OXIDATION AGING AND RESULTING DIELECTRIC PERFORMANCE OF A NATURAL ESTER INSULATION SYSTEM FOR TRANSFORMERS

Kevin RAPP
Cargill – USA
Kevin_Rapp@cargill.com

Alan SBRAVATI
Cargill – Brazil
Alan_Sbravati@cargill.com

John LUKSICH
Cargill – USA
John_Luksich@cargill.com

David BINGENHEIMER
Cargill – USA
David_Bingenheimer@cargill.com

ABSTRACT

This paper provides the dielectric performance of a natural ester insulation system during controlled laboratory oxidative aging at elevated temperature. The results are discussed in connection with aging by-products that indicate practical limits of air and temperature exposure. The limits are discussed in the context of IEEE and IEC standards.

INTRODUCTION

Natural ester insulating liquids have been applied in over 600,000 transformers during the past eighteen years with distribution transformers making up the majority of the units [1]. The insulation system of a natural ester-filled transformer has been the subject of intensive study focusing mostly on thermal aging factors, but oxidation of the insulation system, and its effects on dielectrics should be more fully explored for practical application in manufacturing and repair. The understanding of these factors is also important for field maintenance when a transformer tank may be opened for varying periods of time.

There are differences in the oxidation aging of natural ester insulation systems compared to mineral oil insulation systems. Differences also exist in the oxidation of each liquid and the effects, such as by-products of oxidation on the dielectric performance, including exposure time and influence of temperature.

This paper discusses the effect of oxidation on the dielectric characteristics of a natural ester insulation system compared to a mineral oil system. The AC, lightning impulse and switching impulse creep breakdown strengths were measured on cellulosic pressboard specimens after long-term hot air exposure. The conditions were chosen to provide transformer stake holders practical knowledge that will benefit manufacturing, shipping, field service and required maintenance.

FLUID OXIDATION AND THERMAL AGING

The first aspect to understand is the effect temperature has on the long-term oxidation, and in particular, the insulation system aging process.

The majority of transformers use a combination of liquid plus solid (cellulosic) insulation system. Especially at operating temperatures above 100 °C, the stability of both a natural ester fluid and cellulose insulation system is superior to one designed with mineral oil operating at temps below 100C, as long as oxygen (air) exposure is limited [2-4].

The second relevant aspect is the oxidation reaction by-products and their effects on the transformer. Mineral oil oxidation and aging by-products produce short-chain carboxylic acids that have been shown to be corrosive to metal and can accelerate the aging of cellulose insulation [5, 6]. Further reaction will eventually result in the formation of sludge that can deposit on components and cooling duct surfaces [7].

The long-term effects on transformers from mineral oil sludging are over heating due to reduced cooling and degradation of the dielectric strength of the insulation system.

The by-products of natural ester oxidation are hydroperoxides and long-chain acids, which are mild in comparison to short-chain acids from mineral oil and do not result in sludge formation. The hydroperoxides and unsaturated groups in the fatty acid chains react to form branched and even longer chains that increase the molecular size and viscosity of the liquid. Chemically, this is called oligomerization, which will eventually result in a slow increase in the transformer temperature if air oxidation continues long term.

Figure 1 shows a comparison of the inside surfaces of aging vessels used to age mineral oil and natural ester liquid with thermally upgraded Kraft paper, aluminium and copper for 2000 h at 170 °C [8].

Figure 1: Comparison of sludge formation in aging vessel used for mineral oil versus natural ester aged Kraft paper.

In the case of natural ester impregnated pressboard exposed to long periods of hot open air conditions, oxidation may form polymeric structures that will first become viscous, then tacky and will eventually harden to a varnish-like coating. Higher outdoor temperature and UV light (sun) exposure with air induced oxidation outside the bulk liquid will speed this process. Insulation exposure time outside the tank should be limited.

DIELECTRIC INVESTIGATIONS

The dielectric testing for this paper will focus on interfacial creep of cellulose pressboard in Envirotemp™ FR3™ natural ester insulating liquid compared to mineral oil, both before oxidation and after selected time periods of air oxidation at 40 °C up to six months. A foundation of understanding of creep breakdown of natural ester-pressboard interfaces was established from project work published in 2008 [9]. Some details and results from that work are provided in this paper.

Design of Test Electrode Arrangement

The electrode arrangement was designed to avoid the presence of any oil wedges where partial discharge could originate. There were no sharp points on the electrodes where localized stress could initiate breakdown independent of the materials being tested. The electrode configuration was developed using 3D finite element analysis (FEA) by Weidmann Electrical Technologies. The design maintained the creep stress greater than the design curve and the stress in the oil less than the design limit. The electrode configuration is shown in Figure 2.

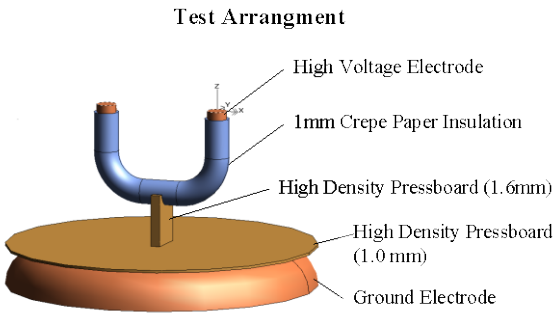

Figure 2: Test electrode arrangement for interfacial creep breakdown testing.

Figure 3: Creep test specimen at 35 mm distance with breakdown arc path from HV electrode to pressboard spacer which covers ground plane electrode.

The high voltage electrode was constructed into a "U" shape using copper tube wrapped with 1 mm thick Kraft crepe insulation. The opposing metal ground plane electrode had a machined radius top edge and was covered with a 1 mm thick high-density pressboard spacer. The crepe paper wrapped high voltage electrodes and pressboard spacers that cover the ground plane electrode were impregnated with the liquid being tested and were changed out to new before each creep test specimen. The creep interface test specimens were 1.6 mm thick high density pressboard that had a machined notch that conformed to the diameter of the crepe paper wrapped HV electrode. New insulating liquid was used for each test specimen.

A creep test specimen, HV electrode and ground plane pressboard spacer are shown in Figure 3. The creep sample was cut at a distance of 35 mm and displays an actual breakdown arc path.

Sample Preparation Procedures

Pressboard test specimens for testing new and not oxidized samples in both liquids were cut at creep distances of 10, 20 and 35 mm. The creep test samples, paper wrapped HV electrodes and the pressboard spacers that cover the ground plane electrode were dried for 24 hours in an air-circulating 105 °C oven, vacuum dried at 105 °C and less than 100 µm for 24 h, oil impregnated under 67 Pa vacuum and allowed to oil soak for 24 h in accordance with [10]. All samples and components were transferred with minimal exposure to air and assembled in the test vessel under oil.

The new insulating liquids were processed before use to degas and dry to a moisture level of about 10 mg/kg for mineral oil and 100 mg/kg for natural ester liquid. The liquids were tested for moisture content and acceptable dielectric strength using ASTM test methods D1533 and D1816, respectively [11, 12].

Oxidation Aging Procedure

The specimens to investigate the effect of oxidation on creep dielectric breakdown were cut at a distance of 35 mm only. The samples were initially prepared using the procedure detailed in the above section. The specimens were removed from the impregnation liquid, patted dry and placed on racks in a dry air oven at 40 °C for 30, 60, 90 and 180 d.

After the appropriate oxidation time period, the samples were placed in a vacuum drying oven at an elevated temperature for about 24 h to assure dryness. Spot samples were taken to confirm that the moisture content was near 0.5 % by weight. The samples were re-impregnated with the appropriate insulating liquid before testing.

Dielectric Testing Procedures

The oxidation aged creep samples were tested for 60 Hz breakdown according to ASTM D149 [13]. Negative impulse 1.2 x 50 µs full-wave testing was done in accordance with ASTM D3426 [14]. Negative switching surge impulse using a 250 x 2500 µs waveform was done using a similar procedure according to ASTM D3426. Figure 4 shows the dielectric test setup with the upper

and lower stress reducing rings in conjunction with the high voltage and ground plane electrodes respectively.

Figure 4: Creep test setup for impulse breakdown.

RESULTS AND DISCUSSION

60 Hz AC

Results from 60 Hz testing of creep samples prior to air oxidation are summarized in Table 1. They show that average AC breakdown and withstand (1% 2-p Weibull distribution) voltages for pressboard/liquid interfacial creep before oxidation compare for natural ester liquid and mineral oil. The results in Figure 5 after air aging oxidation at 40°C show that average 60 Hz breakdown at 35 mm is unchanged after 30 d, but decreases steadily beyond 30 d until the end of testing at 180 d. After 60 d of air aging the AC breakdown voltage drops 29 %.

TABLE 1. 60HZ AC BREAKDOWN AND WITHSTAND VOLTAGES OF CREEP SPECIMENS BEFORE OXIDATION.

Oil Gap	**10mm**		**20mm**		**35mm**	
Fluid	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***
U_{avg} (KV)	162	163	214	230	280	305
$U_{1\%W}$ (KV)	98	91	150	149	193	172
α (scale)	171.1	173.7	227.9	241.8	293.1	326.3
β (shape)	8.19	7.05	11.0	9.52	11.0	7.18
R^2_W	0.956	0.916	0.966	0.920	0.956	0.882

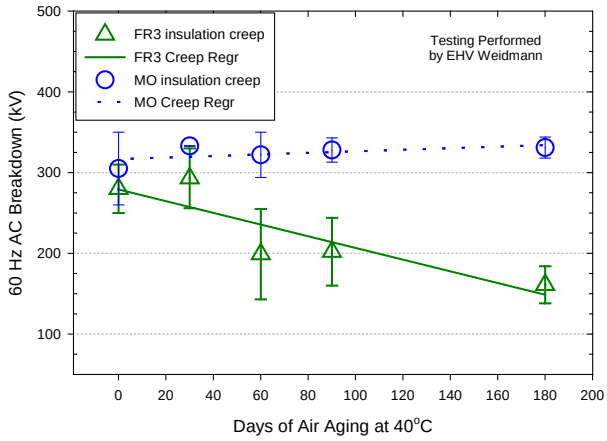

Figure 5: 60 Hz breakdown of 35 mm creep samples after oxidation at 40 °C.

Negative Lightning Impulse

Table 2 contains the results from measuring negative lightning impulse on un-oxidized creep specimens. Average -1.2 x 50 µs breakdown and withstand voltages for natural ester liquid and mineral oil are comparable.
The negative lightning impulse breakdown results at 35 mm after air oxidation at 40 °C are shown in Figure 6.

TABLE 2. NEGATIVE LIGHTNING IMPULSE BREAKDOWN AND WITHSTAND VOLTAGES OF CREEP SPECIMENS BEFORE OXIDATION

Oil Gap	**10mm**		**20mm**		**35mm**	
Fluid	***NE***	***MO***	***NE***	***MO***	***NE***	***MO***
U_{avg} (KV)	386	396	549	576	638	674
$U_{1\%W}$ (KV)	243	259	425	399	455	453

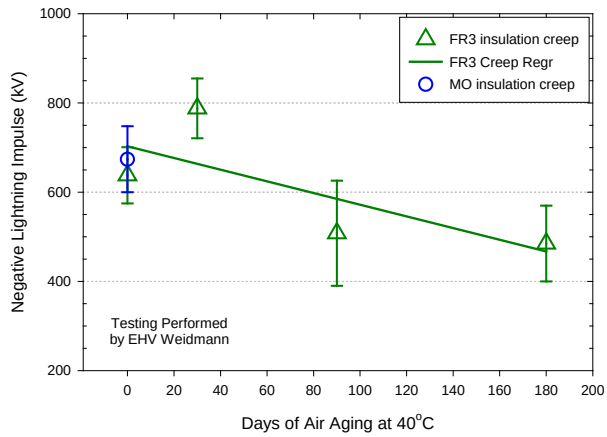

Figure 6: Negative lightning impulse after air oxidation

Mineral oil samples oxidized for 30-180 d were not included in the lightning impulse portion of the study since both the 60 Hz and switching surge results were unchanged for mineral oil. The 40 °C air oxidized natural ester samples were stable and unchanged for 30 d. No 60 d samples for lightning impulse were included. Oxidation of natural ester creep specimens in air for 90 and 180 d resulted in 20 and 24 % decreases in negative lightning

impulse voltage, respectively.

Negative Switching Impulse

Un-oxidized creep specimens at 10, 20 and 35 mm distances were not previously measured with the creep testing configuration shown in Figure 2 so no data was available. Negative switching impulse results of oxidized creep specimens at 35 mm are shown in Figure 7.

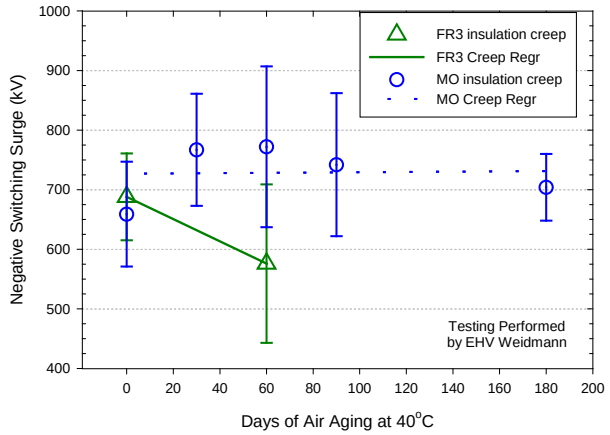

Figure 7: Negative switching impulse of 35 mm creep samples after air oxidation at 40 °C.

Natural ester specimens were only oxidized for 60 d. The mineral oil samples were completed for all aging times. The results show that the switching impulse breakdowns of the mineral oil samples oxidized for up to 180 d are unchanged. The average switching impulse breakdown of natural ester creep specimens oxidized for 60 d decreased 16 %. The results at 30 d were not included, but would be expected to be unchanged based upon the lightning impulse and 60 Hz data.

CONCLUSIONS

Natural ester impregnated pressboard interfacial creep specimens oxidized in air at 40 °C are dielectrically stable for 30 d as measured by 60 Hz, negative full-wave and switching impulse breakdowns. After 30 d and up to 60 d of air aging, the creep dielectric breakdown characteristics slowly decrease 16 to 29 % using negative switching surge and 60 Hz respectively. After 90 d of oxidation, the lightning impulse breakdown drops about 20 % compared to un-aged samples.

Mineral oil impregnated creep samples were stable for the full 180 d of testing. The results indicate that oxidation by-products will alter the creep dielectric breakdown characteristics of natural ester impregnated pressboard after 30 d of air exposure at 40 °C.

It is likely that in most situations the temperature of previously impregnated insulation exposed to air would average less than 40 °C. Furthermore, it is likely that manufacturing and repair processes of previously impregnated insulation material would not extend beyond 30 d. Thus, there is no reason to change normal operating procedures. However, drying previously impregnated natural ester insulation in a hot air circulating oven must be avoided.

Oxidation of the natural ester impregnated pressboard was the reason for the reduction of the interfacial creep breakdowns after 30 d at 40 °C. Inside a filled transformer the pressboard oxidation process does not occur. Exposure of the liquid to ambient air will lead to consumption of oxidation inhibitor and, in the long term, may result in some oxidation of the fluid.

Field experience includes a shunt reactor operating at full loading and free-breathing condition during more than seven years without any dielectric performance issues, despite the increase of fluid neutralization number and dissipation factor above the continuous operation limits, which proves the application of natural ester liquid is a robust solution, even in situations where the recommended conditions are not fulfilled. This case is detailed in [5].

Acknowledgments

The authors would like to thank the Weidmann Electrical Technology staff in St. Johnsbury, VT for their work in completing this project.

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