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Fire Resistant Natural Ester Dielectric Fluid and Novel Insulation System for Its Use

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Abstract: Insulation systems for electrical power and distribution transformers are being re-evaluated based on total owning cost from both economic and risk exposure perspectives. A recently developed high fire point dielectric fluid, based on natural esters, has superior safety, environmental, and health properties compared to current dielectric fluids. An insulation system developed for this fluid addresses the lower inherent resistance of esters to oxidation. Accelerated transformer life testing compares transformers using standard mineral oil to those with the natural esters dielectric system. Results of these accelerated life tests show the ester fluid to be suitable for transformer use and suggest the possibility of extended insulation life compared to mineral oil systems.

Keywords: Dielectric coolant, dielectric materials, dielectric measurements, ester insulation, life estimation, liquid dielectric materials, power transformer insulation testing, oil insulation, transformers

I. INTRODUCTION

It is becoming increasingly apparent that dielectric fluids must provide a better balance of functional performance inside the transformer versus environmental impact in the event of release. Inside the transformer, a stable, chemically inert fluid having good thermal and dielectric properties is desired. Externally, the fluid should become environmentally benign, and be readily and completely biodegradable.

Liquid-filled transformers have long used mineral oils as the insulating fluid. Halogenated dielectric fluids, principally Askarel fluids, once promoted for their excellent fire safety properties, are now undesirable due to health hazards and environmental persistence. The phase-out of Askarels led to a succession of other “non-flammable” halogenated fluids such as perchloroethylene, chlorobenzenes, and chloro-fluorocarbons. These have since completely exited the new transformer market.

In applications where fire safety is a concern, silicone oils and high molecular weight hydrocarbons (HMWH) continue to be the prevalent “less flammable” fluid choices. To a much lesser extent, synthetic ester-based fluids are also used.

Synthetic ester dielectric fluids, most commonly aliphatic polyol esters, have suitable dielectric properties and are more readily biodegradable than mineral oil and HMWH fluids. Due to their high cost compared to other less-flammable fluids, synthetic esters are used mainly in specialty applications such as traction and mobile transformers.

Natural esters have been considered unsuitable for use in transformers, although evaluations in capacitor applications hint at considerable potential [1,2]. Their susceptibility to oxidation has been a primary obstacle to utilization as a dielectric fluid. However, modern transformer design practices, along with suitable fluid additives and minor design modifications, compensates for this characteristic.

Outside the transformer, oxidative degradation is regarded as an environmentally beneficial property. The application of natural esters in transformers can achieve a balance of desirable transformer and external environmental properties not found in other dielectric fluids. An attractive source of natural esters are the seed-based edible oils. Used mainly in foodstuffs, these agricultural commodity oils are a renewable resource increasingly utilized in non-food industrial applications.

This paper evaluates, side by side with mineral oil, full scale accelerated aging of a recently developed insulation system based on natural food-grade seed oil esters. Transformer insulation life is primarily related to aging of the cellulose paper [3]. By exposing the insulation system to elevated levels of thermal, mechanical, and electrical stresses, transformer end-of-life can be found in a practical amount of time. The normal life expectancy can then be extrapolated from the life span found for high stress levels.

The IEEE Standard Test Procedure for Thermal Evaluation of Oil-Immersed Distribution Transformers [4], often referred to as the “Lockie Method”, is the protocol used to evaluate the suitability of this insulation system for transformer applications. The normal expected life of a transformer, operating as defined in the IEEE loading guide [3] at a 30°C average ambient, is about 20 years. The average duration of this test is 500% of expected life, or the equivalent of 100 years of operation.

II. APPARATUS

A. Test Specimens

Three identical sets of test transformers were constructed as summarized in Table 1. Test specimens were slightly modified production 1PH, 15kVA, 7200/12470Y-120/240V transformers. The design change consisted of a modest decrease in coil ducting to simplify reaching the desired hot spot temperatures. All specimens included thermocouples to monitor top oil temperature, a nitrogen blanket in the headspace, and a headspace pressure transducer. Solid insulation was kraft paper thermally upgraded for 65°C rise use.

All bushing gaskets were nitrile. Units A3, B3, and C3 contained mineral oil and used nitrile cover gaskets. All other units contained the ester fluid and had either Viton® or nitrile cover gaskets. Viton was selected to reduce the oxygen permeability of the system.

Transformers designated as “thermal monitors” were fitted with strategically placed thermocouples wound inside the coils to determine the hottest-spot temperature. The thermal monitors carried load current with their secondary windings short-circuited. This allowed rated secondary current to flow while minimizing the voltage gradients on the coil thermocouples.

To safeguard the more easily oxidized esters, the fluid blend contained food-grade antioxidant additives. Some of the ester-filled transformers were fitted with a proprietary headspace oxygen absorber system. The system consists of an absorber material contained in an oxygen-permeable container. The container serves to isolate the absorber from the dielectric fluid and still allow oxygen to reach the active material. Two absorber formulations were evaluated.

B. Test Cells

Three test cells, designed specifically to meet the IEEE thermal evaluation requirements, were constructed – one test cell for each test temperature. Each cell contained five test transformers, one of which was a thermal monitor. The primaries of the five specimens were wired in series to ensure that all units carried the same current and therefore were subjected to the same thermal stress.

Current levels of the 7.2kV primaries were automatically controlled to maintain the hottest-spot temperature. The secondary windings were energized at the rated 240V. Data loggers collected 60 channels of test cell data. Test conditions were maintained using motor-driven current and voltage autotransformers. The autotransformers were in turn regulated by dedicated programmable logic controllers monitoring the data loggers.

Table 1. Transformer test cell specimens for accelerated aging evaluation.

Test Unit	Base Fluid[a]	O_2 Absorber	Cover Gasket
1 (thermal monitor)	natural ester	none	Viton[b]
2	natural ester	empty container	Viton
3	mineral oil	none	nitrile
4	natural ester	formulation I	Viton
5	natural ester	formulation II	Viton
C4b (spare)	natural ester	none	nitrile

[a] CPS Envirotemp® FR3 ester or Exxon Univolt® inhibited mineral oil

[b] Viton is a registered trademark of DuPont Dow Elastomers

III. PROCEDURE

A. Test Parameters

Transformer loading was determined using (1), the Arrhenius reaction rate adapted for insulation deterioration of 65°C rise transformers [3]. This model uses the hottest-spot temperature T (°K) to calculate expected life h (hrs). Fig. 1 shows the normal expected life curve.

$$\log_{10} \text{life(h)} = -11.269 + \frac{6328.8}{T} \qquad (1)$$

The thermal evaluation test specifies that the transformers under test survive 500% of expected life at test temperature. Three test temperatures were selected. Test time accumulated only when the hottest-spot temperature was no lower than 3°C below set point.

B. Test Sequence

The total aging time, five times the expected life at temperature, was divided into about 10 test periods. Each period, representing half the expected life calculated from (1), consisted of maintaining the hottest spot temperature for a prescribed number of hours, then allowing the temperature to fall to ambient. This elevated/ambient temperature cycle was repeated four times per period. Cooling to ambient took about nine hours. Time at ambient was at least 24 hours. Rise time back to temperature set point was about six hours.

After each completed accelerated aging period, the specimens were taken off-line and subjected to a series of

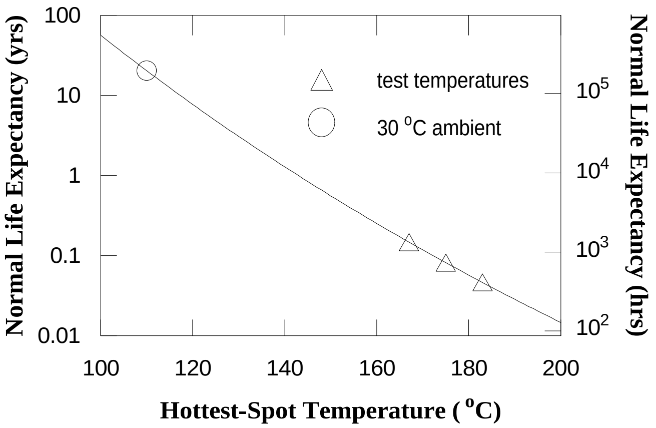

Fig. 1. Liquid-type transformer life expectancy for 65°C insulation systems based on the hottest-spot temperature [4].

Table 2. Test parameters for transformer accelerated aging evaluation.

Test Cell	A	B	C
Hottest-Spot Temperature (°C)	167	175	183
Expected Life (hrs)	1,302	721	407
500% Expected Life (hrs)	6,510	3,604	2,036
Aging Periods	11	9	10
Cycles/Aging Period	4	4	4
Duration (hrs/cycle)	150	100	50
Stress Tests (performed off-line at the completion of each aging period)			
Short Circuit	25 x rated current for 2 sec		
Full Wave Impulse	62 kV (65% of new unit value)		
Applied Potential	22 kV, 60 Hz, 1 min (65% of new)		
Induced Potential	400 Hz, 130% rated, 7200 cycles		

four electrical/mechanical stress tests. Dielectric fluid samples were also taken after each test period. Table 2 shows the accelerated aging and stress test parameters.

IV. RESULTS

Units A5, B5, C2, C3, and C4b completed 500% of normal expected life and were disassembled for inspection. Units A1, A2, A3, B1, B2, B3, C1, and C5 completed the 500% of expected life and remained on test. Units A4, B4, and C4 were removed from test early in the process due to transient test system malfunctions.

A. Visual Inspection

Tear-down and visual inspection of ester-filled units A5 and B5 showed the high-to-low insulation barrier discolored and brittle in the hottest-spot region. The paper away from the hottest-spot was in good condition. Neither unit contained free water or sludge. Gaskets showed a slight decrease in flexibility.

In the severest temperature cell, ester-filled units C2 and C4b were in better overall condition than mineral oil unit C3. The kraft paper at the hottest-spot in C2 was charred and moderately deteriorated. The paper away from the hot-spot was still in good condition. C4b showed notably less paper deterioration than did C2[1]. Neither unit contained free water or sludge, and both tanks were free of corrosion. The gaskets in C2 (Viton/nitrile) and C4b (nitrile) were flexible with little set, and appeared to be in good condition.

Tear-down and visual inspection of mineral oil unit C3 revealed significant deterioration throughout the transformer. The kraft paper solid insulation was almost entirely deteriorated, with the hottest-spot well dispersed around the coil assemblies. The tank bottom contained free water, sludge, and signs of corrosion. The wire insulation and gaskets were hard and brittle.

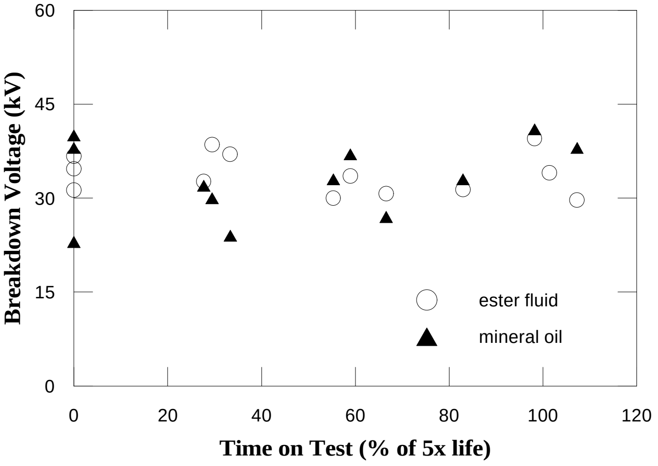

Fig. 2. Dielectric Breakdown Voltage [5] of ester fluid and mineral oil versus aging time as a percent of five times normal expected life.

B. Fluid Analysis

Dielectric strength is shown in Fig. 2. The breakdown voltage remained between 30-40kV for all ester fluids over the course of the test. Most mineral oil samples were in this range, although three samples fell below the 30 kV acceptable level for new fluid [6].

Flash and fire points, shown in Fig. 3, dropped only slightly over the life of the test. Viscosity, stable over the life of the tests, is shown in Fig. 4. Moisture content, represented as percent of fluid saturation, is presented in Fig. 5.

V. CONCLUSIONS

The main objective of submitting the natural ester-based insulation system to accelerated aging tests was to determine its suitability for use in distribution-class transformers. The transformers survived the full five times expected life test

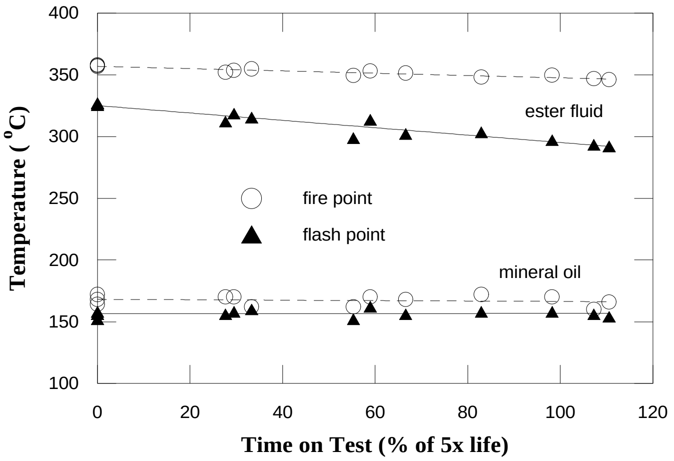

Fig. 3. Flash and fire points [7] of ester fluid and mineral oil versus aging time as a percent of five times normal expected life.

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[1] C2 and C4 experienced a thermal runaway condition due to power shedding affecting the HVAC system on a very hot day. C4b replaced C4 after this unusual event.

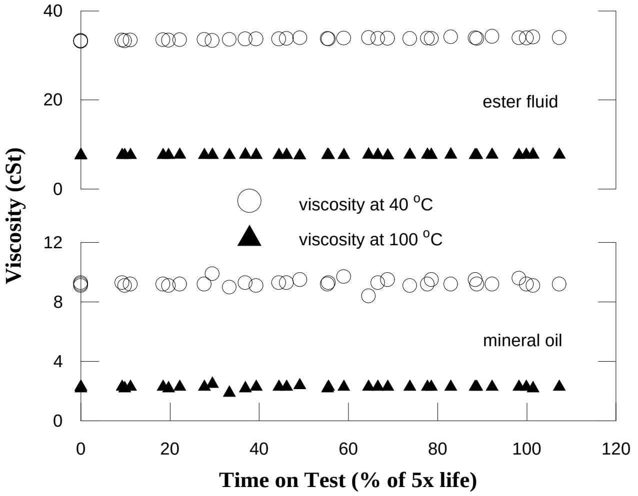

Fig. 4. Viscosity of ester fluid and mineral oil versus aging time as a percent of five times the normal expected life.

duration. Visual inspection showed less deterioration in the ester-filled units than was found in the mineral oil units. No undue oxidative deterioration of the ester fluid was observed. Based on these results, this ester dielectric fluid used in conjunction with standard transformer materials successfully completed the requirements of 65°C rise transformer insulation systems. The precautionary choice of Viton as a cover gasket material was found to be unnecessary.

The key fluid performance characteristics (dielectric strength, flash point, fire point, and viscosity) remained close to the new fluid values. The changes in the indicators frequently used to monitor fluid condition (moisture content, neutralization number, DC leakage, interfacial tension, and dissipation factor) were higher than found in mineral oils. The indicator levels found are characteristic of ester-based fluids and had no observable impact on transformer performance or life.

The ester fluid dissipation factor and absolute moisture content, higher than those found in the mineral oil, reflect the chemical nature of the natural ester fluid. The ester fluid has a much higher tolerance for moisture, having a saturation level of greater than 1000 ppm of water compared to 40-60 ppm at 25°C for standard mineral oil [9]. This higher moisture content results in some hydrolysis of the fluid, forming the mild free fatty acids typical of ester-based fluids.

The water present inside a properly sealed transformer increases when cellulose degrades. The high moisture affinity of the ester fluid hampers the formation of free water over the temperatures seen in this test. The presence of free water in the mineral oil unit is a result of the low moisture saturation point forcing condensation and pooling at room temperature.

The aging characteristics of ester-based fluids generally differ from those of mineral oil. Interpreting the significance of the fluid condition indicating properties must take the differences into account. Changes that are insignificant for the ester fluid might appear to be significant in a mineral oil system.

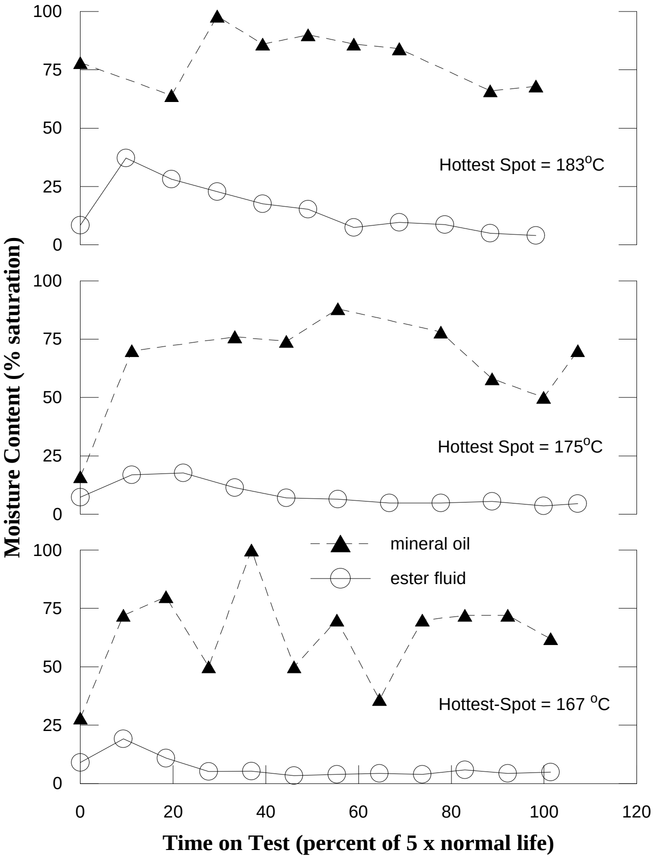

Fig. 5. Moisture content [8], as percent of fluid saturation, of mineral oil and ester fluid versus aging time as a percent of five times normal expected life.

Visual inspections of the paper insulation after aging suggest that the ester fluid extends paper life. These results correlate with the preliminary small-scale accelerated life tests conducted prior to the Lockie test.

Continuing these “Lockie Method” aging tests beyond the 500% expected life to actual failure will assist us in formulating specific loss of life curves for insulation systems based on this ester fluid. Additional small scale accelerated life tests to evaluate paper aging in the ester fluid and mineral oil will provide degree of polymerization and tensile strength measurements, allowing a direct quantitative comparison.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

[1] F.M. Clark, *Insulating Materials for Design and Engineering Practice*, New York, Wiley, 1962, pp. 210-218, 342-345

[2] A.C.M. Wilson, *Insulating Liquids: Their Uses, Manufacture and Properties*, New York, Institution of Electrical Engineers, London and New York, Peter Peregrinus, 1980, p. 171

[3] ANSI/IEEE C57.91-1981 "IEEE Guide for Loading Mineral-Oil-Immersed Overhead and Pad-Mounted Distribution Transformers Rated 500 kVA and Less with 65 °C or 55 °C Average Winding Rise", *Distribution, Power, and Regulating Transformers*, New York, Institute of Electrical and Electronics Engineers Inc, 1995

Note: The referenced loading guide was current when this test began. It is superseded by IEEE Standard C57.91-1995 "IEEE Guide for Loading Mineral Oil Immersed Transformers", New York, Institute of Electrical and Electronics Engineers Inc, 1996

[4] ANSI/IEEE C57.100-1986 "IEEE Standard Test Procedure for Thermal Evaluation of Oil-Immersed Distribution Transformers", *Distribution, Power, and Regulating Transformers*, New York, Institute of Electrical and Electronics Engineers Inc, 1995

[5] ASTM D 877-87 "Standard Test Methods for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes", 1998 Annual Book of ASTM Standards, Vol. 10.03, *Electrical Insulating Liquids and Gases; Electrical Protective Equipment*, American Society for Testing and Materials, 1998

[6] ASTM D 3487-88 "Specification for Mineral Insulating Oil Used in Electrical Apparatus", 1998 Annual Book of ASTM Standards, Vol. 10.03, *Electrical Insulating Liquids and Gases; Electrical Protective Equipment*, American Society for Testing and Materials, 1998

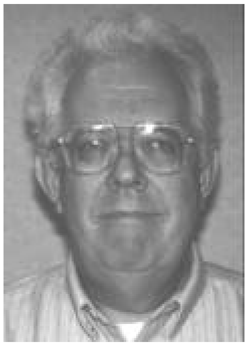
[7] ASTM D 92-90 "Standard Test Method for Flash and Fire Points by Cleveland Open Cup", 1996 Annual Book of ASTM Standards, Vol. 5.01, *Petroleum Products, Lubricants, and Fossil Fuels*, American Society for Testing and Materials, 1996

[8] ASTM D 1533-96 "Standard Test Methods for Water in Insulating Liquids (Karl Fischer Reaction Method)", 1998 Annual Book of ASTM Standards, Vol. 10.03, *Electrical Insulating Liquids and Gases; Electrical Protective Equipment*, American Society for Testing and Materials, 1998

[9] "Univolt 60 and N61 Water Saturation Curve", *Univolt Electrical Insulating Oils*, Lubetext DG-2C, Exxon Corp, 1988, p. 7

VIII. BIOGRAPHIES

C. Patrick McShane was born in Winnebago, Minnesota, on April 27, 1947. He received a BS in Electrical Engineering from Marquette University in 1970, and an MS in Engineering Management from the Milwaukee School of Engineering in 1998. Currently the Product Line Manager for Dielectric Fluids at Cooper Power Systems Transformer Products, his employment experience includes International Area Manager for RTE Corp. and Regional Technical Director for the State of Sao Paulo (Brazil) Rural Electrification Program. His professional activities include USA Delegate IEC TC99, IEC TC99 Liaison to TC64, IEC TC89 Expert Delegate, Chair ASTM W.G. D-5222, and W.G. Chair IEEE TC Dielectric Fluids Subcommittee C57.121. Several of his proposals have been adopted by USA Codes and Standards (NEC, NESC, FMRC). He has presented papers at domestic and international engineering conferences including IEEE, EPRI, Doble, and CIRED. He is a Factory Mutual ANSI Accreditation Standards Reviewer.



Gary A. Gauger received his BS in Chemistry from the University of Wisconsin-Oshkosh in 1963, and studied organic chemistry in the University of Wisconsin-Milwaukee Graduate Program during 1970-1972. Professional affiliations include the American Chemical Society Division of Petroleum Chemistry and Division of Environmental Chemistry, American Association for the Advancement of Science, and the ASTM D-27 Dielectric Liquids and Gases Committee. Gary joined Cooper Power (then McGraw-Edison) in 1970 as an Analytical Scientist. He has been involved in dielectric materials development since 1975, and is currently Manager of Analytical Services for the Thomas A. Edison Technical Center.

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