobic
Liquid Rubber$_1$	13,000	Still Hydrophobic
Liquid Rubber$_2$	13,000	Still Hydrophobic

[Table 2] QUV Test Results — Minimum requirement is 8,000 hours. Silicone Rubber 1, Silicone Rubber 2, Liquid Silicone 1 and Liquid Silicone 2 are commercially available insulating compounds.

CORONA

Corona discharges form at the surface of an insulator when the electric field gradients on the surface exceed the breakdown strength of air. Corona generation is dependent upon atmospheric conditions such as air density, humidity, and geometry of the insulator. The effects of corona are radio interference, TV interference, noise generation, ozone production, and energy loss.

Corona accelerates the aging of polymers by generating ozone and ultraviolet light. The UV light produced includes the spectra of light damaging to polymers. In addition, the electric discharge subjects the insulator to severe electrical strain and chemical degradation. A polymer must be able to withstand this chemical degradation throughout its service lifetime. Electrical insulation that may be subject to corona must be made from a properly compounded silicone rubber.

The presence of corona combines UV and heat with a high level of ozone. Hubbell Power Systems' corona-cutting chamber combines this with mechanical stress to accelerate the degradation of a polymer. Polymer insulator samples are subjected to a mechanical stress of approximately 300,000 microstrain by bending the sample over a grounded electrode. Figure 2 shows a sample of silicone rubber.

[Figure 2] Silicone rubber corona cutting sample mounted, prior to placement of electrode.

Corona is continuously generated by applying 12 kV to a Wolfram needle electrode placed 1 mm above the strained surface of the sample. Under a combination of mechanical strain and continuous surface corona, an unaged polymer should be capable of surviving at least 1,000 hours without cracking, splitting, cutting or flashing over. The test can be conducted under dry air or with controlled humidity. Based on field experience, the test is run for at least 1,000 hours, or until the sample fails. Test results are listed in Table 3.

MATERIAL	CYCLES	COMMENTS
HPS Silicone Rubber	2,720	Ongoing Test
Silicone Rubber$_1$	350	Failure
Silicone Rubber$_2$	1,650	Pass
Liquid Rubber$_1$	200	Failure
Liquid Rubber$_2$	1,100	Pass

[Table 3] Corona Cutting Results — 1000-hour minimum requirement. Silicone Rubber 1, Silicone Rubber 2, Liquid Silicone 1, and Liquid Silicone 2 are commercially available insulating compounds.

OXIDATIVE STABILITY

Antioxidants are incorporated into a polymer compound to inhibit the attack of oxygen and ozone on the compound's chemical composition. The effectiveness of an antioxidant is very important in electrical insulation applications.

An oxidative stability test measures the time required to deplete the antioxidants within a material under controlled conditions. Oxidative stability is measured by using the thermal analysis technique of differential scanning calorimetry (DSC). The DSC measures the amount of heat flowing into (endothermic) or out of (exothermic) the sample as a function of sample temperature.

Oxidation is a highly exothermic process and is readily studied by DSC techniques. A test sample is rapidly heated in a nitrogen atmosphere to the test temperature of 200 degrees Celsius. The atmosphere is then changed to oxygen and the temperature is maintained until the sample begins to oxidize. When the sample oxidizes or decomposes, an exothermic reaction is registered. This indicates all of the antioxidant has been consumed and the rubber sample is no longer protected. Good compounds typically exhibit oxidation in times greater than 400 minutes in oxygen at 200 degrees Celsius. Typical results are listed in Table 4.

MATERIAL	CYCLES	COMMENTS
HPS Silicone Rubber	400+	No Failure, End of Test
Silicone Rubber$_1$	400+	No Failure, End of Test
Silicone Rubber$_2$	400+	No Failure, End of Test
Liquid Rubber$_1$	400+	No Failure, End of Test
Liquid Rubber$_2$	400+	No Failure, End of Test

[Table 4] Oxidative Stability Test Results — 400-minute minimum requirement. Silicone Rubber 1, Silicone Rubber 2, Liquid Silicone 1 and Liquid Silicone 2 are commercially available insulating compounds.

SUMMARY

This paper has presented details on the different material test methods that HPS performs when evaluating polymer formulations for its high-voltage non-ceramic insulators. Some of the tests are industry recognized and published by worldwide leading organizations such as ASTM, ANSI, and IEC. Others tests are HPS' independent tests developed and introduced as a result of pioneering work in the research of polymer formulations for high-voltage applications.

The test results presented in this paper confirm that not all commercially available silicone compounds supplied to the high-voltage insulator market are equal. Furthermore, the results of continuous tests prove that the selection of the base material and the addition of additives and fillers involve just a few of the many factors that must be considered while designing a polymer compound suitable for high-voltage insulation. In fact, polymer compounds depend as much on the formulation as they do on the base material, the compounding method, the curing time or pressure.

Hubbell Power Systems' success with developing polymer compounds for the high-voltage market began with Ohio Brass' work in the early 1960s. The Company built upon forty years of compounding experience to develop and test its own silicone rubber compound, which was introduced in the 1990s and has been used successfully in the field since 1996. In an effort to provide customers with the best products on the market, HPS controls all aspects of the silicone rubber compound — formulation, compounding, molding, material testing and development.

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