

# Natural Ester Dielectric Fluid Development

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**Abstract**—Since the early 1980s, Cooper Power Systems has been actively involved in exploring and developing ester-based dielectric fluids. Introduced in 1984, our first commercialized ester was a synthetic polyol ester, developed primarily as an environmentally acceptable Askarel substitute. Although its technical performance is very good, the cost is prohibitive for most applications. The desirable properties of the polyol ester spurred exploration into other, more cost-effective, ester chemistries. This led to the evaluation of a natural (vegetable oil) ester dielectric coolant having many of the same performance advantages of synthetic esters, but much more economical. The major disadvantages of the natural esters are their inherent susceptibility to oxidation and higher pour point. We undertook a massive natural ester research and development program beginning in the early 1990s. Significant improvement low temperature flow was achieved. Oxidation inhibitors together with proper method-of-use overcome the oxidation stability issues. In many ways the natural esters perform better than the less-flammable fluids they replace, and offer significant advantages for applications where naphthenic mineral oils are traditionally applied. Although initially developed for distribution transformers, application in medium and large power transformers is becoming more common. This paper summarizes our laboratory and field experience.

**Index Terms**—dielectric liquids, dielectric materials, insulation life, environmentally preferred, less-flammable dielectric fluid, natural ester, oil insulation, polyol ester, thermo-hydrolytic degradation, thermo-kinetic degradation

## I. INTRODUCTION

THIS paper addresses the development and performance of natural ester dielectric coolants. In 1984, we completed the development of a high fire point synthetic ester substitute for Askarels (PCB). It was intended for specialty applications, primarily in compact railroad traction transformers, but also in scientific apparatus such as Klyston modulators and particle accelerator power supplies. These applications required low viscosity, high lubricity, and very low pour points in order to justify their high cost. Traction transformer service provided the first signs that esters possess properties that allow improved transformer thermal life expectancy. Although compact transformers retrofilled with synthetic ester fluid were getting older, their failure rates decreased dramatically. This led to our interest in determining if natural esters, having significantly lower cost than its synthetic cousin, could be formulated to improve oxidation resistance and low temperature flow. Optimized formulations, combined with suitable equipment design, provide ample compensation for the oxidation stability and pour point characteristics.

## II. KEY PROPERTIES

In addition to the key material selection criteria of performance and value, overall environmental and total life cycle costs are increasingly important factors. Due in part to the PCB legacy and tightening regulation of petroleum products, minimizing the potential for unfavorable environmental and health risks was paramount. These criteria intensified the interest in natural esters, as many are inherently non-toxic, readily biodegradable, do not produce harmful, persistent thermal by-products, can be readably reconditioned or recycled, and have ample availability from renewable sources.

The most practical source of natural esters are seed oils, most of which are edible and traded in the commodity market. In 1993, two-dozen food grade base oils and blends were evaluated. Some oils contained a high percentage of unsaturated fatty acids, resulting in lower viscosity and better low-temperature properties. Others had a higher percent of saturated fats, which improved oxidation stability. The ratio between the two types of fatty acid oils requires a careful balance.

After an optimal balance was selected, the next step was to improve the oxidation and pour point performance. In 1994, the process for selecting additives began. Included in the study were several food-grade materials. After completing small scale accelerated aging and other tests, the combination and quantities of additives was selected. In the end, additives were found that did not adversely affect the non-toxicity or the quick biodegradation rate of the base oil.

### A. Environmental Safety

The final formulation was tested for biodegradability, and can be classified in the most favorable EPA categories of “ultimately biodegradable” and “readily biodegradable” [15,16]. It was then tested for acute aquatic toxicity [17]. The original formulation failed that test, with 100% mortality within 24 hours of the test. The cause of the mortality was determined to be the oxidation inhibitor, even though it was food grade! After further research, an equally effective oxidation inhibitor, having equal electrical and biodegradable qualities, was identified. The results of the acute toxicity test for the new formulation were the opposite of the first formulation: zero mortality through the standard test period of 96 hours at 1000 mg/kg [18].

While the EPA is still considering SPCC rule modifications to fully realize the intent of the Edible Oil Regulatory Reform Act, other entities have modified their standards to differentiate between edible and non-edible oils. For example, a transformer having Factory Mutual Global Approval, using natural esters having environmental properties verified by recognized third parties (i.e. EPA Environmental Technology

Verification), can have more than five times the threshold volume of mineral oil before containment is required [19].

### B. Fire Safety

One consequence of the aging transformer infrastructure in the US is an increase in the rate of transformer failures. A small but significant percentage of substation transformer failures are “eventful”, often resulting in oil fires that are difficult to extinguish. In addition, the fire can also propagate to nearby equipment and buildings. When GSUs are involved, often the generators must be shut down, resulting in very high consequential losses.

Such fires can be avoided by using natural ester dielectric fluids listed as “less flammable” by a Nationally Recognized Testing Laboratory. Based on testing and field history, Factory Mutual Global increased the threshold volume of approved fluid considered an equivalent safeguard to space separation, fire suppression systems, and fire barriers, from 1,000 to 10,000 gallons [19]. This reduces the minimum separation distance for both equipment-equipment spacing (Table I) and equipment-building spacing (Table II).

### C. Material Compatibility and Accelerated Life Tests

Small-scale laboratory testing focused on the compatibility and aging characteristics of common transformer materials in natural ester fluid. The materials tested performed as well or better in natural ester fluid than in mineral oil. Full-scale accelerated aging studies using production transformers evaluated the insulation system as a whole [1].

Common nitrile gasket formulations shrink about 5% in natural ester and swell about 5% in mineral oil. Both conductive and non-conductive EPDM insulation and jacket materials are severely deteriorated by mineral oil, swelling to 2-3 times the original volume. The same materials in natural ester fluid swelled 1-7%. Kraft paper aged in natural ester retains much more of its tensile strength compared to the same paper aged in mineral oil [1-5]. We observed that the rate of impregnation in paper and pressboard is significantly slower than mineral oil.

Coking tendency tests indicate that the natural ester fluid resists coke formation on hot metals. For example, significant coke formation was seen on hot bare copper in mineral oil even with a nitrogen blanket. Under the same current loading conditions, coking was nearly undetectable in natural ester.

Mineral oil subjected to elevated temperatures and air exposure darkens much more than the natural ester, forming decomposition precipitates (Fig.1). A disadvantage of natural

esters is the tendency of thin films of fluid to polymerize. On hot surfaces exposed to air they polymerize at a much faster rate than mineral oils. Although the polymerized fluid has excellent dielectric strength, the films may affect mechanism movements and should be avoided. This is not an issue unless an impregnated core/coil is un-tanked and stored for several weeks. Natural ester formulations using higher oleic oils decrease somewhat the rate of thin film oxidation, but at a cost of higher viscosity and pour point.

Based on the positive results obtained in the small-scale tests, we decided to proceed with full-scale testing. This was no minor decision, as these tests require considerable investments of both capital and time. Per ANSI/IEEE C57.100 [20], a new insulation system should be evaluated and compared to mineral oil. Duplicate sets of production transformers are placed in three cells, each energized and run at a different pre-determined hottest-spot temperature (Fig. 3). The transformers are periodically subjected to impulse, ac withstand, and through-fault tests. All transformers survived the test sequence.

A natural ester transformer from each cell, along with a mineral oil transformer, underwent post-evaluation tear down analyses. The mineral oil had a cloudy appearance due to water saturation, and had free water at the bottom of the tank. The insulation was very dark and brittle. The gaskets were also brittle. The companion natural ester fluid was clear and bright, had no free water, and showed significantly less paper degradation. The gaskets remained pliable. Solubility of water in mineral oil and natural ester is shown in Fig. 2.

Since no failures were seen during the standard method test duration, the remaining natural ester units continued on test. Failures were finally seen at approximately three times the C57.100 requirement (Table III).

In order to understand why the natural ester full-scale test results were so unexpectedly positive, thermal aging tests focused on the relative aging rates of Kraft insulation in natural ester fluid versus mineral oil. The method employed was essentially the sealed tube method described in the current IEEE C57.100 [10]. These tests showed a consequential retardation of paper aging rates in natural ester fluid [1], and could lead to significant changes in transformer technology and application.

### D. Kraft Paper Aging Rates

IEEE characterizes the transformer insulation life *versus* temperature for thermally upgraded Kraft paper in mineral oil

TABLE I  
SEPARATION DISTANCE BETWEEN OUTDOOR LIQUID INSULATED TRANSFORMERS AND BUILDINGS [19]

Liquid	Approved Transformer Or Equivalent	Liquid Volume gal (m <sup>3</sup> )	Horizontal Distance ft (m) (based on construction type)			Vertical Distance ft (m)
			2 Hr Fire Resistant	Non-Combustible	Combustible	
Approved Less- Flammable fluid	Yes	N/A	3 (0.9)	3 (0.9)	3 (0.9)	5 (1.5)
	No	≤10,000 (38)	5 (1.5)	5 (1.5)	25 (7.6)	50 (15.2)
		>10,000 (38)	15 (4.6)	15 (4.6)	25 (7.6)	50 (15.2)
mineral oil or unapproved fluid	N/A	<500 (1.9)	5 (1.5)	15 (4.6)	25 (7.6)	25 (7.6)
		500-5,000 (1.9-19)	15 (4.6)	25 (7.6)	50 (15.2)	50 (15.2)
		>5,000 (19)	25 (7.6)	50 (15.2)	100 (30.5)	100 (30.5)

TABLE II  
OUTDOOR LIQUID-INSULATED EQUIPMENT SEPARATION DISTANCE [19]

Liquid	Approved Transformer or Equivalent	Liquid Volume gal (m <sup>3</sup> )	Distance ft (m)
Approved Less-Flammable fluid	Yes	N/A	3 (0.9)
	No	≤10,000 (38)	5 (1.5)
		>10,000 (38)	25 (7.6)
Mineral oil or unapproved fluid	N/A	<500 (1.9)	5 (1.5)
		500-5,000 (1.9-19)	25 (7.6)
		>5,000 (19)	50 (15.2)

insulation systems in terms of “A” and “B” factors in an exponential model [10]. Sealed tube aging studies evaluated thermally upgraded Kraft paper in natural ester fluid and in mineral oil [2]. Tensile strength and degree of polymerization data were used to determine the time to insulation end-of-life for the paper/fluid systems at each test temperature. “A” factors for paper/mineral oil and paper/natural ester systems were calculated, giving insulation life versus temperature equations. The “A” factor for thermally upgraded Kraft insulation in natural ester fluid calculated from the experimental data is  $7.82 \times 10^{-17}$ . The slope (“B” factor) was assumed to be the same as for the mineral oil system.

Based on these data, the temperature at which the paper/mineral oil insulation life is unity is calculated to be 112°C. This is consistent with the unit life temperature defined in the IEEE loading guide (110°C). The unit insulation life temperature for the paper/natural ester system is calculated to be 131°C (21°C higher than that defined for paper/mineral oil system). See Fig. 4.

#### E. Oxidation Stability

Numerous discussions about the oxidation stability of seed oils took place early in the development of natural ester dielectric fluids. The historically held opinion that the oxidative stability of natural esters was insufficient excluded them from consideration as dielectric fluids. Many times these opinions were based on the results of oxidation stability tests such as ASTM 2112 and 2440. These tests, meant to evaluate the inhibitors used in mineral oil, are not indicators of in-service performance. However, they are sometimes mistakenly used in that way. When these methods are applied to natural esters, the esters do poorly.

The attention given to oxidation stability is a consequence of the degradation products of mineral oil precipitating out as sludge. This sludge coats the inner surfaces of a transformer, eventually reducing heat transfer and causes excessively high operating temperatures. Natural ester fluids oxidize differently

TABLE III  
TRANSFORMER ACCELERATED AGING PARAMETERS AND RESULTS [1]

	Hours (equivalent “normal” years)		
	167 °C	175 °C	183 °C
Hottest-Spot Temperature			
“Normal” Life (a)	1,302 (21)	721(21)	407 (21)
Test Life (5x “normal” life) (b)	6,510 (105)	3,604 (105)	2,036 (105)
Actual Time to Failure	15,240 (246) (c)	10,186 (297)	6,623 (342)

(a) ANSI/IEEE C57.91-1981

(b) ANSI/IEEE C57.100-1986

(c) end of test – no failure

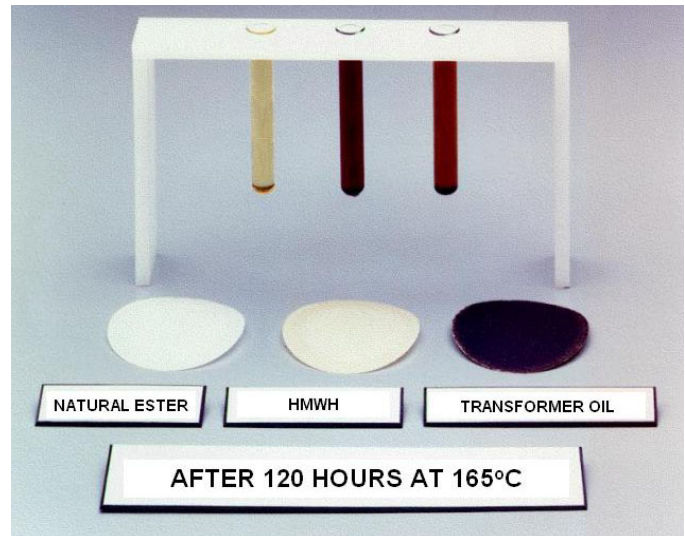


Fig. 1. Natural ester fluid, high molecular weight hydrocarbon, and mineral oil after oven aging. Filterable particulate oxidation products shown on filter papers.

than mineral oils: they do not generate sludge precipitates, but instead tend to eventually polymerize and can be seen as an increase in viscosity. Oxidation is a concern in natural ester dielectric fluids, but for different reasons than in mineral oil.

Some attempts to formulate a natural ester fluid meeting the mineral oil oxidation stability requirements blend natural esters with less environmentally friendly synthetics. Others combine seed oils modified to have high oleic content with a significantly increased amount of stabilizer chemicals. The tradeoff is higher viscosity and increased toxicity. Although these techniques can result in fluids meeting the mineral oil oxidation requirements, they are still not suitable for use in free-breathing transformers. Our approach was to maintain cold temperature flow and low toxicity by developing a natural ester dielectric fluid with adequate oxidation stability in a sealed transformer design [1].

Doble Engineering developed the Power Factor Valued Oxidation (PFVO) and Sludge Free Life (SFL) tests as indicators of the oxidation stability of transformer oil [11]. The PFVO and SFL tests applied to natural ester dielectric fluids offer more realistic operating environment than many

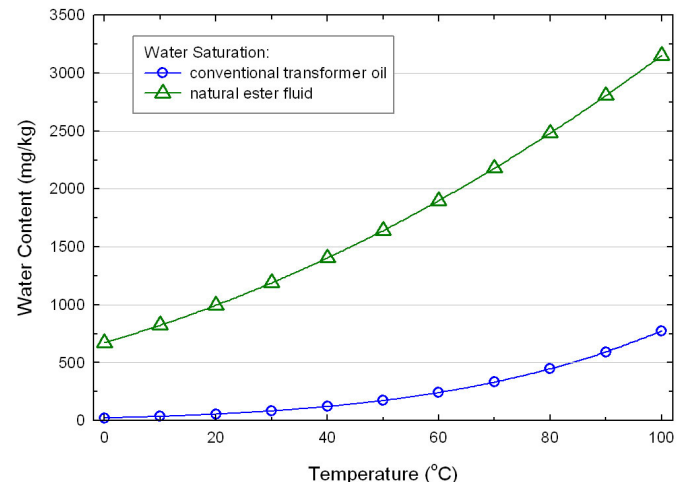


Fig. 2. 100% water saturation versus temperature of natural ester fluid [7] and conventional transformer oil [8].

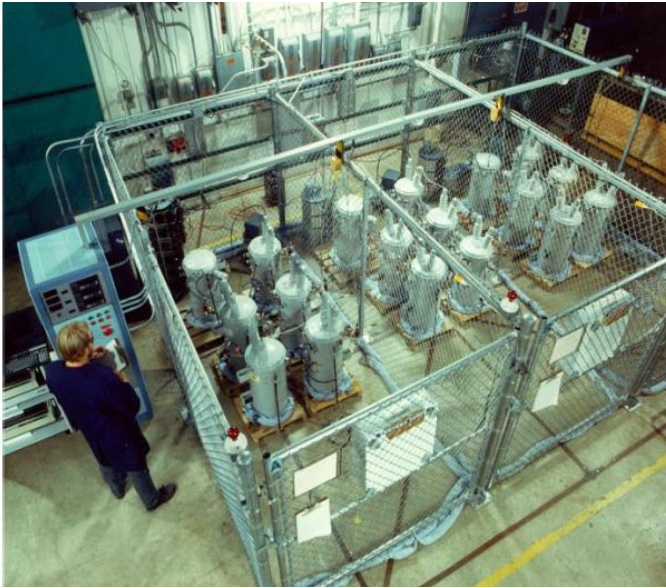


Fig. 3. Test cells for full-scale accelerated aging test sequence.

other oxidation test methods. Fig. 5 shows the power factor of soy-based natural ester, high oleic sunflower-based natural ester, and synthetic polyol ester after 140 hours of PFVO testing at 95°C [21]. All of the fluids tested had acceptable SFL. Only the soy-based natural ester completed PFVO testing below the maximum acceptance limit of 4.5% power factor.

A transformer developing an air leak above the fluid level exposes the fluid to gradual oxidation at the fluid-headspace interface. A multi-year study evaluating the consequences of using natural ester fluid in free-breathing transformers is ongoing [12]. After 7 years, oxidation of the natural ester fluid is detectable as a modest 8.6% increase in viscosity. Significant antioxidant additive depletion is evident. However, the transformers are still operating normally and pass periodic IEEE C57.100 electrical stress tests at regular intervals. Despite these results, we recommend only using natural ester dielectric fluids in sealed transformer designs.

Pole and pad mount transformers filled with natural ester fluid, in their 9<sup>th</sup> year of continuous operation, show very little

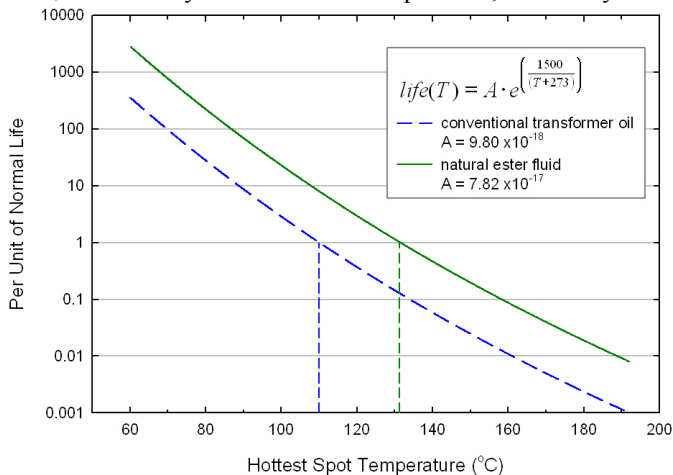


Fig. 4. Calculated transformer insulation life vs. winding hottest-spot temperature of thermally upgraded Kraft paper in natural ester fluid [9] compared to the published IEEE curve for the same paper in mineral oil [10].

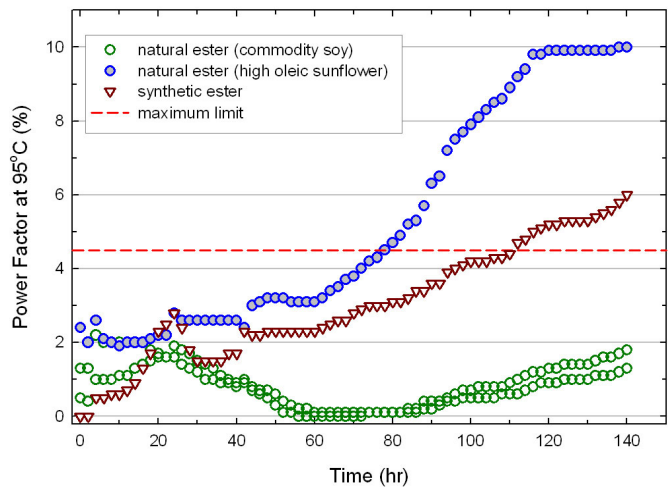


Fig. 5. Power factor valued oxidation results for two natural ester fluid formulations and a synthetic ester [21].

change in functional fluid properties [13]. A pole unit was visually inspected and tested after eight years of continuous operation. Both the fluid and internal components appeared as like-new condition. The results of the PFVO and SFL tests, full and analyses of in-service transformers demonstrate that natural ester dielectric fluid maintains excellent stability in sealed design transformers.

### III. FIELD EXPERIENCE

The first prototype natural ester-filled transformers were installed in 1996. Since then, more than 10,000 transformers have been built or refilled with natural ester fluid, ranging in size from 10 kVA to 200MVA at voltages as high as 230kV.

Several dozen transformers have been accessible for periodic fluid testing, including dissolved gas analysis. Changes in these transformers over time correspond with the changes predicted by accelerated life testing. In short, the types of changes seen in mineral oil are also seen in the natural ester fluids [14].

As the fluid ages, whether mineral oil or natural ester, acid number, water content, and dissipation factor tend to increase. Resistivity and interfacial tension tend to decrease. Natural esters do not differ in the type of change, but differ in baseline values and change magnitude. Faults generate the same types of dissolved gases seen in mineral oil: arcing produces acetylene, hot metal faults produce hydrocarbon gases, and paper aging produces carbon oxides. These properties can be used, as for mineral oil, as diagnostic indicators.

### IV. CONCLUSIONS

The growing demands for improved fire and environmental safety of distribution and small power transformers triggered the development of natural ester dielectric fluid formulations and methods of use. Based on its success in terms of performance, material compatibility, electrical and thermal properties, accelerated life testing, and field experience, we found that the application of natural esters met these

requirements. ASTM published a natural ester standard [22], and a working group draft of an IEEE acceptance and maintenance guide is nearing completion. Several specifications for utilities and other power delivery entities have begun the conversion.

Because of its success in distribution and small power applications, natural esters are beginning to see use in both new medium and large power transformers, and retrofitting existing units.

## V. REFERENCES

- [1] C. P. McShane, G. Gauger, and J. Luksich, "Fire Resistant Natural Ester Dielectric Fluid and Novel Insulation System for Its Use", IEEE/PES Transmission & Distribution Conf., 1999, New Orleans, USA.
- [2] C. P. McShane, K. J. Rapp, J. L. Corkran, G. A. Gauger, and J. Luksich, "Aging of paper insulation in natural ester dielectric fluid", IEEE/PES Transmission & Distribution Conf, 2001, Atlanta, USA.
- [3] C. P. McShane, K. J. Rapp, J. L. Corkran, G. A. Gauger, and J. Luksich, "Aging of plain Kraft paper in natural ester dielectric fluid", IEEE/DEIS Conf. on Dielectric Fluids, 2002, Graz, Austria.
- [4] C. P. McShane, K. J. Rapp, J. L. Corkran, and J. Luksich, "Aging of cotton/Kraft blend insulation paper in natural ester dielectric fluid", TechCon Asia-Pacific, 2003, Sidney, Australia.
- [5] C. P. McShane, J. L. Corkran, K. J. Rapp, and J. Luksich, "Aging of paper insulation retrofilled with natural ester dielectric fluid", IEEE Conf. on Electrical Insulation and Dielectric Phenomena, 2003, Albuquerque, USA.
- [6] H. P. Moser and V. Dahinden, Transformerboard II, 2nd ed., Rapperswil: H. Weidmann AG, 1999, pp. 137-144
- [7] L. Lewand, "Laboratory evaluation of several synthetic and agricultural-based dielectric liquids", Doble Int. Client Conf, 5E, 2001, Boston, USA.
- [8] *IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment*, C57.106-2002, New York: IEEE, Nov. 2002, p. 9
- [9] J. Luksich, "IEEE loading guide A and B factors for Envirotemp FR3 fluid and thermally upgraded Kraft insulation", Eng. Dev. Report TP03-DR-009, Rev. 1, Cooper Power Systems, June 12, 2003
- [10] *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*, IEEE Standard C57.91-1995, April 1996
- [11] F. S. Oliver, "Doble Power Factor Valued Oxidation Tests," Doble Conference Minutes 1960, Insulating Fluids/ 10-401, pgs 1-9
- [12] "Oxidation stability of Envirotemp FR3 fluid as measured by power factor valued oxidation," Dielectric Fluids Engineering Report CP0502, Cooper Power Systems, Jan. 20, 2005
- [13] "Field analysis of Envirotemp FR3 fluid in sealed versus free-breathing transformers," Dielectric Fluids Engineering Report CP0414, Cooper Power Systems, Dec. 13, 2004
- [14] J. Luksich, "Evaluating new and in-service vegetable oil dielectric fluids", presented at the Weidmann-ACTI 3rd Annual Technical Conference, Sacramento, CA, Nov.8-10, 2004
- [15] "Aerobic Aquatic Degradation", OPPTS 835.3100, "Fate, Transport, and Transformation Test Guidelines", EPA Publication 712-C-98-075, Office of Prevention, Pesticides, and Toxic Substances, US Environmental Protection Agency, January 1998
- [16] "Ready Biodegradation", OPPTS 835.3110, "Fate, Transport, and Transformation Test Guidelines", EPA Publication 712-C-98-076, Office of Prevention, Pesticides, and Toxic Substances, US Environmental Protection Agency, January 1998
- [17] "Fish, Acute Toxicity Test", OECD 203, Effects on Biotic Systems, OECD Guidelines for the Testing of Chemicals, Organization for Economic Cooperation and Development, July 17, 1992
- [18] "Final Report: Acute Trout Toxicity Testing for Two Envirotemp FR3 Formulations"; GlobalTox International Consultants, Guelph, ON, Canada, Dec. 1, 1999
- [19] "5-4 Transformers", Section 2.3.1.1.1 Separation Distance, Property Loss Prevention Data Sheets, Factory Mutual Global, May 2003
- [20] *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*, IEEE Standard C57.91-1986, 1986

- [21] C. Locke, "Laboratory analysis of power factor valued oxidation and sludge free life on ester fluids", Test Report 59762, Doble Engineering Co., Watertown, MA, Nov. 5, 2004
- [22] *Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus*, ASTM Standard D6871-03, Aug. 2003

## VI. BIOGRAPHIES



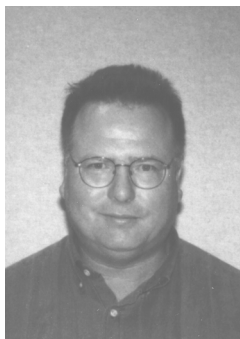
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