Envirotemp™ FR3™ Fluid

Reference Data

Loading Guide A and B Factors for Envirotemp FR3 Fluid and Thermally Upgraded Kraft Insulation

R2110

INTRODUCTION

The IEEE® transformer loading guide defines transformer insulation life versus temperature for thermally upgraded Kraft paper in mineral oil insulation systems in terms of "A" and "B" factors in an exponential model. Sealed-tube aging studies compared thermally upgraded Kraft paper in Envirotemp FR3 fluid to the same paper in mineral oil. The aging studies were done at 130, 150, 160, and 170°C. Tensile strength and degree of polymerization data were used to determine the time to insulation end-of-life of the paper/fluid systems at each temperature. "A" factors for paper/mineral oil and paper/Envirotemp FR3 fluid systems were calculated, giving insulation life versus temperature equations. The temperature giving unit insulation life of paper/mineral oil from this experiment (112°C) is comparable with that defined in the IEEE loading guide (110°C). The unit insulation life temperature for the paper/ Envirotemp FR3 fluid system is calculated to be 131°C (21°C higher than the paper/mineral oil system). The experimentally determined "A" factor for Envirotemp FR3 fluid and thermally upgraded Kraft insulation is calculated to be 7.82×10^{-17}.

BACKGROUND

IEEE Std. C57.91™-1995 standard [1] defines transformer insulation life as a function of winding hottest-spot temperature and is normalized to transformer insulation life at 110°C (1 per unit insulation life for mineral oil and thermally upgraded Kraft paper continuously operated at 80°C winding hottest-spot rise over a 30°C ambient).

The IEEE transformer insulation life as a function of temperature, shown in Figure 1, is given as:

$$\mathrm{life}(T) := A \cdot e^{\left(\frac{B}{T+273}\right)} \quad \text{where} \quad \begin{bmatrix} A \\ B \end{bmatrix} := \begin{bmatrix} 9.80\cdot10^{-18} \\ 15000 \end{bmatrix}$$

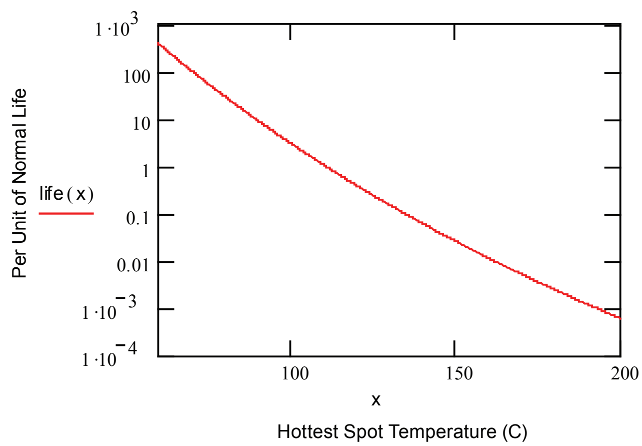

Figure 1.
Unit normal life versus hottest spot temperature from "IEEE Guide for Loading Mineral-Oil-Immersed Transformers", IEEE C57.91™-1995 standard.

Benchmark insulation end-of-life points at 110°C from IEEE Std. C57.91 standard, as well as times to insulation end-of-life calculated for higher temperatures, are given in Table 1.

PROCEDURE

Three sealed tube aging experiments were carried out using paper/fluid systems based on IEEE Std.C57.100-1999 standard Annex A "Standard test procedure for sealed tube aging of liquid-immersed transformer insulation" [2]. The first experiment compared the insulation aging rates of thermally upgraded paper in mineral oil with the same paper in Envirotemp FR3 fluid at 130, 150, and 170°C [3]. The second experiment simulated an Envirotemp FR3 fluid retrofill of an in-service mineral oil transformer. This experiment was carried out at 160 and 170°C [4]. The data from the mineral oil/ paper and Envirotemp FR3 fluid/paper reference systems are included in this "A" factor determination. Another experiment compared the insulation aging rates of paper in mixtures of Envirotemp FR3 fluid and mineral oil [5]. The 160 and 170°C mineral oil/paper and Envirotemp FR3 fluid/paper reference system results through 2000 hours are used here.

TABLE 1
Normal insulation life of a well-dried, oxygen-free 65°C average winding temperature rise insulation system at the reference temperature of 110°C [times at 150, 160, 170°C calculated using t = life(T) x endpoint]. From "IEEE Guide for Loading Mineral-Oil-Immersed Transformers", IEEE Std. C57.91™-1995 standard.

	Time to End Point (hrs)			
End-of-Life Basis	110°C	150°C	160°C	170°C
50% retained tensile strength	65,000 (7.4 yrs)	1,602	706	323
25% retained tensile strength	135,000 (15.4 yrs)	3,327	1,467	671
200 degrees of polymerization	150,000 (17.1 yrs)	3,697	1,630	746
IEEE composite "normal" life	180,000 (20.5 yrs)			

TABLE 2
Time to insulation life end point, in hours and unit life of IEEE Std. C57.91 standard unit life for paper in mineral oil and Envirotemp FR3 fluid calculated from curve fits of experimental results. A double exponential model was used except for mineral oil systems at 150°C

		Time to End Point (hrs)			Unit Life (Time to End Point)/(IEEE 110°C Basis)		
	Temperature	Tensile Strength		DvP	Tensile Strength		DvP
Fluid	(°C)	50%	25%	200	50%	25%	200
Mineral oil	150	3,179 [2]	4,086 [2,*]	3,462 [1]	0.049	0.030	0.023
	160	1,401	2,678	1,800	0.022	0.020	0.012
	170	384	742	534	0.0059	0.0055	0.0036
Envirotemp FR3 fluid	160	5,920	13,530 *	13,050 *	0.091	0.100	0.087
	170	1,400	6,107 *	3,335	0.022	0.045	0.022

* extrapolated [1] single exponential: $y(t)=ae^{bt}$ [2] sigmoidal: $y(t)=\frac{a}{1+e^{-\left(\frac{t-t_0}{b}\right)}}$ double exponential: $y(t)=ae^{-bt}+ce^{-dt}$

RESULTS

At 130°C, neither the paper/mineral oil system nor the Envirotemp FR3 fluid/paper system reached any IEEE benchmark end-of-life points by the end of the test. At 150°C, the Envirotemp FR3 fluid/paper systems again did not reach benchmark end-of-life points.

Mineral oil/paper reached nearly all benchmark end-of-life points (50% retained tensile strength, 25% retained tensile strength, and 200 degrees of polymerization) at 150, 160, and 170°C. The one exception was 25% retained tensile strength at 150°C. The duration of the 150°C experiment was 4000 hours; we extrapolated the data to reach the 25% retained tensile strength time of 4086 hours.

Paper in Envirotemp FR3 fluid reached 50% retained tensile strength during the 160°C test duration, and 50% retained tensile strength and 200 degrees of polymerization at 170°C. The times to other end-of-life points were extrapolated from the test data.

For paper in mineral oil at 130°C, paper aging did not progress far enough to allow extrapolation to any benchmark end-of-life points. For paper in Envirotemp FR3 fluid, neither paper aging at 130°C nor 150°C progressed far enough to extrapolate to any benchmark end-of-life points. The determination of the mineral oil/paper "A" factor uses 150, 160, and 170°C data; "A" for Envirotemp FR3 fluid/paper uses 160 and 170°C data.

Generally, the most simple equation of physical significance that reasonably represents the data is used to model experimental results. A single exponential model fits much of the tensile data well. However, when extrapolating beyond the experimental data range, the single exponential model does not give realistic values of time to end-of-life. A double exponential model is usually used for degree of polymerization [6]. Except for mineral oil at 150°C, a double exponential model was used to fit both tensile and degree of polymerization aging data. The double exponential model gave realistic values when extrapolating beyond experimental data to estimate time to end-of-life.

Degree of polymerization and retained tensile strength results from the three experiments are used to estimate "A" factors for both the paper/mineral oil and paper/Envirotemp FR3 fluid systems. Because the temperature range over which the time to insulation end points were determined is small, the slope ("B" factor) of the unit life versus temperature curves is assumed to be parallel to that given in IEEE Std. C57.91 standard. The results are shown in Table 2 and Figure 2.

Assuming that the life versus temperature curve for Envirotemp FR3 fluid is parallel to the curve for mineral oil ("B" constant), the Table 2 unit life for each temperature and end point are used to estimate "A" (iterative Levenberg-Marquardt method). The estimated "A" factor is used to calculate the per unit insulation life at 110°C and the temperature giving unit insulation life (Table 3 and Figure 3). The temperature calculated from experimental data to give unit insulation life in mineral oil (112°C) is reasonably close to the temperature defined in IEEE Std. C57.91 standard (110°C).

TABLE 3
Comparison of insulation unit life of thermally upgraded Kraft paper in Envirotemp FR3 fluid and mineral oil.

		Mineral Oil	Envirotemp FR3 fluid
"A" factor		9.80×10^{-18}	7.82×10^{-17}
Unit Life	110°C	1.00	7.98
	131°C	0.13	1.00

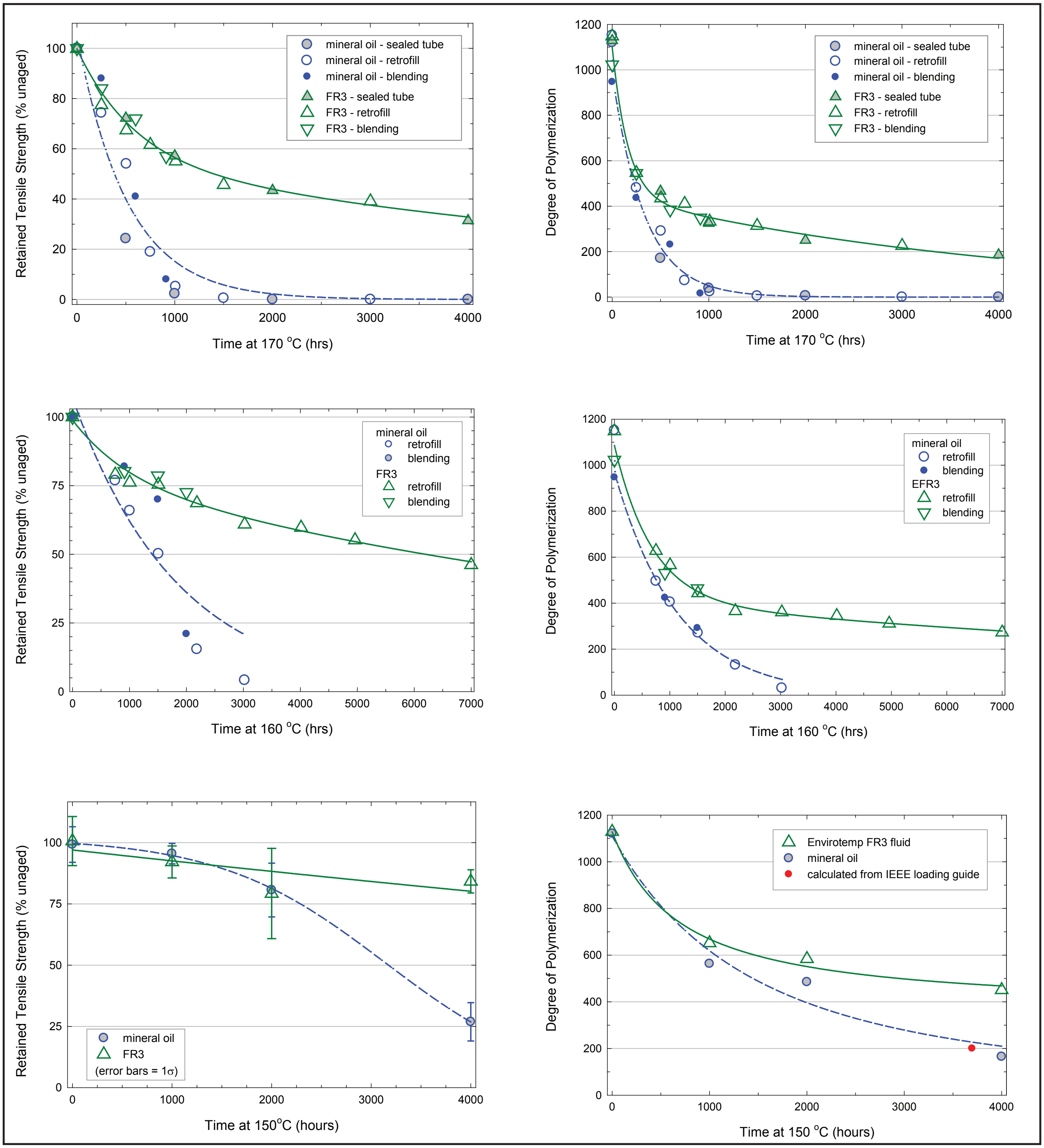

Figure 2.
Sealed tube accelerated aging test results for paper/mineral oil and paper/Envirotemp FR3 fluid systems.

CONCLUSIONS

The "A" and "B" factors for thermally upgraded Kraft paper in Envirotemp FR3 fluid are estimated to be 7.82×10^{-17} and 15,000, respectively. For transformers, paper in Envirotemp FR3 fluid at 101°C hottest-spot temperature rise should age no more rapidly than paper in mineral oil at 80°C hottest-spot rise.

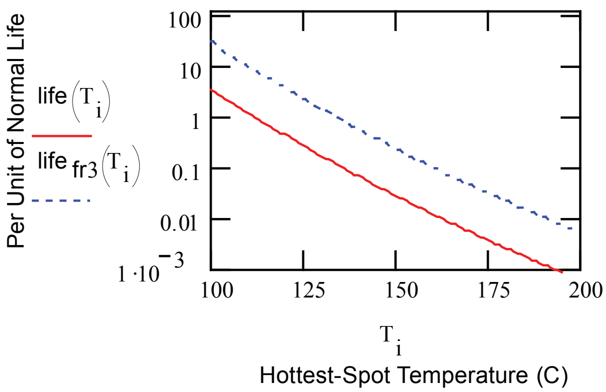

Figure 3.
Calculated transformer insulation life versus winding hottest-spot temperature of thermally upgraded Kraft paper in Envirotemp FR3 fluid compared to the IEEE curve for the same paper in mineral oil.

REFERENCED DOCUMENTS

[1] "IEEE Guide for Loading Mineral-Oil-Immersed Transformers", IEEE Std C57.91-1995

[2] "IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers", IEEE Std C57.100-1999

[3] "Sealed Bomb Accelerated Thermal Aging Study", K. Rapp, Report No. ML 152-2000, Thomas A. Edison Technical Center

[4] "Sealed Thermal Aging Study for Retrofills", K. Rapp, Report No. ML 215-2001, Thomas A. Edison Technical Center

[5] "FR3™/T.O. Aging Study for 2000 Hours at 160/170°C", K. Rapp, Report No. ML 300-2002, Thomas A. Edison Technical Center

[6] Transformerboard II, H.P. Moser and V. Dahinden, 2nd Ed., p. 171, H. Weidmann AG, 1999

Cargill Industrial Specialties
P.O. Box 5700, MS 66
Minneapolis, MN 55440-5700
1-800-842-3631
envirotempfluids.com