EVALUATION OF HIGH-TEMPERATURE FLUORINATED ETHERS (PFPE) FOR POWER CONNECTORS OPERATING AT EXTREME SERVICE CONDITIONS

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*Abstract – A number of high temperature (PFPE) lubricants were evaluated based on their effect on the performance of bolted power connections under current-cycling conditions, resistance to UV exposure, and thermal stability under long-term exposure to high temperature. Thermo-gravimetric analysis of these lubricants was also performed. The results of current cycling tests showed that only two lubricants (N3 and C1) had beneficial effect on the performance of bolted joints and wedge-type connectors as manifested by the stable operation. Long-term exposure to high temperature showed that some lubricants were susceptible to cracking***.**

INTRODUCTION

The electric power industry is undergoing fundamental change in moving from a regulated monopoly to a competitive industry. As a result, electric utilities are now forced to shift from system growth to prolonging the operating life of existing facilities. Furthermore, steadily increasing energy consumption in densely populated areas imposes severe operating conditions on transmission and distribution systems, which have to carry greater loads than in the past and operate at higher temperatures. Greater loads raises the average operating temperature of conductor lines beyond 130°C, that, in turn, may significantly impair the stability and performance of power connectors.

Cable manufacturers have responded by developing a new type of high temperature conductor, ACSS – aluminum conductor self-supporting. Many power companies are considering this new offer from the cable manufacturers to accomplish necessary plant upgrades in the most cost-effective way [1,2]. However, since power connections are generally the weak links in the power delivery system, this raises serious questions about their stability and performance at such extreme operating conditions.

Practice has shown that lubrication of power connections has beneficial effect on their performance. Braunovic [3-5] has evaluated several contact aid compound commonly used for aluminum, copper and copper plated busbars. It was shown that there is a significant difference in the effect of these compounds on the stability and performance of bolted joints and their ability to protect the contact zone against fretting. It should be pointed out, however, that these compounds, currently used by utilities for power connections, are unable to meet the new, high temperature requirements. This is due to their low thermal stability (low melting point), tendency to oxidize and evaporate.

In search for a connector lubricant capable of meeting the high-temperature operation conditions, Antler [6,7] has shown that fluorinated ethers are the best candidates due to their thermal stability, inertness and low viscosity and surface tension. The effect of fluorinated ethers on the tribological properties of hot-dipped tin separable contacts has been extensively studied by Noel et. al [8,9]. It was shown that the beneficial effects of fluorinated ethers are dictated by their compositions (linear or branched), viscosity and surface tension.

The work reported here is a continuation of the work on the contact-aid compounds, specifically aimed at determining as to whether the PFPE- and PFAE-based lubricants can be used for power connectors operating at temperatures as high as 200°C and under emergency conditions reaching 320°C. The evaluation is based on the effect of these lubricants on the performance of bolted aluminum-aluminum joints and wedge-type connectors under current-cycling conditions, stability to UV and long-term high-temperature exposure.

EXPERIMENTAL DETAILS

Lubricants

For the purpose of this study, four fluoroether-based and one Teflon-based lubricants were selected. The lubricants selected and some of their physical properties are listed in Table 1. The primary selection criterion for selecting these compounds was their maximum operating temperature ranges. These lubricants are specially formulated to operate at very high temperature ranges with base oils and additives designed to suit the extremes in temperature. Some of them include special thickeners that do not melt, and provide improved adhesion to the substrate, as well as lower wear rates.

Table 1 Selected properties of the lubricants used in this work.

Lubricant	Temperature Range (°C)	Composition Base/Thickener
N1	-50 / +225	PFPE/PTFE
N2	-50 / + 225	PFPE/PTFE
N3	-15 / + 250	PFPE/PTFE
S1	-43 /+ 232	Teflon
C1	-20 / +300	PFAE/PTFE

PFPE – polyfluoropolyether
PTFE – polytetrafluoroethylene
PFAE – perfluoropolyalkylether

UV Resistance

Ultra violet resistance was measured in accordance with ASTM G-53-95 and ASTM D-638-95. Test specimens were placed in an Accelerated Weathering Tester operating on a continuous cycle of four hours UVB at 60^0C followed by four hours condensation cycle at 50^0C.

Each window of the UVB frames was covered with aluminum foil. The lubricant samples were spread over the 2x3" windows using a tongue depressor. To insure an even and smooth application, the tongue depressor was raked across the top of the window. Excess lubricant was removed from the edges of the frames.

Specimens were removed periodically and visually examined for discoloration, cracking and hardening of the candidate material for up to 2,000 hours. The lubricant was judged to have failed when it could no longer be spread with a spatula or had severe cracking.

Long-Term Temperature Exposure

Samples were placed in a forced air oven at 200^{o}C and were removed periodically and visually examined for discoloration, cracking and hardening of the candidate material for up to 2,000 hours. The lubricant was judged to have failed when it could no longer be spread with a spatula or had severe cracking.

Thermogravimetric Analysis (TGA)

The thermal stability of the selected lubricants was determined using a Perkins Elmer TGA 7 analyzer. TGA measures mass flow into or out of a sample (weight change).

Computer controlled graphics calculated precisely weight percent losses. A sample of each lubricant of about 10 mg was heated at a rate of 10 °C/min in air and the temperature and variation from initial weight was recorded. The principal parameter extracted from this test was the temperature at which the samples start to loose weight and degassing.

Sample for Current Cycling Tests

The test samples used for the current cycling test were overlapping aluminum busbars and wedge connectors. The busbar test samples 25 mm x 6 mm x 200 mm bars cut from EC-1350 grade aluminum. Prior to each test, the contacting surface of the busbars were machined and degreased by wiping the overlapping surfaces with cotton swabs soaked in a dissolvent. A thin layer of the lubricant was spread over the overlapping zones and the joints assembled.

Tests with the wedge connectors were carried out using aluminum conductor 336.4 kcmil ACSS grade. Three wedge connectors were used for each lubricant. Assembling of the connectors was realized in accordance with the manufacturer's specifications.

Current-Cycling Tests

Two types of current cycling tests were used: on bolted busbar joints and wedge connectors. For the busbar joints, the current cycling procedure consisted of rapidly heating the joints for 5 min to 200°C (ON period) followed by cooling to room temperature during the next 15 min (OFF period). This procedure was repeated three times followed by a prolonged cooling for the next 45 min. Once an ON/OFF cycle (three short cycles + prolonged cooling = 105 min) was completed, the whole procedure was repeated. All the busbar joints were tightened to 50-Nm force torque, which corresponds to an initial contact force of 16 kN.

The lubricants subjected to this type of current cycling test are listed in Table 1. Each joint comprising a combination of two disc-spring and two thick flat washers placed on each side of the joints to minimize the stress relaxation [10]. For each lubricant, two bolted joints were used and tested simultaneously.

The contact resistance and temperature were monitored continuously. The contact resistance was derived from the contact voltage drop measured between the bolted busbars in a cross-rod configuration. Each joint's temperature is monitored using chromel–alumel thermocouples (type K) inserted in holes drilled about 5mm from the contact interfaces.

These parameters were recorded at 30 s intervals using an HP-3852A data logger whose output was transferred to a Unix HP 745i microprocessor for computing processing. The same microprocessor was used to control the ON and OFF switching of the power supply. The system automatically shuts down whenever any of the joints temperature exceeds 250°C.

Current cycling with the wedge connectors was realized using a modified 500 cycles ANSI current cycling procedure. The modification consisted of passing a high AC current sufficient to raise the temperature of the control conductor to 200°C.

For each connector, the temperature was measured at the end of ON periods whereas the contact resistance was derived from the contact voltage drop measured between the equalizers and across the wedge connectors at the end of OFF periods. A 20 A DC current was used for the voltage drop measurements.

RESULTS

UV Resistance

The results of resistance to UV and long-term thermal exposure are summarized in Table 2. The results are shown as a function of time to failure during exposure to UV and at 200^{o}C.

Table 2 Time to failure of lubricants exposed to UV radiation and thermal ageing.

Lubricant	Time to Failure (hrs) in UV Test	Time to Failure (hrs) at 200°C in Thermal Ageing Test
N1	>2051	720
N2	>2051	720
N3	> 2051	>2400
S1	305	504
C1	> 2051	>2400

The results in Fig. 1A and 1B illustrate the appearances of the lubricants before and after exposures to the thermal tests. Figure 1A is characteristic of the lubricant that passed the tests while Fig. 1B depicts the ones that failed.

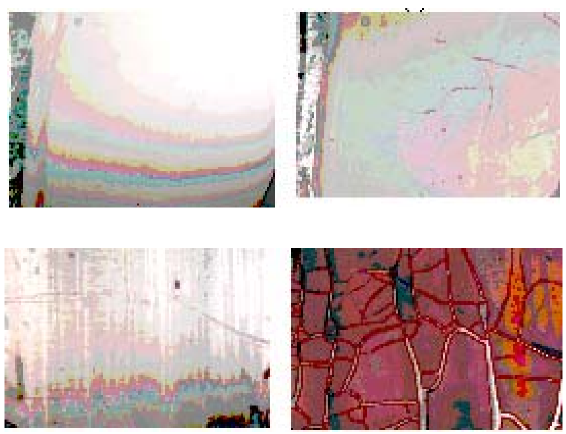

Fig. 1 Typical appearance of the lubricants before and after exposure to thermal ageing.

Thermogravimetric Analysis (TGA)

The results of thermogravimetric analysis are shown in Table 3 and examples of the typical weight loss-temperature dependence of some of the lubricants are illustrated in Fig. 2. It can be seen that all the compounds have stable behaviour below 200 °C, with N3 having the highest, close to 400 °C.

Table 3. The results of TGA analysis.

Lubricant	Decomposition onset (°C)
N1	257,3
N2	243,3
N3	396,9
S1	306,0
C1	351,0

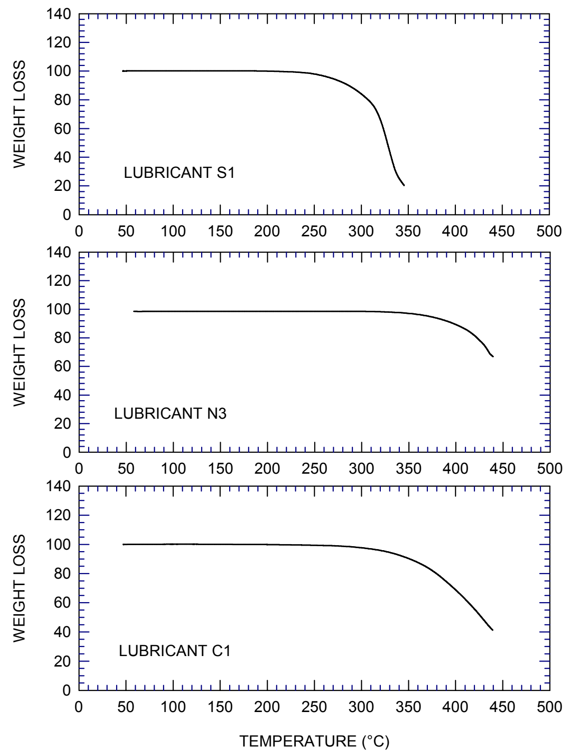

Fig. 2 Typical weight loss-temperature dependence of some PFPE lubricants

Current-Cycling Tests

Current cycling tests were carried out on lubricants C1 and N3, rendered as the most stable following the UV and thermal ageing exposures. The results are shown in Figs. 3 and 4.

Fig. 3 depicts the changes in normalized contact resistance and temperature as a function of the

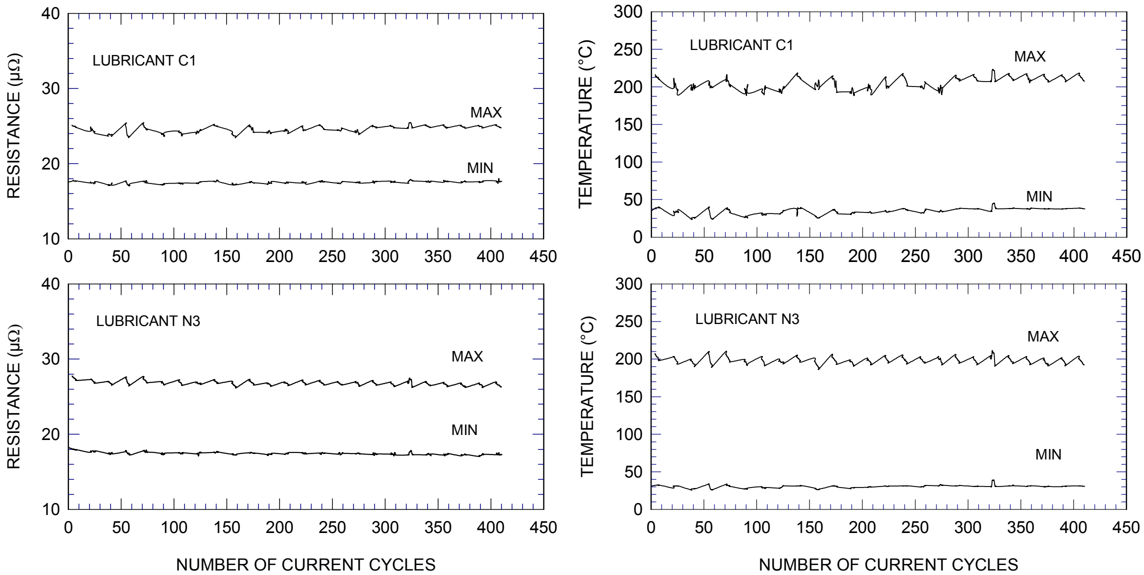

Fig. 3 Effect of current-cycling on the contact resistance and temperature of lubricated aluminum-to-aluminum busbar bolted joints.

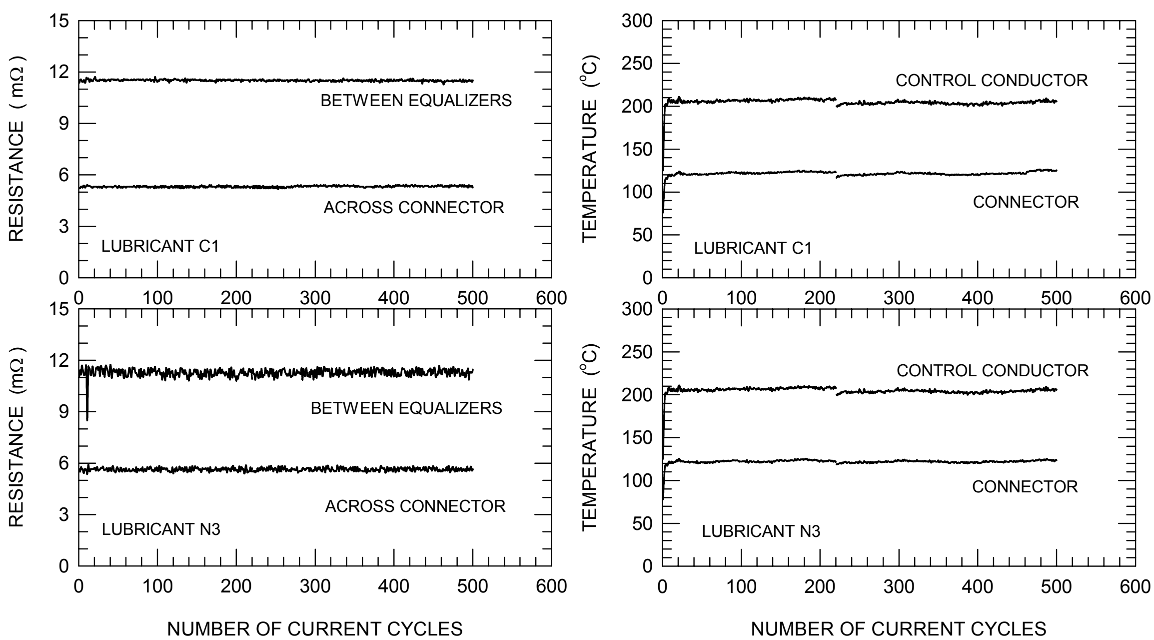

Fig. 4 Effect of current-cycling on the contact resistance and temperature of lubricated aluminum-to-aluminum wedge connectors.

number of current cycles for aluminum-to-aluminum busbar joints. The MAX and MIN values indicate respectively the changes in contact resistance measured at the end of ON and OFF periods.

Fig. 4 illustrates the changes in resistance measured between equalizers and across wedge connectors and

the connector temperature The results of current cycling tests indicate that contact resistance and temperature of busbar joints and wedge connectors lubricated with the lubricants N3 and C1 remained very stable thorough the tests. Hence, these lubricants can be used as the base formulation for effective high temperature applications.

DISCUSSION

The results of this preliminary screening testing identified two PFPE lubricants with sufficient UV and thermal stability to warrant further testing as contact-aid compounds for high temperature connector applications.

The stability of these lubricants was manifested not only when exposed to the UV radiation and thermal ageing, but more importantly when used as contact-aid compounds in bolted busbar and wedge type joints subjected to current cycling tests.

Hence, in view of ever-increasing demand to raise the operating temperatures of the transmission and distribution lines to higher levels, it is of great importance to establish whether the selected lubricants will have the same effect under the field service conditions where many extraneous and variable influences such as water, dust, dirt, rain, extremes of ambient and operating temperatures etc., become very influential parameters.

In conclusion, it should be emphasized that the results presented in this paper were obtained under controlled laboratory conditions using laboratory equipment. Future work will be focused on clarifications of mechanisms determining the effectiveness of PFPE lubricants in controlling the performance of power connectors operating at high-temperatures are the same as those characteristic for the low-temperature operation.

The results presented here, however, clearly demonstrated that the selected lubricants could be considered as potential candidates for high-temperature power applications in which the necessary fillers and metallic additions can be incorporated to make them as effective contact-aid compounds.

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