Highly Conductive Insulation for Large, High-Speed Machines

Daniel Saban PhD
Direct Drive Systems
DSaban@DirectDriveSystems.net
www.directdrivesystems.net

Andy Cloud
Arlon Silicone Technologies
acloud@arlon-std.com
www.arlon-std.com

Paulo Guedes-Pinto
Direct Drive Systems
pGuedes-Pinto@directdrivesystems.net
www.directdrivesystems.net

Abstract: Silicone-impregnated fiberglass insulation has long been used as stator-coil electrical-insulation for low-voltage, direct current, traction motors. Silicone-based insulation is particularly suited for this application because its thermo-oxidative stability ensures excellent long-term resistance to arc tracking and dielectric breakdown. Next generation, high-speed, multi-megawatt, rotating machines provide an insulating challenge for traditional silicone-impregnated fiberglass and epoxy-mica stator-coil-insulation systems. A high-frequency voltage supply for these rotating machines is required to produce the high rotational speed and to deliver greater power output. A disadvantage of increased frequency is greater loss density, from both higher losses and smaller heat rejection surfaces, which ultimately leads to higher operational temperatures that can cause machinery life degradation. This paper investigates functional electrical insulation integrity of highly thermally-conductive silicone-impregnated-fiberglass insulation through short-term, highly accelerated aging tests. This insulation system offers up to three times the thermal conductivity of traditional insulation, which facilitates rapid heat transfer and provides a design element for reducing rotating-machine operational temperature.

Key Terms: insulation, rotating machine, highly thermally conductive

Content

Introduction

New high-speed, multi-megawatt, rotating machines with high-frequency drives can be designed to deliver the same power rating as a conventional machine design with a smaller footprint. The design drawback to rotating machine operation at such high frequency in a smaller assembly is higher loss density, which leads to the requirement for improved thermal management. Higher stator operating temperature and greater thermal loading can lead to rotor deformation, imbalance, or failure; loss of stator-coil-insulation integrity; and ultimately the potential for machine damage. Choices for stator coil construction, insulation, and a systemic cooling design are therefore critical to

Presented at the 2009 CWIEME, May 5-7, 2009, Messe Berlin, Germany. www.coilwindingexpo.com

successful operation. Conventional H-class insulation thermal conductivity is at least a factor lower than required to facilitate effective heater transfer from high speed machine stator coils to an actively cooled housing jacket. Additionally, conventional H-class insulation does not have the thermal stability to maintain electrical insulation integrity when operating at temperature in excess of 180°C. Highly thermally-conductive silicone-impregnated-fiberglass insulation may be incorporated as an effective and integral component of an actively cooled system and offer the required electrical insulation longevity for stator coils operating in access of 180°C. In this paper, review of cooling design options for multi-megawatt, high-speed machines is used to identify the issues with standard electrical insulation and the potential benefits of highly thermally conductive stator-coil-insulation. Highly thermally conductive electrical insulation property review is utilized to verify that the proposed insulation system is fit for use. Finally, short-term, highly accelerated thermal aging analysis focused on insulation electrical integrity is used to verify whether longer term accelerated aging analysis utilizing actual stator bar assemblies is a valid next step in the development process.

Cooling System Design

Large, high speed, rotating electrical machines are used in a number of turbo generator applications and can also compete with in applications where gas turbines are generally specified. Cooling system designs target the stator coil assembly, which are either directly or indirectly cooled. In each case a gas is used to cool the stator conductors and convectively transmit unwanted thermal energy to an active glycol/water system, which ultimately cools the rotating electric machine. In either case, as power density for machines increases the importance of stator cooling design also increases. Direct stator cooling designs consist of a cooling gas that is circulated directly through hollow stator conductors. These cooling designs have the added benefit of removing machine heat without the interference and thermal damming created by low thermal conductivity stator-coil electrical-insulation. However, these cooling systems are more complex and can be more expensive because of the need for auxiliary cooling components, which hampers operational reliability [1]. A simpler cooling system design is an indirect method where the cooling gas is circulated through stator winding vents and over end windings to convectively remove waste heat from the stator conductors. The waste heat is rejected to the environment via the exhaust air in an open system, or recirculated after possibly cooling by a liquid (typically water/glycol) heat exchanger in a closed system. Some cooling system designs may also take advantage of the heat transfer available by a glycol/water cooling jacket that is directly fit on the stator core outer diameter [2]. Although the indirect cooling system is more basic and subsequently more reliable, the electrical insulation system becomes a thermal dam between the hot stator conductor and the cooling gas. There are several solutions to this design problem including a reduction in the thickness of the electrical insulation (which would require a higher dielectric strength to achieve the same voltage rating); an increase in the thermal conductivity of the electrical insulation; and utilization of an electrical insulation with a higher operating temperature [3]. A combination of an increase in the thermal conductivity as well as an increase in the operational temperature-rating of the electrical insulation is a potential solution to current difficulties with a more basic indirectly cooled stator-coil assembly.

Advances in cost-effective silicone-elastomer technology for highly thermally-conductive fiberglass-impregnation compounds can meet both the need for electrical insulation with greater thermal conductivity as well an electrical insulation operational integrity above 180°C. The goal of utilizing this type of stator-conductor insulating system is reduced coil temperature and increased power density. Tari, Yoshida, and Sekito indicate that by simply increasing the thermal conductivity of electrical insulation in an indirectly cooled rotating machine by a factor can help achieve reductions in stator-coil temperature by $\geq$10°C and machine power-density by $\geq$10% even without increasing machine operating-temperature [4]. Current silicone technology offers the potential for even greater increases for indirectly cooled rotating machines by offering improvements in thermal conductivity several factors above current insulation systems and an operational temperature of 200°C.

This paper investigates the electrical integrity of highly thermally conductive silicone-impregnated-fiberglass insulation through highly accelerated thermo-oxidative aging. The study verifies the need for a subsequent step, longer-term accelerated-aging tests required to determine whether such insulation systems are truly applicable for large, multi-megawatt, rotating machines.

Highly Thermally Conductive Insulation

Highly thermally conductive silicone compounds used in the manufacture of electrical insulation are designed and manufactured with cost, processing, application ease of use, insulation effectiveness and integrity parameters in mind. Utilization of commercially available high-molecular-weight siloxanes or processes to artificially enhance extending filler carrying capacity is required to maximize thermal conductivity but balance base raw material costs. Optimization of the thermally conductive extending filler-packing-effect in the siloxane matrix and incorporating highly thermally conductive yet cost-effective reinforcing filler is necessary to balance improvements in compound thermal conductivity versus processing and material properties. Processing and material concerns include compound rheology, crosslinked elastomer flexibility and strength, electrical insulating integrity, and thermal stability. Packing-effect-optimization yields desired compound thermal conductivity but also yields material plasticity and elasticity parameters conducive to fabric coating operations. Typical target values for plasticity and elasticity are less than 3.00 mm and 0.5 mm respectively. These parameters also ensure that automatic or manual stator-coil winding and lamination operations are straightforward and feasible. Acceptable crosslinked-elastomer flexibility and strength is verified through the use of an r/t ratio, $r/t = (1-\epsilon)/2\epsilon$, where r is the bend radius, t is the thickness, and ϵ is the elongation of a highly thermally conductive silicone impregnated fiberglass insulation. An ideal elastomer r/t ratio to ensure adequate elastomer compliance and strength in a simple composite insulation system is $r/t \leq 0$. The r/t ratio can additionally be used to help evaluate and or compare elastomeric integrity of thermally aged insulation systems. [5]

Highly thermally conductive elastomers impregnated into fiberglass fabrics are designed to yield electrical insulation parameters including good volume resistivity (VR), excellent dielectric breakdown strength (DBS), and high voltage, dry arc resistance (HVAR). Table I below compares these properties in a highly thermally conductive silicone/fiberglass insulation, 51A50X020, versus a standard silicone/fiberglass electrical insulation, 51580R020.

Parameter	51A50X020	51580R020	Test Method
VR (ohm-cm)	E+14	E+14	ASTM D257
DBS (VPM)	677	1026	ASTM D149
HVAR (seconds)	193.5	126.3	ASTM D495
Apparent Thermal Conductivity (W/mK)	1.68	0.87	ASTM D5470
Compound Thermal Conductivity (W/mK) @ 100C	1.4	0.4	ASTM E1530

Table I – Insulation Properties

Additionally, ASTM D5470 is good method for determining apparent thermal conductivity of a composite insulation system. The test method measures the time rate of heat flow normal to a unit area, per unit temperature gradient, under steady state conditions. The average insulation test specimen temperature is 50°C. The term apparent thermal conductivity is used because the insulation system is considered a heterogeneous composite [6]. This test method is a reliable industry standard when evaluating and comparing the apparent thermal conductivity of materials. In comparison, the apparent thermal conductivity of a conventional silicone impregnated fiberglass insulation, is generally less than 0.5 W/mK. This value is also similar to literature values for epoxy and polyester impregnated mica coil insulation.

Experiment

The highly thermally conductive insulation under evaluation, 51A50X020, is an 0.008" thick, style 7628 fiberglass impregnated and coated with a highly thermally conductive siloxane for an overall insulation thickness of 0.020". A baseline testing insulation, 51580R020, was chosen because it is a UL recognized electrical insulation with a relative thermal index (RTI) of 200°C. Although this insulation system is generally not used in rotating machinery, the siloxane type is very similar to siloxanes used as coil insulation (particularly in traction machines) except that it has both the UL RTI rating and has been field tested as an electrical insulation for over 20 years. Relative thermal index (RTI) is defined in the UL746B standard, Polymeric Materials – Long Term Property Evaluations, as the temperature below which both dielectric-breakdown strength and tensile strength of an insulation system will not be unacceptably compromised through thermal degradation over the life of the material. The analysis is relative to a reference material, which has a confirmed and acceptable corresponding performance [7]. In the case of the reference insulation, the service life was determined to be 100,000 hours at 200°C.

Both materials were prepared utilizing calendering equipment and cured in a platen press at 121°C for 5 minutes and then post cured for 1 hour at 200°C. The test specimens were then conditioned under the highly accelerated thermal aging schedule seen below in Table II.

Temperature C	Electrical Test Time Interval - hrs	Total Test Time - hrs
225	24	216
250	24	216
275	24	144
300	12	72

Table II – Testing Schedule

The testing temperature range was chosen because it covers a temperature range at which the rate of polymer degradation is governed by excessive crosslinking and the formation of pure silica through oxygen to silicon bonding in the oxidation process. The siloxane is basically rapidly aging but pendant groups are not being too aggressively stripped off of the polymer backbone as would occur at temperatures above 300°C [8].

In order to cover a large voltage test-range, several electrical test-responses were used at each test interval. ASTM D257 was chosen to cover the low-voltage range, at 1000 volts. ASTM D257 determines DC Resistance of Insulating Materials as, "the volume resistance multiplied by the ratio of specimen volume dimensions (cross-sectional area of the specimen between the electrodes divided by the distance between the electrodes) [9]." Responses evaluated at the high end of the testing voltage range were covered by ASTM D149 and ASTM D495. ASTM D149 determines the dielectric breakdown voltage of solid electrical insulating materials at commercial power frequencies. Although high-speed, multi-megawatt machines operate at higher frequencies, the commercial frequency test is a good comparative tool. ASTM D149 defines dielectric breakdown voltage as, "The potential difference at which dielectric failure occurs under prescribed conditions in an electrical insulating material located between electrodes [10]." Finally, ASTM D495 is utilized to evaluate the high-voltage, low-current, dry-arc resistance of solid electrical-insulation. ASTM D495, operating at 12,500 volts, determines the, "resistance to the action of a high-voltage, low current arc close to the surface of insulation, intending to form a conductive path therin or in causing the material to become conducting due to localized thermal and chemical decomposition and erosion [11]."

The goal of the highly accelerated thermal-aging test with the three electrical responses was to capture a specific thermo-oxidative rate of insulation decay and determine any changes in electrical behavior. Comparative end-of-service life-equations as a function of all three electrical testing responses for both insulation materials in the highly accelerated testing can be developed to provide insight into the potential for the highly thermally conductive stator coil insulation to be used in large rotating machines. UL746B explains, "The thermal-aging characteristics of a material can be determined by measuring the changes in its properties to a predetermined level by aging at each of several elevated temperatures; plotting log of time to end-of-life at each temperature against the reciprocal of absolute temperature, and plotting the best-fit straight line by regression analysis [12]." Additionally this data can be used to verify whether longer term accelerated aging study is warranted for the highly thermally conductive insulation.

Volume Resistivity Results & Discussion

The highly thermally conductive insulation, 51A50X020, and the baseline insulation, 51580R020, both became increasingly resistive to the 1000 volt test voltage as they aged at all four accelerated aging temperatures as seen in Figures I and II below. The data for both materials does not lend itself to developing a comparative end-of-service life equation. However, it should be noted that the volume resistivity of both materials does increase substantially by at least an order of magnitude during any single aging time and temperature period. This is likely a result of some oxidation or the formation of silica in the polymer matrix. The 300°C aging temperature for both materials caused the greatest rate increase due to the fact that a small quantity of siloxane pendant groups are being stripped from the polymer and accelerating the thermo-oxidative process. In this case the volume resistivity electrical property of 51A50X020 improves during highly accelerated aging. Although the insulation material remains elastic, the thermo-oxidative process does reduce elastomer compliance and flexibility.

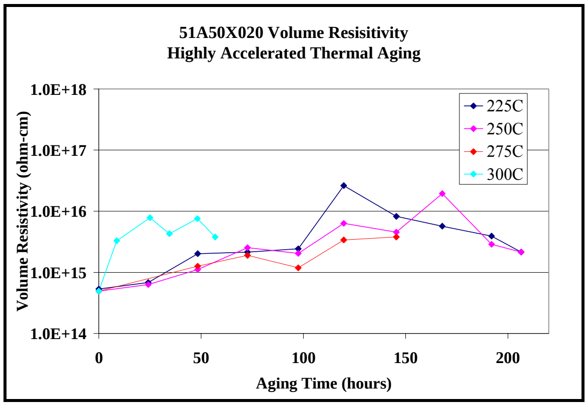

Figure I – 51A50X020 Volume Resistivity

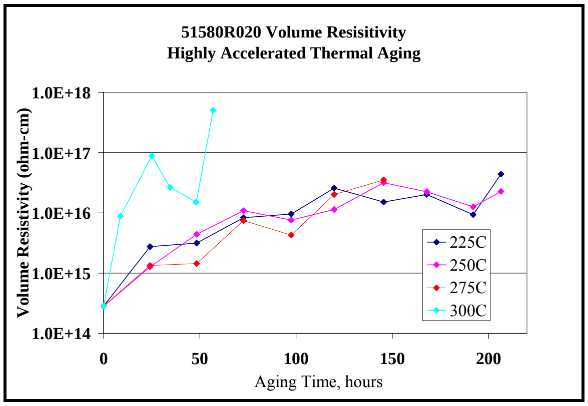

Figure II – 51580R020 Volume Resistivity

Dielectric Breakdown Strength Results & Discussion

The dielectric breakdown strength for both 51A50X020 and 51580R020 is considered very stable for both insulation materials as seen in Figures III and IV. However, the baseline insulation, 51580R020 does show a significant loss in dielectric breakdown strength when aged at 300°C and this is likely a result of loss of elasticity and micro-crack damage to the oxidized test-specimens. As discussed previously the rate of siloxane damage can accelerate at temperature above 300°C and with aging oven temperature variability of ± 10°C this may have exacerbated polymer damage.

Although it is only to be used for comparative purposes, Figure V below indicates that the 51A50X020 insulation should have similar longer term aging characteristics to the UL recognized 51580R020 insulation when dielectric-breakdown-strength is the response. Figure V was developed by using linear regression for dielectric-breakdown-strength response for each highly accelerated thermal aging temperature per insulation material. End-of-life was determined by solving for an extrapolated end of insulation life value, or 50% of the initial dielectric breakdown strength. The natural log of the end-of-life value for each temperature is then plotted versus the inverse accelerated thermal aging temperature in K^{-1}. Finally, a best-fit straight line is completed by regression analysis. It is difficult to say that the 51A50X020 insulation has better thermal stability. However, it does age in a similar manner as the field tested 51580R020 material, providing a degree of confidence that the highly thermally conductive insulation should do well in longer term accelerated aging tests when dielectric-breakdown-strength is the electrical response.

It should be noted that even though the unaged dielectric breakdown strength of the 51A50X020 is 66% of the 51580R020 insulation, this difference was likely caused by specimen preparation. The high density silicone used in the 51A50X020 did not penetrate the fiberglass fabric as well as the silicone for the 51580R020 insulation on laboratory equipment, resulting in lower initial dielectric-breakdown-strength. For production material, process parameters can be modified to ensure better silicone impregnation of the fiberglass fabric.

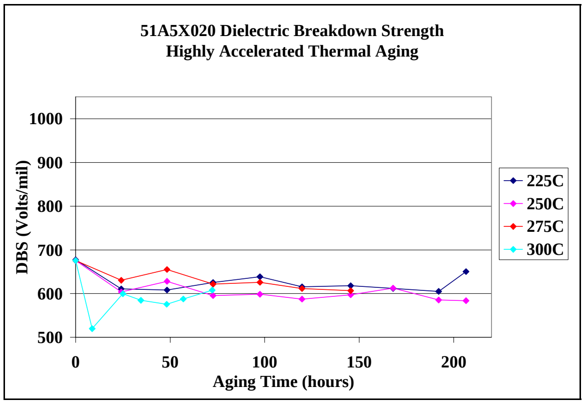

Figure III- 51A50X020 DBS

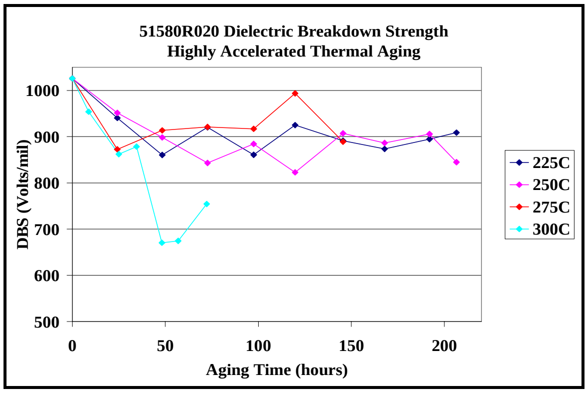

Figure IV- 51580R020 DBS

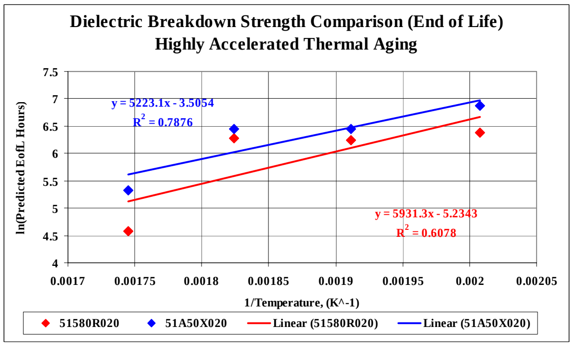

Figure V - DBS End-of-Life Comparison

Arc Resistance Results & Discussion

The time-to-arc-tracking at 12,500 volts for the 51A50X020 insulation is approximately 50% greater than the baseline insulation, 51580R020. Silicone-based insulation systems generally have very high time-to-arc-tracking because the path of decomposition of the arc mostly contains silica ash and is therefore fairly nonconductive. Insulation systems with carbon-based impregnation resins generally decompose to form a conductive path much more rapidly. The very high time-to-arc-tracking values for the 51A50X020 insulation can be explained simply by its high thermal conductivity. Heat generated by the high-voltage arc is rapidly dissipated throughout the insulation volume and therefore cannot support decomposition. The arcing rate on the 51A50X020 must be nearly continuous compared to the arcing rate on 51580R020 to generate enough heat to begin polymer decomposition and the development of an electrically conductive path-to-track.

Figures VI and VII below show the time-to-arc-tracking for both insulation materials. The baseline insulation, 51580R020, has very consistent arc resistance regardless of the highly accelerated thermal-aging temperature or test time. The time-to–arc-track for the

51A5X020 appears to deviate much more than the 51580R020, but after 180 seconds the arc-firing-rate is dramatically increased and other degradation modes beyond insulation surface damage contributes to result variability.

Unfortunately the highly accelerated aging data for time-to-arc-track does not lend itself to developing comparative end-of-service-life equations for both insulations. The 51A50X020 material does exceptionally well in high-voltage arc-track testing because of its ability to dissipate heat build-up from an electrical arc. The arc-track-resistance is relatively consistent at elevated aging temperatures, which is exemplified by the excellent arc resistance when evaluated at any time during 300°C thermal aging.

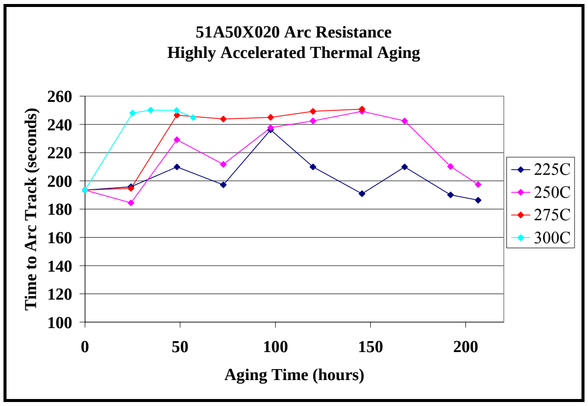

Figure VI – 51A50X020 Arc Resistance

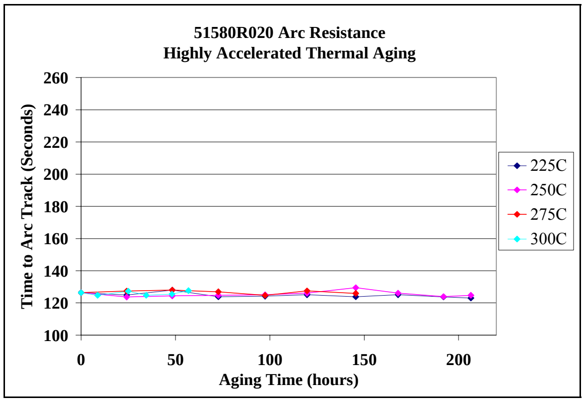

Figure VII – 51580R020 Arc Resistance

Summary

The insulation systems available for high-speed, rotating, electric machines are typically based on mica impregnated with epoxy or polyester resins, which usually have relatively low thermal conductivity (≤0.5 W/mK). Additionally these systems generally have a maximum continuous operating temperature limited to 180°C or 155°C (class H or class F respectively). The combination of low thermal conductivity and limited operating temperature constrains the current that can be drawn through the machine conductors, therefore limiting the maximum torque the machine can deliver. A large, high-speed, rotating machine with an insulation system that has higher thermal conductivity and higher operating temperature would be able to operate with higher current densities and thus deliver more torque. Additionally, the machine would be able to withstand overloading for longer periods of time compared to an equivalent size machine utilizing conventional insulation. Alternatively, for the same torque and power output, a machine with such an insulation system would be smaller than a machine with conventional insulation.

Thermally conductive, silicone-based, electrical insulation faired well when compared to a field tested and UL recognized insulation system, through highly accelerated thermal-aging analysis. A range of voltages was utilized to thoroughly evaluate the electrical resistivity of both the volume and surface of the thermally conductive insulation. Measured responses of Volume Resistivity, Dielectric Breakdown Strength, and Arc Resistance under short term exposure to elevated temperatures proved that the new insulation system is stable and able to absorb aggressive thermal spikes often seen in conductors in overloaded electric machines.

Thermally conductive insulation may provide a solution to enhancing existing indirectly cooled stator coil assembly designs because it both reduces the thermal dam created by conventional insulation and replaces conventional insulation with insulation that has a higher operational temperature. For these same reasons, it gives the design engineer the option to increase power density for future high-speed rotating machinery concepts.

A path forward for continued field-readiness analysis of the thermally conductive coil-insulation can be achieved through thermal aging over a longer time frame at the laboratory level. This next study will evaluate insulation integrity but at medium voltage and higher operational frequencies. Finally, a mechanical-work component, possibly in the form of vibration, should be introduced as another factor in the thermal-aging evaluation for insulation electrical integrity. This process can revisit the r/t ratio and determine what effect loss-of-insulation-compliance and flexibility has on electrical integrity.

Acknowledgement: The authors want to thank David Timpe, Sr. Research & Development Chemist, and Geno Amalfitano, Research & Development Chemist, for their assistance with this paper.

References

[1,3,4] Tari M., Yoshida. K., Sekito S. (2001). A High Voltage Insulating System with Increased Thermal Conductivity for Turbo Generators. Berlin, Germany: Coil Winding, Insulation and Electrical Manufacturing Conference.

[2] Baily C., Saban. D., Guedes-Pinto P., (2007). Design of High-Speed, Direct- Connected, Permanent- Magnet Motors and Generators for the Petrochemical Industry. Petroleum and Chemical Industry Technical Conference, IEEE.

[5] Cloud, Timpe, Zhang, US Utility Patent Application Arln002usp, Silicone Based Compositions for Thermal Interface Materials, 2006.

[6] Standard Test Method for Thermal Transmission Properties of Thin Thermally Conductive Solid Electrical Insulation Materials, ASTM D5470, American Society for Testing and Materials International, West Conshohocken, PA, 2001.

[7,12] Underwriters Laboratories Standard for Safety for Polymeric Materials – Long Term Property Evaluations, UL746B, Northbrook, Il, ISBN 0-7629-0065-2, 1996.

[8] Dvornic, P.R. (2004). Silicon Compounds: Silanes & Silicones – A Survey of Properties an Chemistry. High Temperature Stability of Polysiloxanes. (pp. 424). Morrisville, PA: Gelest, Inc.

[9] Standard Test Method for DC Resistance or Conductance of Insulating Materials, ASTM D257, American Society for Testing and Materials International, West Conshohocken, PA, 1999.

[10] Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies, ASTM D149, American Society for Testing and Materials International, West Conshohocken, PA, 1997.

[11] Standard Test Method for High Voltage, Low Current, Dry Arc Resistance of Solid Electrical Insulation, ASTM D495, American Society for Testing and Materials International, West Conshohocken, PA, 1999.