Presented at the 2003 IEEE/DEIS Conference on Electrical Insulation and Dielectric Phenomena, Oct. 19-22, 2003, Albuquerque, NM

Aging of paper insulation retrofilled with natural ester dielectric fluid

C.P. McShane[1], J.L. Corkran[1], K.J. Rapp[2], J. Luksich[1]
[1]Cooper Power Systems, Waukesha, WI USA
[2]Thomas A. Edison Technical Center, Cooper Power Systems, Franksville, WI USA

Abstract: The aging rate of transformer insulation Kraft paper is much slower in natural ester (vegetable oil) dielectric fluid than in conventional transformer oil. This study investigates the effect that replacing transformer oil with natural ester fluid (retrofilling) has on the aging rate of thermally upgraded (65°C rise) paper initially aged in transformer oil. Sealed steel aging vessels containing copper, aluminum, dried thermally upgraded Kraft paper, and dielectric fluid (transformer oil or natural ester) were aged at 160 and 170°C for 250, 500, 750, 1000, 1500, and 3000 hours. Half of the transformer oil systems were retrofilled with natural ester fluid after initial aging times of 750 and 250 hours at 160 and 170°C, respectively. Paper degradation after aging is determined using paper tensile strength and degree of polymerization measurements. After replacing the transformer oil with natural ester, the aging rate of the paper initially aged in transformer oil showed an abrupt change to the reduced aging rate for paper in a natural ester.

Introduction

Natural (vegetable oil) ester insulating fluid offers fire safety, environment, and insulation aging advantages over mineral oil, and are found to be suitable for use in transformer insulation systems [1]. Previous sealed tube [2] aging studies show that the thermal aging rates of virgin paper insulation in natural ester insulating fluid are significantly slower than those in mineral oil [3-5].

The studies to date compare insulation papers exposed only to mineral oil or natural ester fluid, simulating their use in new construction. Existing in-service mineral oil-filled transformers are sometimes retrofilled (that is, the in-service fluid is replaced with new fluid). How is the paper insulation aging rate in natural ester fluid affected by previous aging in mineral oil?

This experiment examines the aging characteristics of thermally upgraded Kraft insulation paper aged in mineral oil, then retrofilled with natural ester fluid.

Experiment

Detailed descriptions of the test apparatus and procedures are given in [2]. Thermally upgraded Kraft insulation paper[1], aluminum and copper conductor materials, and dielectric fluid[2] were sealed in steel tubes with a nitrogen headspace. The fluid, immersed materials, and headspace are in proportions typical of distribution transformers. The paper was dried to approximately 0.5 wt% water content. The insulating fluids were dried and degassed.

Three sets of sealed tube aging systems were prepared, one set using natural ester fluid, and two sets using mineral oil. Each set of systems contained a sealed tube for each sampling time and temperature, shown in Table 1.

For each temperature, the duplicate mineral oil systems were removed from the aging ovens at the first scheduled sampling time, drained of mineral oil, refilled with natural ester fluid, and returned to the aging ovens.

Table 1. Times and temperatures for sealed tube aging systems using thermally upgraded paper in either mineral oil or natural ester fluid. Retrofills of duplicate mineral oil systems are done at end of first test period for each temperature.

	Temperature		
Time (hrs)	ambient	160°C	170°C
0	x		
250			x
500			x
750		x	x
1000		x	x
1500		x	x
2000		x	
3000		x	x

[1] Whiteley Ltd. Grade K T/U 0.255mm thermally upgraded Kraft paper

[2] Ergon Hyvolt II inhibited insulating mineral oil, Cooper Power Systems Envirotemp® FR3™ natural ester dielectric fluid

Table 2. Results of thermally upgraded Kraft paper sealed tube aging at 160 and 170°C in mineral oil and natural ester. Total furanic compounds are given as mg furans per liter of fluid per initial kg of paper.

Temperature	20°C	160°C					170°C					
Time (hrs)	0[a,b]	750[b]	1005	1500	2184	3022	250[b]	505	750	1009	1500	3002
Water Content of Paper [wt%]												
in mineral oil	0.46	0.37	0.71	0.66	2.22	6.29	0.58	0.99	1.55	5.92	4.28	2.79
in natural ester	0.72	0.38	0.34	0.29	0.20	0.25	0.15	0.12	0.10	0.08	0.17	0.20
retrofill	0.46	0.37	0.39	0.27	0.15	0.20	0.58	0.16	0.18	0.21	0.20	0.16
Tensile Strength of Paper [MPa]												
in mineral oil	148	114	97.7	74.4	22.9	6.2	110	80.1	28.1	7.7	0.7	-[c]
in natural ester	142	112	108	107	97.6	86.5	111	96.8	88.7	79.6	66.5	57.3
retrofill	148	114	101	98.7	92.1	80.8	110	83.5	77.9	66.3	57.2	53.9
Degree of Polymerization of Paper												
in mineral oil	1,152	496	405	271	132	31	481	291	73	24	5	0
in natural ester	1,148	628	566	444	366	361	547	435	411	333	314	226
retrofill	1,152	496	422	387	331	320	481	348	328	299	268	202
Furanic Compound Content of Fluid [mg/l/kg]												
mineral oil	nd	1,442	1,216	9,018	30,783	17,193	1,662	11,976	52,981	25,977	15,653	14,957
natural ester	1,044	613	959	608	649	928	966	637	502	611	1,058	851
retrofill	nd	1,442	2,818	1,002	1,010	1,508	1,662	1,162	465	917	1,003	792

[a] baseline values

[b] retrofill values at these times are identical to mineral oil sealed tube systems

[c] too degraded to measure

Results

The extent of paper degradation is determined using the changes in paper tensile strength and degree of polymerization (DvP). The water contents of the paper and furanic contents of the insulating fluid were also determined. The results are presented in Table 2.

Paper Condition at Retrofill: The initial condition of the retrofill systems is the condition of the mineral oil systems at their first sample point.

The 160°C mineral oil systems reached about 77% of initial tensile strength and 43% of initial degree of polymerization at 750 hours. The duplicate 160°C mineral oil systems were retrofilled at this point.

The 170°C mineral oil systems reached about 74% of initial tensile strength and 60% of initial degree of polymerization at 250 hours. The duplicate 170°C mineral oil systems were retrofilled at this point.

Tensile Strength: The paper tensile strength over time is shown in Fig. 1. After retrofilling with natural ester, the decline in tensile strength of the duplicate mineral oil systems changed from the mineral oil rate to that of the natural ester system.

The tensile strength of the mineral oil system fell below 25% that of unaged paper by 2000 hours at 160°C, and 750 hours at 170°C.

Both the natural ester and retrofill systems

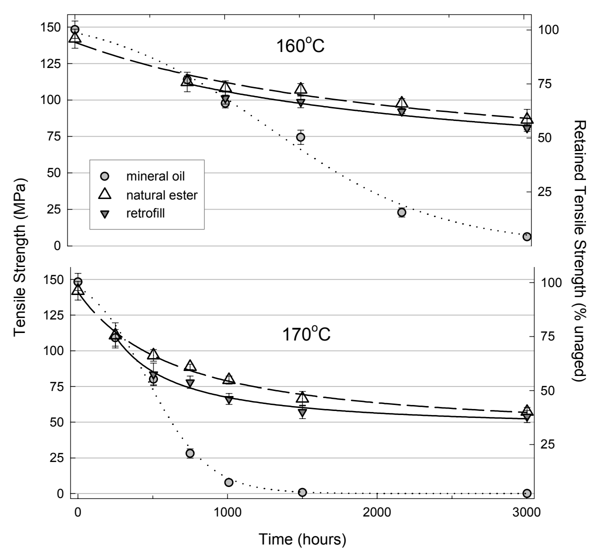

Figure 1: Tensile strength *versus* time at temperature for thermally upgraded Kraft paper in sealed tube aging systems. Duplicate mineral oil systems were retrofilled with natural ester fluid at 250 and 750 hours at 170 and 160°C, respectively.

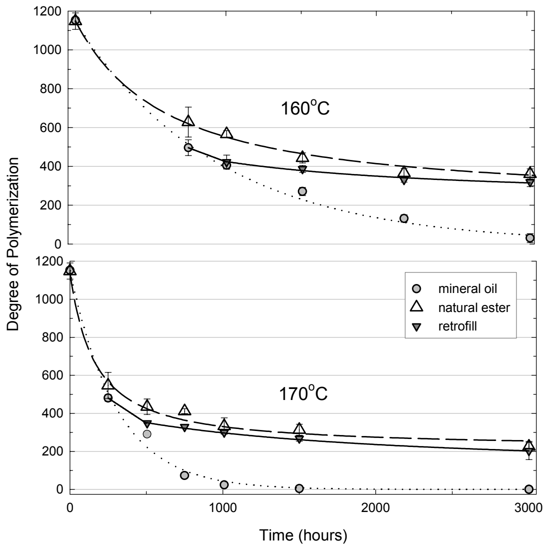

Figure 2: Degree of polymerization *versus* time at temperature for thermally upgraded Kraft paper in sealed tube aging systems. Duplicate mineral oil systems were retrofilled with natural ester fluid at 250 and 750 hours at 170 and 160°C, respectively.

remained above 25% of unaged paper. At the end of test (3000 hours) at 160°C, the natural ester system was 61%; the retrofill system was 40%. At the end of test at 170°C, the natural ester system reached 40% of unaged; the retrofill system reached 36%.

Degree of Polymerization: D_vP over time is shown in Fig. 2. As in tensile strength, the retrofill rate of paper degradation as measured by D_vP changed from that of mineral oil to that of natural ester.

Paper in mineral oil fell below 200 D_vP between 1500 and 2000 hours at 160° C and 500-750 hours at 170°C. At 3000 hours, both the natural ester and retrofill systems remained above 300 D_vP at 160°C, and slightly above 200 D_vP at 170°C.

Furanic Compounds: Furanic compounds found in insulating fluid are the result of cellulose degradation, and can be used to monitor the insulation degradation of in-service transformers [6]. The furanic compounds content of the insulating fluids over time are shown in Fig. 3.

The amounts of furanic compounds (total content of 2-furaldehyde, 5-hydroxymethyl-2-furfural, 2-acetyl furan, and 5-methyl-2-furfural) found in the natural ester and retrofill systems remained an order of magnitude lower than those found in the mineral oil system.

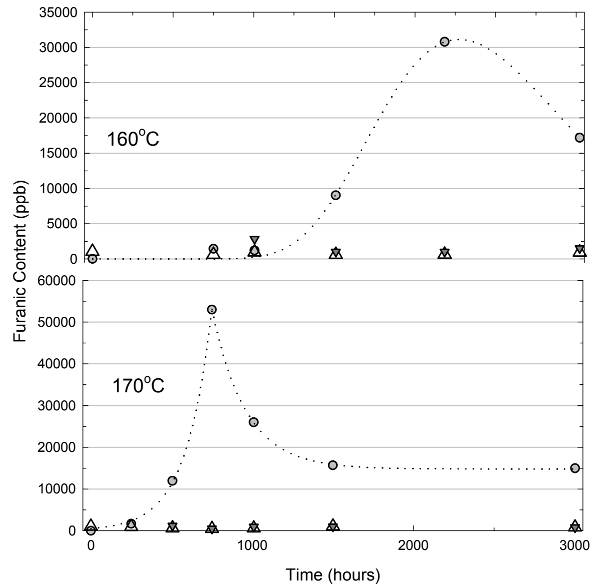

Figure 3: Furanic content *versus* time at temperature for thermally upgraded Kraft paper in sealed tube aging systems. Duplicate mineral oil systems were retrofilled with natural ester fluid at 250 and 750 hours at 170 and 160°C, respectively.

Water Content: Water is produced during the degradation of cellulose, and accelerates further breakdown. The water contents of paper over time is shown in Fig 4.

The paper in both the natural ester and retrofill systems remained dry, falling well below the initial water content. The paper in the mineral oil systems became very wet, reaching 6 wt%.

Discussion

The tensile strength, D_vP, and furanic content results establish that the aging rate of thermally upgraded Kraft paper initially aged in mineral oil can be modified by retrofilling with natural ester insulating fluid. Upon retrofilling, the rate of paper degradation changes from that of paper in mineral oil to the slower rate of paper in natural ester fluid.

At both temperatures the paper aged in mineral oil degraded beyond three recognized IEEE end-of-life criteria [7]: 50% tensile strength, 25% tensile strength, and 200 D_vP. The paper in natural ester and retrofill paper did not reach any end-of-life point at 160°C. At 170°C, the paper aged in natural ester fluid reached only the 50% tensile strength end-of-life point. The retrofilled paper reached 50% tensile strength end-of-life and nearly reached 200 D_vP.

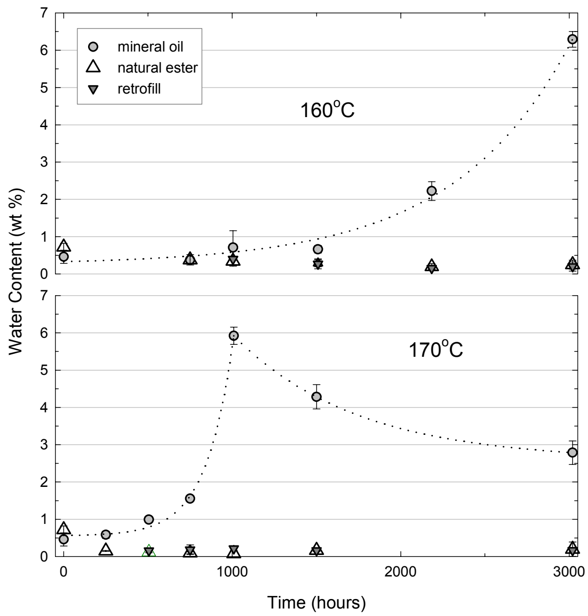

Figure 4: Water content *versus* time at temperature for thermally upgraded Kraft paper in sealed tube aging systems. Duplicate mineral oil systems were retrofilled with natural ester fluid at 250 and 750 hours at 170 and 160°C, respectively.

The water in paper data provides a rationale for the contrast in paper degradation rates between mineral oil and natural ester fluid. Firstly, the presence of water accelerates cellulose aging. Secondly, as paper thermally degrades it produces water, promoting further degradation through hydrolysis.

Natural esters have a greater affinity for water than does mineral oil, so less water will remain in the paper as the water partitions itself between headspace, paper, and fluid. Water is consumed by hydrolysis of the natural ester, producing free fatty acids. These may react with the cellulose backbone via transesterification and protect the cellulose from hydrolysis.

References

[1] C.P. McShane, G.A. Gauger, J. Luksich, "Fire Resistant Natural Ester Dielectric Fluid and Novel Insulation System for Its Use", IEEE/PES Transmission & Distribution Conference, April 12-16, 1999, New Orleans, LA USA

[2] "Standard test procedure for sealed tube aging of liquid-immersed transformer insulation", Annex A, "IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers", IEEE Std C57.100-1999, June 26, 1999, IEEE, New York, USA

[3] C.P. McShane, K.J. Rapp, J.L. Corkran, G.A. Gauger, J. Luksich, "Aging of Paper Insulation in Natural Ester Dielectric Fluid", 2001 IEEE/PES Transmission & Distribution Conference, October 28 - November 2, 2001, Atlanta, GA USA

[4] C.P. McShane, K.J. Rapp, J.L. Corkran, G.A. Gauger, J. Luksich, "Aging of Plain Kraft Paper in Natural Ester Dielectric Fluid", IEEE/DEIS 14th International Conference on Dielectric Fluids, July 7-12, 2002, Graz, Austria

[5] C.P. McShane, K.J. Rapp, J.L. Corkran, J. Luksich, "Aging of Cotton/Kraft Blend Insulation Paper in Natural Ester Dielectric Fluid", TechCon 2003 Asia-Pacific, May 7-9, 2003, Sidney, Australia

[6] Unsworth, J., Mitchell, F. "Degradation of Electrical Insulating Paper Monitored with High Performance Liquid Chromatography", IEEE Trans EI, Vol. 25, No. 4, pp. 737-746, Aug 1999

[7] "IEEE Guide for Loading Mineral-Oil-Immersed Transformers", IEEE Std C57.91-1995, April 25, 1996, IEEE, New York, USA