EFFECT OF NATURAL ESTER (VEGETABLE OIL) DIELECTRIC FLUID ON THE WATER CONTENT OF AGED PAPER INSULATION

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ABSTRACT

Previous insulation aging studies show a significant reduction of paper insulation aging rate when aged in natural ester dielectric fluid compared to paper aged in mineral oil. This study examines the effects at typical transformer operating temperatures of the natural ester fluid on previously degraded Kraft insulation paper with elevated water contents. To replicate service-degraded insulation, thermally upgraded Kraft paper was aged in mineral oil at 170°C for 400 hours, resulting in a decrease of the tensile strength to about 70% of the original value and an increase in its water content. The aged paper was equilibrated to 1 and 3 %wt water contents, representing "wet" transformers. Seventy sealed tube systems were assembled using combinations of aged paper with new dried, degassed, and filtered (hereafter referred to as processed) natural ester fluid, new processed mineral oil, and original mineral oil used in the initial aging of the paper. The systems were held at laboratory ambient, 85°C, and 110°C for 360, 720, 1440, 2160, and 3000 hours. In all cases the water content of paper in the natural ester systems was reduced to a lower level than that obtained in mineral oil. The water contents of paper in the original mineral oil remained unchanged. The decrease in paper water content in conjunction with changes in natural ester water content and acid level reinforce the primary paper aging rate reduction mechanisms proposed in prior work.

INTRODUCTION

Natural ester (vegetable oil) dielectric fluids are in many ways an effective alternative to the mineral oil coolant commonly used in distribution and power transformers. Natural ester fluids have favorable environmental and fire safety properties, most notably rapid and complete biodegradation and categorization as "K" class fluid per IEC 61100.

Previous sealed tube aging studies demonstrate that, under identical conditions, Kraft paper insulation ages significantly slower in natural ester fluid than in conventional transformer oil. Thermally upgraded Kraft [1], plain Kraft [2], and cotton-Kraft blend [3] exhibit this behavior when aged in natural ester fluid alone compared to aging in mineral oil alone. Replacing the original mineral oil with natural ester fluid in sealed tube systems after sufficient aging to moderately degrade the Kraft paper, simulating the retrofill of an in-service mineral oil transformer, demonstrates that the paper aging rate converts from the rate in mineral oil to the slower rate of paper in natural ester fluid [4].

Kraft paper insulation aging rates increase with increasing temperature (thermo-kinetic degradation) and increasing water content (thermo-hydrolytic degradation) [5]. The primary and secondary mechanisms hypothesized to be responsible for the different aging rates are related to differences in how natural ester fluid and transformer oil interact, physically and chemically, with water and cellulose. The primary mechanism is a net movement of water generated by paper aging from the paper into the natural ester fluid, followed by hydrolysis of the ester [6].

In order to obtain results in a reasonable amount of time, the previous studies used aging temperatures of 130-170°C to accelerate the paper degradation process. This work examines the effect of natural ester fluid on partially degraded "wet" Kraft paper at typical transformer operating temperatures.

EXPERIMENTAL

Sample Preparation

The test systems, identical to those used in previous studies [1-4], consisted of heavy-walled steel cylinders having a bolted cover fitted with an o-ring gasket and high temperature valve. The cylinders contained Kraft paper at 1 or 3 %wt water, copper, aluminum, and 350ml of insulating fluid. The sealed tubes were evacuated, and pressurized with nitrogen to 110 kPa.

Initial Aging.

Thermally upgraded electrical grade 0.25mm Kraft paper was cut into 25.4mm x 127mm strips. The strips, along with copper and aluminum sheets in the proportions used in a typical distribution transformer, were placed into large steel tanks. The tanks were placed into forced air ovens to initiate the drying of the components. After the initial drying process, the containers were transferred to a preheated vacuum oven where drying was completed. This drying

procedure produces paper water contents of approximately 0.5 %wt. Processed mineral oil was then introduced under vacuum into the steel cylinders to fully impregnate the paper with oil. The cylinders were cooled under vacuum to laboratory ambient. The cooled cylinders were removed from the vacuum oven and immediately sealed and pressurized with nitrogen to 110 kPa so that the internal pressure remained above the vapor pressure of water at 170°C. These assembled test systems were placed in a forced air oven at 170°C for 400 hours. This combination of time and temperature degrades the paper to about 70% of the original tensile strength and increases the water content to about 1 %wt.

Establishing Water Content.

At the completion of the paper aging sequence, the systems were opened and the materials placed in a glass container sufficient to hold the entire contents of all test systems. This permits the contents to be easily blended into a homogeneous system. Multiple random samplings of paper from the homogenous system confirmed a 1 %wt paper water content. Half of the paper strips from the homogenous system were removed, blotted to remove any residual surface oil, and suspended in an incubator maintained at 25°C (Fig 1). A large pan of water was placed directly beneath the circulating fans in the chamber and the chamber closed. This results in a relative humidity level in the chamber of 40-45%. The temperature and humidity were monitored and maintained for 10 days. Randomly selected paper strips were evaluated and found to have stabilized at approximately 3 %wt water content.

Retrofill and Dry-Out

With the paper water contents established at approximately 1 and 3 %wt, new aging systems were prepared to emulate 3 typical aged transformer scenarios:

1) An aged transformer,

TABLE 1 Test matrix for 1 and 3 %wt paper water content test systems.

	Temperature (°C)		
Time (hrs)	ambient	85	110
0	e[1], m[2], o[3]	-	-
360	e	e	e
720	e, m	e, m	e, m
1440	e	e	e
2160	e, m, o	e, m, o	e, m, o
3000*	e, m, o	e, m, o	e, m, o

[1] new processed natural ester fluid
[2] new processed mineral oil
[3] original (aged) mineral oil
* Note: At 3000 hrs, only the 1 %wt paper systems were used with new processed mineral oil. systems

Figure 1 Chamber used to equilibrate the water content of the previously aged Kraft paper. Fans inside the chamber circulate the air to stabilize the humidity throughout and assure consistent exposure of all specimens. Sensors continuously monitor temperature and humidity.

2) An aged transformer that has the original mineral oil reprocessed, or replaced with new processed mineral oil,

3) An aged transformer that has the aged mineral oil replaced with new processed natural ester fluid.

The requisite proportions of paper, copper, aluminum, and processed insulating fluid were placed into the steel aging cylinders and sealed. A vacuum was applied to help re-impregnate the paper with insulating fluid, and the systems were again pressurized with nitrogen to assure that the pressure remained above the vapor pressure of water at the test temperatures. The test systems were inverted and maintained at the test temperatures of laboratory ambient, 85°C, and 110°C for times ranging from 360 to 3000 hours (Table 1).

RESULTS

The paper tensile strength was measured after the initial aging sequence and periodically during the dry-out sequences. After the initial aging, the tensile strength was reduced to about 70% of that of new paper. The subsequent time and temperature sequences had no quantifiable effect on the tensile strength.

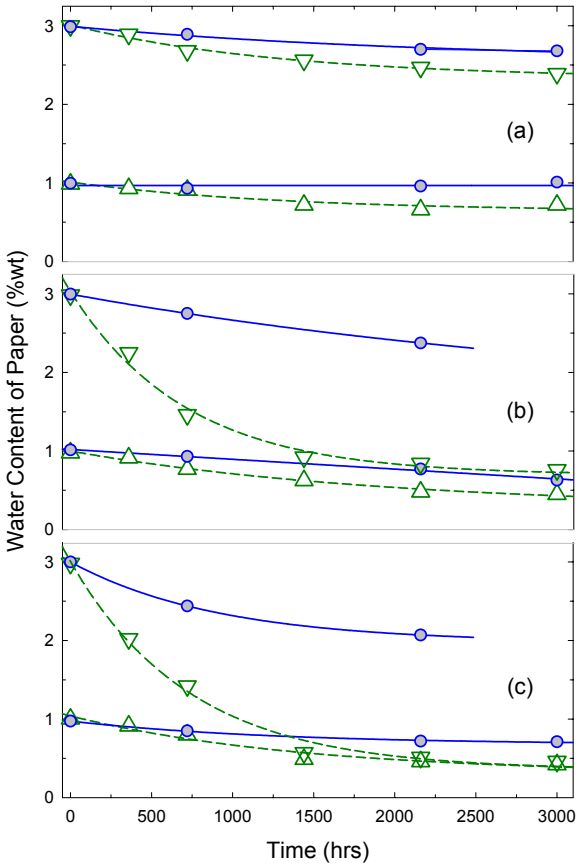

Figure 2 Water content *versus* time of Kraft paper previously aged in mineral oil, brought to water contents of 1 and 3 %wt, and retrofilled with new processed mineral oil (•) and natural ester fluid (△,▽). Temperatures of (a) ambient, (b) 85°C, and (c) 110°C.

Paper Water Content

The water contents of paper from test systems continuing to use the original aged mineral oil varied little from their initial amounts for all times and temperatures.

Fig. 2 shows the water contents of paper in the systems retrofilled with processed fluids. The water contents of 1 %wt paper in mineral oil did not change at ambient temperature and decreased slightly over time at 85°C and 110°C. At 3 %wt, the paper water content decreased slightly at ambient temperature. The decrease became more pronounced with increasing temperature, dropping from 3 %wt to about 2 %wt at 110°C.

At ambient temperature, the water contents of both the 1 and 3 %wt paper in the systems retrofilled with natural ester fluid decreased slightly more than did paper in the equivalent mineral oil systems. At 85°C and 110°C the water contents of the 1 %wt paper decreased to about 0.5 %wt. The change in 3 %wt paper at 85°C and 110°C was more pronounced. At 85°C the water content was reduced to below 1 %wt. At 110°C, the water content decreased to a level equivalent to the 1 %wt paper – about 0.5 %wt.

Fluid Water Content

The original mineral oil contained 15 mg/kg of water after the paper aging sequence. At all temperatures it subsequently increased an additional 2-3 mg/kg in the 1 %wt systems and reached 45-55 mg/kg in the 3 %wt systems.

The water contents of the retrofilled mineral oil in the 1 %wt paper systems, initially at 13 mg/kg, remained essentially unchanged regardless of temperature (Fig. 3). At all temperatures the water contents of natural ester fluid in the 1 %wt systems, initially at 26 mg/kg, increased immediately, then began to fall (Fig. 4). The final natural ester water content decreased with increasing temperature, falling to its initial value at 110°C.

In the 3 %wt systems, the retrofilled mineral oil tended to increase slightly regardless of temperature (Fig. 5). At ambient temperature, the natural ester fluid increased to about 350 mg/kg and remained constant at about that level (Fig.6). At 85°C the water content increased quickly, appearing to peak before samples were taken at 360 hours, then decreased smoothly to about 250 mg/kg. At 110°C, a similar phenomenon of very fast rise and fall in fluid water content is accentuated by the temperature and can be seen in the return of the fluid water content to near-initial level at 720 hours.

Fluid Acid Number

After initial aging, the acid number of the original aged mineral oil was 0.13 mgKOH/g and remained unchanged at ambient temperature in both 1 and 3 %wt systems. In the 1 %wt systems the acid number increased to about 0.18 mgKOH/g at 85ºC and around 0.35 mgKOH/g at 110ºC. The 3 %wt systems exhibited increases to 0.25 mgKOH/g and 1.0 mgKOH/g at 85ºC and 110ºC, respectively.

Acid numbers of the systems retrofilled with mineral oil increased slightly at all temperatures in the 1 %wt systems (Fig. 3). In the 3 %wt systems the change was a bit more pronounced, increasing with temperature from an initial value of 0.002 mgKOH/g to 0.032 mgKOH/g (Fig. 5).

At ambient temperature, the acid numbers of both the 1 %wt (Fig. 4) and 3 %wt (Fig. 6) systems retrofilled with natural ester increased slightly above the initial 0.037 mgKOH/g value. Marked increases were evident, however with increasing temperature and initial paper water content. At 110°C, the 1 %wt system reached about 3.6 mgKOH/g, and the 3 %wt system nearly 11 mgKOH/g.

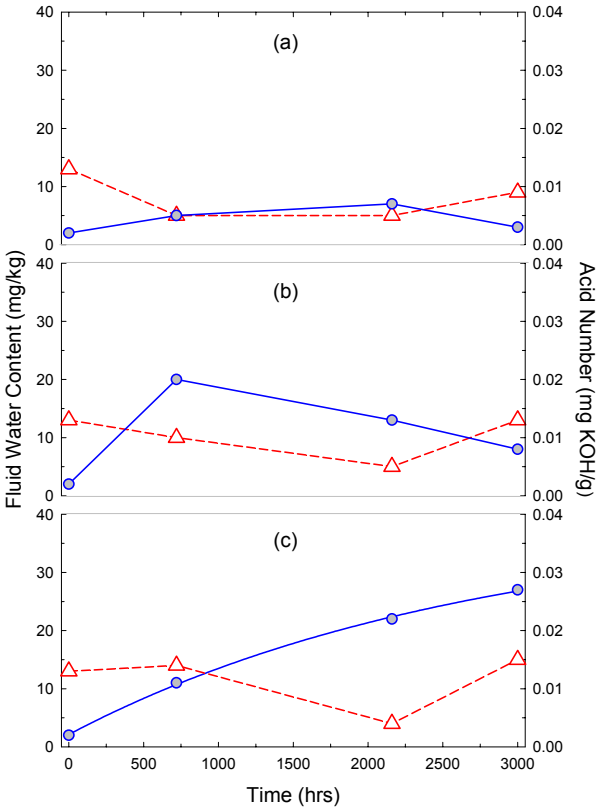

Figure 3 Fluid water content (△) and acid number (•) after retrofilling previously aged Kraft paper at 1 %wt water content with new processed mineral oil. Temperatures of (a) ambient, (b) 85°C, and (c) 110°C.

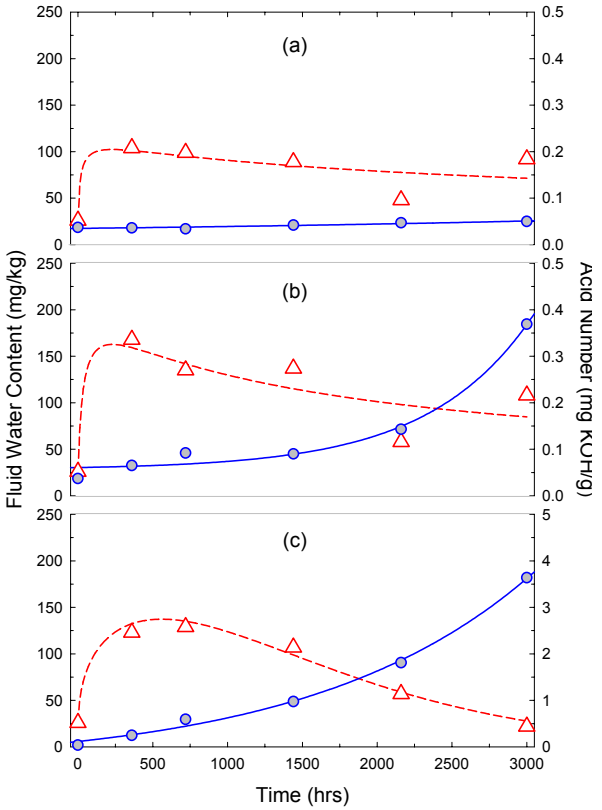

Figure 4 Fluid water content (△) and acid number (•) after retrofilling previously aged Kraft paper at 1 %wt water content with of new processed natural ester fluid. Temperatures of (a) ambient, (b) 85°C, and (c) 110°C.

DISCUSSION

The paper tensile strength measurements confirm that the times and temperatures used in the dry-out sequences of this study did not further degrade the Kraft insulation paper. Changes in the water content of the systems are therefore not affected by water generated as a product of cellulose degradation, and must be the result of other mechanisms.

All dry-out systems using the original mineral oil from the initial paper aging sequence, regardless of time or temperature, showed negligible change in the water content of the paper. The increases in water contents of the original mineral oil is due to the movement from the paper into the oil of the small amount of water needed to balance the paper and oil saturations. These systems mimic on a small scale in-service transformers with appreciable water content.

At laboratory ambient temperature, the relatively small changes seen in paper water contents, along with the changes in the water contents of the fluids, can also be accounted for in both the retrofilled mineral oil and natural ester systems in terms of water redistribution based on relative saturations.

A similar argument can be made for changes seen in the retrofilled mineral oil systems at 85°C and 110°C, where the initial retrofilled mineral oil relative saturations are in the neighborhood of 2-3% at 85°C and 1-2% at 110°C. The decreases seen in the paper water contents suggest that re-processing the mineral oil in an in-service transformer having appreciable water content could provide a slight drying effect on the Kraft paper insulation.

Although water redistribution is occurring in the natural ester fluid systems at 85°C and 110°C, the changes cannot be explained by water redistribution alone. These temperatures are sufficient to allow the effects of the ester hydrolysis reaction to be seen within the time frame of the experiment. The hydrolysis reaction consumes the dissolved water in the natural ester and generates free fatty acids. The rate of the hydrolysis reaction increases with both temperature and increasing water concentration.

The water content of the natural ester fluid increases as water moves from the paper into the fluid trying to equilibrate in terms of relative saturation. As the temperature increases, the rate at which the water moves also increases, as seen in Fig. 4 and Fig.6. Comparing acid number values of the 1 and 3 %wt

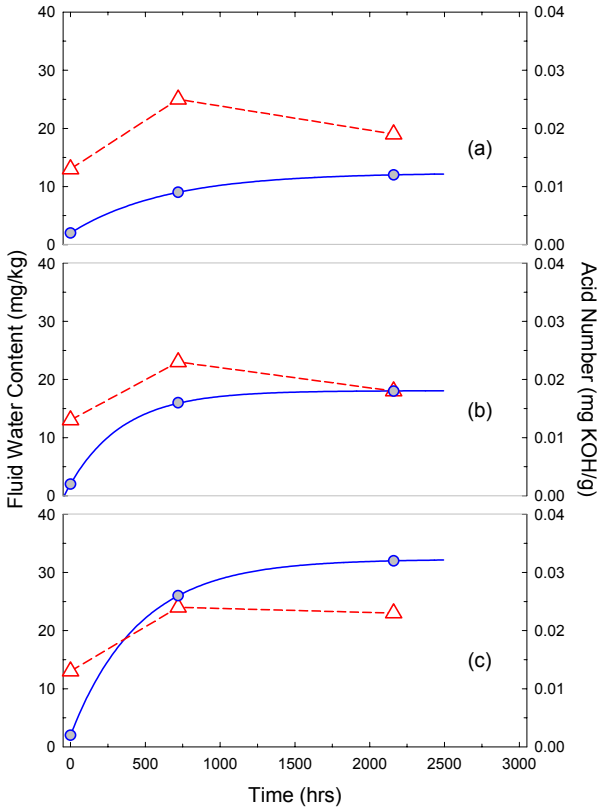

Figure 5 Fluid water content (△) and acid number (•) after retrofilling previously aged Kraft paper at 3 %wt water content with new processed mineral oil. Temperatures of (a) ambient, (b) 85°C, and (c) 110°C.

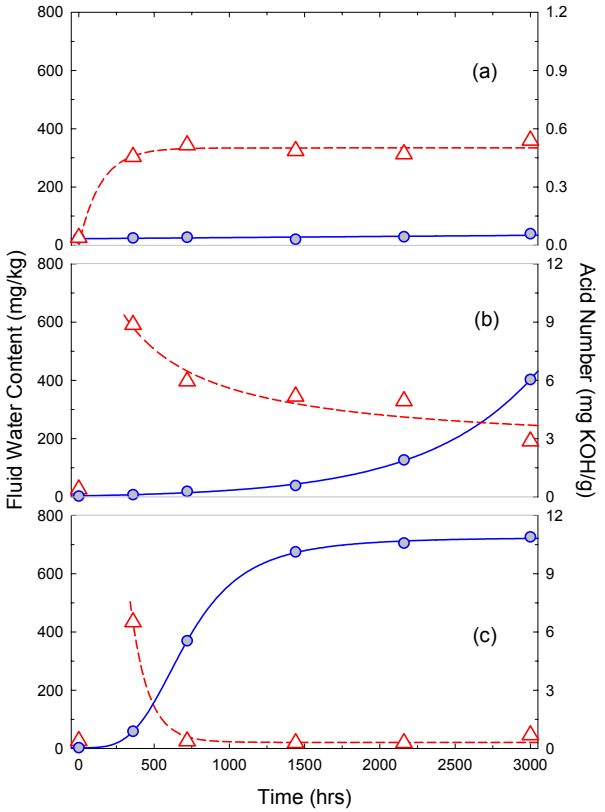

Figure 6 Fluid water content (△) and acid number (•) after retrofilling previously aged Kraft paper at 3 %wt water content with new processed natural ester fluid. Temperatures of (a) ambient, (b) 85°C, and (c) 110°C.

systems show the effect of water availability on the hydrolysis reaction. At equivalent temperatures, considerably larger quantities of free fatty acids are generated.

The strong effect of temperature on the hydrolysis reaction is evident in the changes seen in both fluid water contents and acid numbers. Not only does temperature affect the rate at which water repartitions from the paper to the fluid, it also increases the rate at which the hydrolysis reaction occurs. The initial increase in fluid water content due to water redistribution is followed by a decrease in water content as the water is consumed. The water consumed by the hydrolysis reaction results in the generation of free fatty acids.

The rate at which water migrates between paper and fluid controls the water concentration in the natural ester fluid and affects the rate of acid formation. In order to permit relatively unimpeded movement of water between the paper and fluid, the test systems contained individual paper strips to obtain a large exposed paper surface area. This maximized the water concentration in the natural ester fluid and increased the free fatty acid formation rate as indicated by the elevated acid numbers. The rapid rise in the natural ester water content followed by the slower increase in acid number indicate that, for these test systems, the movement of water happens at a faster rate than the hydrolysis reaction. Hydrolysis becomes the rate-limiting step in the formation of free fatty acids.

Paper insulation in a transformer has a much smaller exposed surface area. Water movement out of the paper depends on diffusion through the cellulose to a greater extent than our test systems. Although driven by the same concentration gradients, the migration of water from the Kraft paper into the dielectric fluid in a transformer takes place at a significantly slower rate as a result. This tends to slow the formation of free fatty acids by limiting the water concentration in the natural ester.

CONCLUSIONS

These results demonstrate that the transfer of water due to equilibrium shift from the insulating paper into the natural ester fluid, followed by an hydrolysis reaction that effectively prevents the interaction of paper and water, occur at normal transformer operating temperatures. These are the primary mechanisms responsible for the slower aging rate of the Kraft paper/natural ester insulation system. Retrofilling an in-service transformer having

appreciable water content with natural ester fluid could significantly reduce the water content in the Kraft paper insulation without compromising the dielectric integrity of the natural ester fluid.

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