Natural ester oil application in liquid filled transformers

Natural ester (vegetable oil) dielectric fluids are an innovative alternative to the mineral oil coolant commonly used in distribution and power transformers. They have preferable environmental properties compared to mineral oil, most notably rapid and complete biodegradation.

Vegetable oil dielectric fluids are a recent addition to the category of less-flammable dielectric fluids [1 to 10]. Less-flammable fluids, sometimes called high fire-point fluids, were introduced in the mid-1970s as alternatives to Askarels for installations requiring a high degree of fire safety.

Table 1: Comparison of some specification values for new as-received mineral oil and natural ester fluid.

Property		ASTM method	Mineral oil ASTM D3487	Natural ester ASTM D6871
Electrical				
Dielectric strength (kV)		D1816 (2 mm gap)	≥35	≥35
Dissipation (%)	25°C	D924	≤0,05	≤0,20
	100°C		≤0,30	≤4,0
Chemical				
Water content (mg/kg)		D1533	≤35	≤200
Acid number (mg KOH/g)		D974	≤0,03	≤0,6
Physical				
Colour		D1500	≤0,5	≤1,0
Visual examination		D1524	clear & bright	clear & bright
Relative density		D1298	≤0,91	≤0,96
Flash point (°C)		D92	≥145	≥275
Fire point (°C)		D92	–	≥300
Viscosity (cSt)	100°C	D445	≤3,0	≤15
	40°C		≤12,0	≤50
Pour point (°C)		D97	≤−40	≤−10

Interfacial tension (dyne/cm)	D971	≥40	–

Less-flammable fluids come in a variety of chemical types. First were the high molecular weight hydrocarbons (HMWH) and silicones, followed in the 1980s by synthetic fluids such as polyalphaolefins (PAO) and polyolesters (POE). Of these, the POEs easily have the most attractive environmental properties. However, their relatively high cost spurred the search for more affordable alternatives.

Vegetable oils (e.g. rapeseed, soybean, sunflower), or "natural" esters, are chemically similar to the POEs and share many of their properties. The natural esters have excellent environmental properties, a high degree of fire safety, and are shown to retard the degradation of paper insulation.

Available commercially since the late 1990s in distribution transformers, they are now beginning to see use in power transformers. The application of vegetable oils in electrical apparatus is expanding beyond the boundaries of less-flammable fluids into applications where mineral oil is ordinarily used.

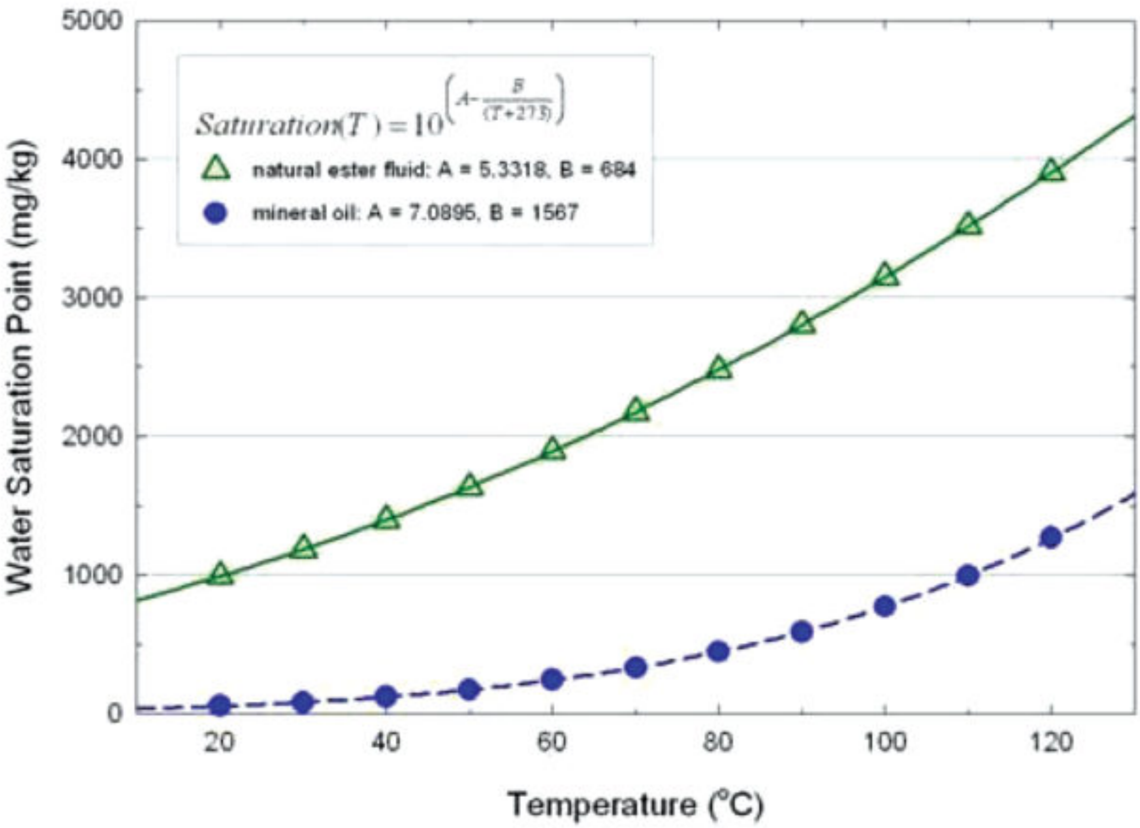

Fig. 1: Water saturation vs. temperature for natural ester fluid and conventional transformer oil [13, 14].

Mineral oil comparison

Petroleum mineral insulating oil is the most commonly used dielectric fluid in transformers. Vegetable oils are triacylglycerols (sometimes called triglycerides) and differ chemically from petroleum products. The differences in chemical composition are manifested in differences in fluid properties. Table 1 shows the American Society for Testing and Materials (ASTM International) acceptance limits of new mineral and vegetable oil fluids [11, 12] and illustrates the similarities and differences.

Dielectric strength

The fluid property most important to the function of a transformer is dielectric breakdown strength. The dielectric strength of vegetable oils must therefore be as good as mineral oil. This is reflected in the standards where the dielectric strength requirements for mineral and vegetable oils are the same.

Viscosity

Fluid viscosity (along with thermal expansion, thermal conductivity, and heat capacity) is used to optimise the transformer cooling design. The viscosity of vegetable oils is slightly higher than mineral oil. This is partially compensated for by other fluid thermal properties such that the transformer's thermal designs will likely be similar for mineral and vegetable oils.

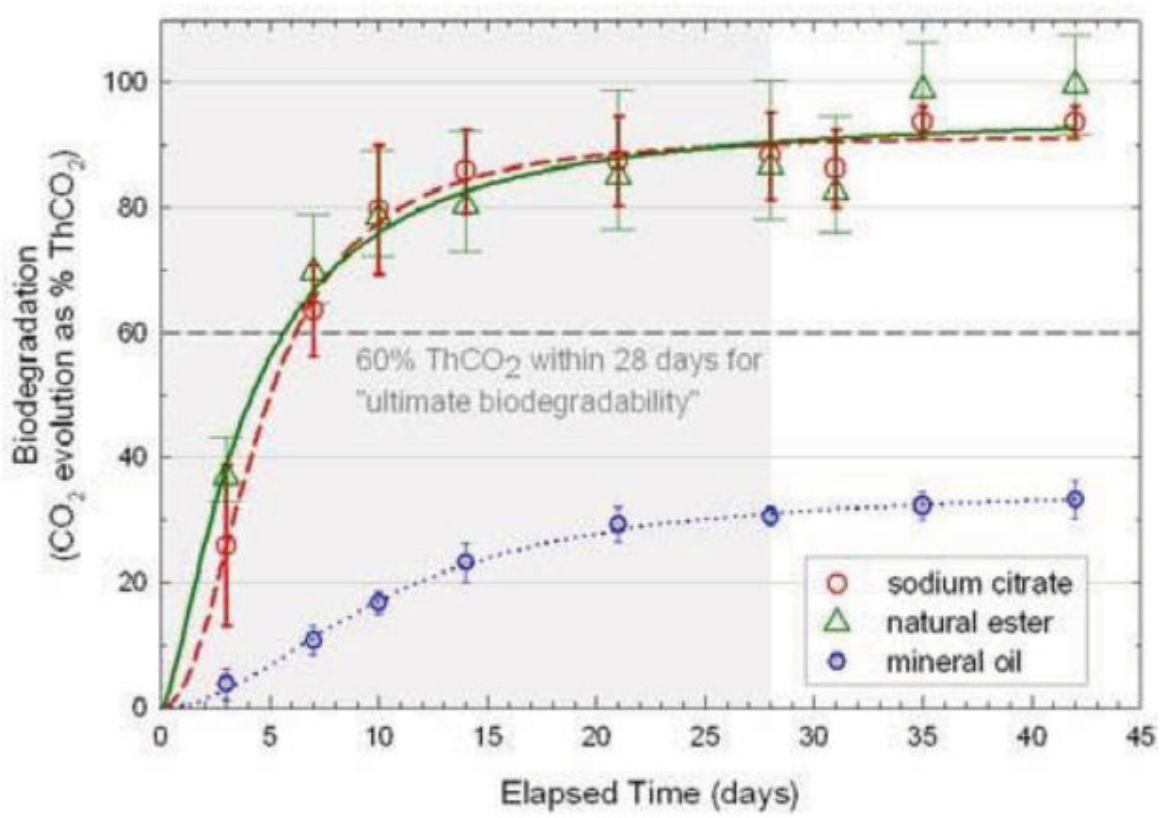

Fig. 2: Aquatic biodegradation of mineral oil, natural ester, and sodium citrate.

Water

Water content of natural ester fluid can be considerably different from mineral oil. Fig. 1 shows water saturation vs. temperature for mineral and vegetable oils. At room temperature, the water saturation of mineral oil is about 60 mg/kg [13]. Natural esters have room temperature saturations of approximately 1000 mg/kg [14]. The dielectric strength of an insulating fluid starts to decrease when the relative saturation increases to between 40 and 50%. Using saturation percentage instead of absolute water content allows direct comparisons between natural ester fluids and mineral oil to be made.

Oxidation

Not shown in Table 1 are oxidation stability criteria. Both mineral and vegetable oils are susceptible to oxidation, but oxidise differently.

The products of oxidation in mineral oil can react to form sludge precipitates. Additives can postpone oxidation in mineral oil. ASTM oxidation stability tests are designed to evaluate the mineral oil additives. They do not predict how oils will perform in service.

The ASTM specification for new mineral oil lists minimum acceptance values for oxidation stability [11]. These tests are not intended for vegetable oils; therefore vegetable oils perform poorly in these tests. However, vegetable oils oxidise differently than mineral oils. The products of oxidation do not form sludge precipitates. Instead, the oil eventually begins to thicken and ultimately polymerise.

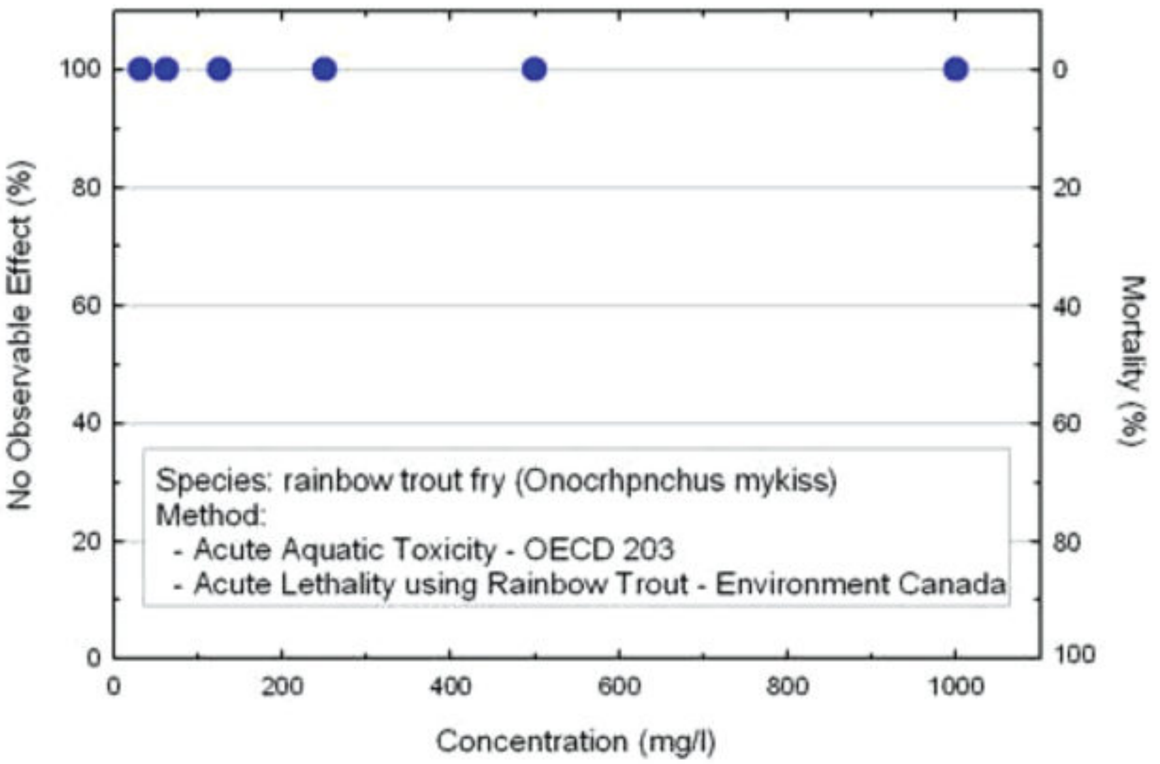

Fig. 3: Acute aquatic toxicity of natural ester fluid to juvenile trout.

The early stages of vegetable oil oxidation are seen as an increase in viscosity. This effect is most often seen in high surface area to volume situations (thin films). UV exposure also accelerates polymerisation. Tests intended to better represent oxidation performance in a transformer have been developed. Vegetable oils are shown to be acceptable for transformer use.

Oxidation is a concern in both mineral and vegetable oils, but for different reasons. Vegetable oils almost certainly will not be suitable for use in free-breathing transformers because of eventual viscosity changes and should be isolated from direct atmospheric contact, but do not form sludge in transformers. Mineral oils can produce sludge
in service.

In repair situations where the transformer or components are removed from the tank and exposed for weeks or months, thin films of vegetable oil may oxidise and eventually polymerise. Mineral oil in this circumstance is not as vulnerable.

Both mineral oil sludge and vegetable oil viscosity increase eventually affect the transformer in the same way – reduced thermal efficiency.

Table 2: Medium power applications using natural ester dielectric fluid.

Base (MVA)	Voltage (kV)		Manufacturer	Type
	High	Low		

200	161	19	Moloney	GSU
120	115	17,5	North American	GSU
50	69	12,47	Westinghouse	GSU
45	69	13,8	Westinghouse	Distribution
30	34,5	0,562	Fuji	Rectifier
30	115	6,9	GE	Distribution
27	37	0,654	Toshiba	Rectifier
25	19	13,2	Delta Star	Aux. Power
20	69	13,2	ABB	GSU
20	46	13,8	Ferranti-Packard	Distribution
18	69	20	Kuhlman	Distribution
14	69	4	GE	GSU
11	20	4,4	Allis Chalmers	Aux. Power
10	18	2,4	GE	Aux. Power
10	69	4,16	Uptegraff	Distribution
10	33	11	LEEEC (China)	Mobile
10	34,5	4,16	Cooper	Distribution

Other properties

Other fluid properties are useful primarily in transformer diagnostics, and have little or no effect on transformer operation. Values for dissipation factor, water content, and acid number are inherently higher in natural esters than compared to mineral oil; resistivity and interfacial tension are lower.

As the natural esters age in service, these properties change and are interpreted in the same way as for mineral oil. Dissipation, water content, and acid number tend to increase; interfacial tension and resistivity decrease.

The power factor of a new transformer is used as an indication that the solid insulation has been satisfactory dried during the manufacturing process. The fluid dissipation factor of vegetable oils is naturally higher compared to mineral oil. Depending on the type of transformer construction, this may affect the power factor of a new transformer.

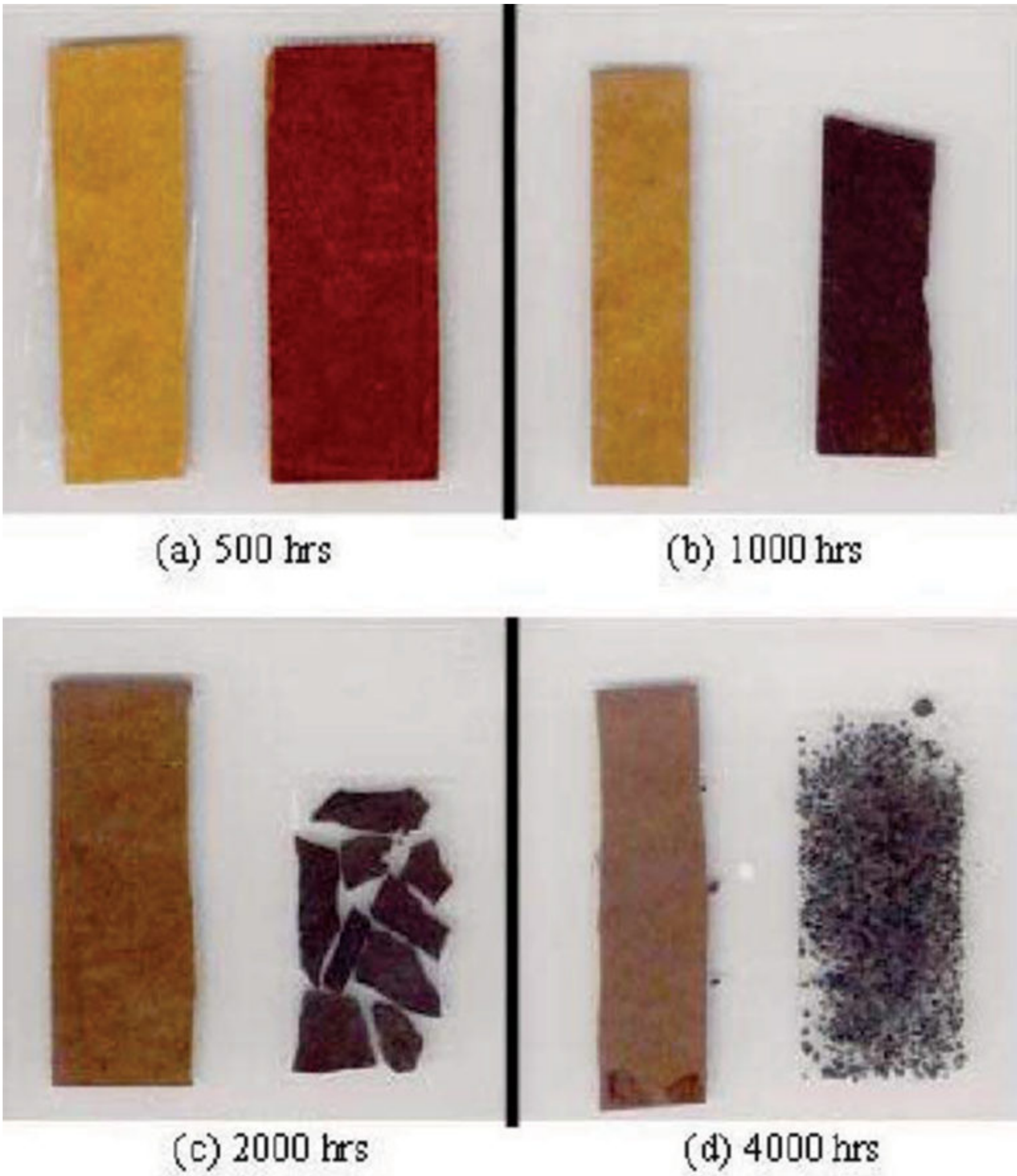

Fig. 4: Thermally upgraded Kraft paper after sealed tube aging in natural ester and mineral oil at 170°C [21]

Transformers using disk windings have oil as the majority of high-low space insulation. In this case the power factor may be as much as double that of an identical mineral oil transformer of identical insulation dryness.

This is less of a factor in distribution class transformers having mostly solid insulation in the high-low space. The effect of fluid type on the power factor should be taken into account when specifying a new transformer.

Environmental properties

The environmental properties of vegetable oils are excellent. They biodegrade quickly and completely and exhibit very low or no toxicity. Fig. 2 compares the aquatic biodegradation of mineral oil and vegetable oil. Fig. 3 shows the results of aquatic toxicity tests per OECD 203.

Vegetable oil dielectric fluids do not contain halogens, polynuclear aromatics, volatile or semi-volatile organics, or other compounds that can be present in mineral oils or other dielectric fluids.
Site assessment tests such as the determination of total petroleum hydrocarbons may, if not carefully done, indicate the presence of petroleum contamination where none exists.

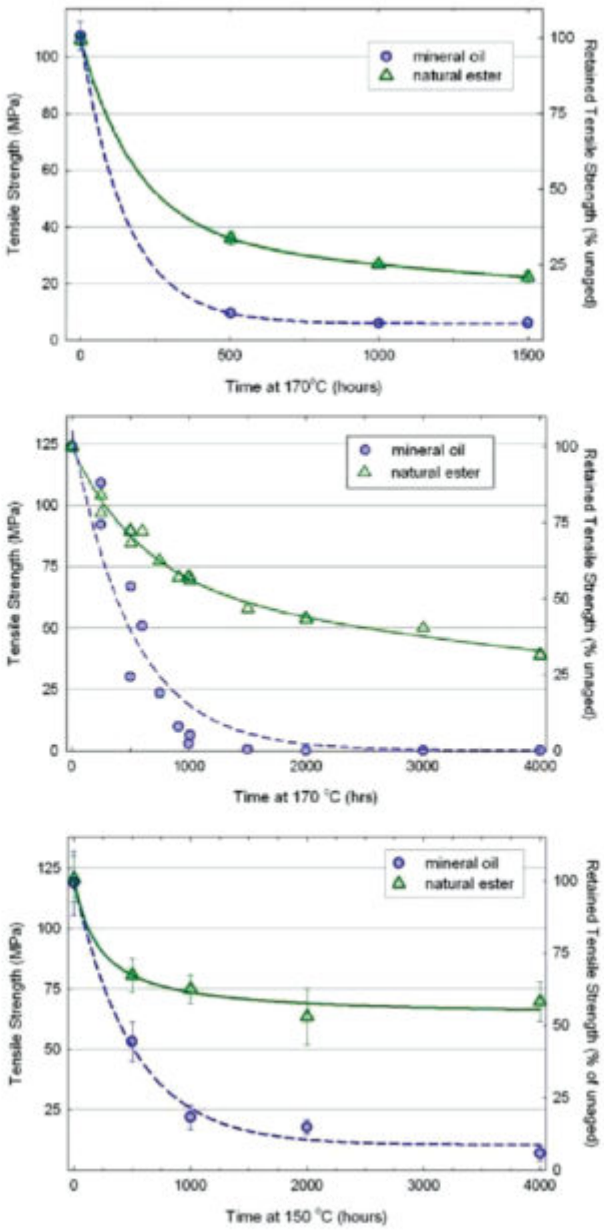

Fig. 5: Tensile strength, as MPa and % unaged, of insulation paper aged in sealed tubes with natural ester and mineral oil.

Fire safety

The fire safety of high fire point dielectric fluids is well known. Natural esters have the highest fire points in this class of dielectric fluid. Natural ester dielectric fluids have a fire point of 360°C and qualify as "K" class per IEC 61100. They have practical installation and regulatory advantages in many types of sites [15-19].

Thermal capability

Vegetable oil dielectric fluids differ noticeably from mineral oils in thermal degradation of both the solid insulation and the oil itself.

Kraft insulation

Kraft paper insulation, both plain and thermally upgraded, degrades more slowly in natural ester fluid than in mineral oil. A series of experiments establish that the thermal degradation of paper insulation decreases by a factor of five to eight times in natural ester compared to the degradation in mineral oil [20-24].

Fig. 4 shows actual paper samples during the course of the thermal aging experiments. Figs. 5 and 6 compare paper degradation in terms of tensile strength and degree of polymerisation.

The rate at which paper insulation degrades increases with both temperature and water content. A product of paper degradation is water, which serves to accelerate the aging. The slower paper degradation in natural ester fluid is explained by a sequence of mechanisms, starting with water equilibrium.

In Fig. 4, the papers on the left in photographs a-d, aged in natural ester, did not reach any IEEE end-of-life criteria [25]. The papers on the right, aged in mineral oil, reached the all of the IEEE retained tensile strength and degree of polymerisation endpoints by 1000 hours.

Natural esters can hold much more water than mineral oil (Fig. 1). In order to reach equilibrium, a greater amount of water must move from the paper into the fluid than in the mineral oil equilibrium. This reduces the water in the paper, thus reducing the aging due to water. This equilibrium shift is the main contributor to reduced aging rate.

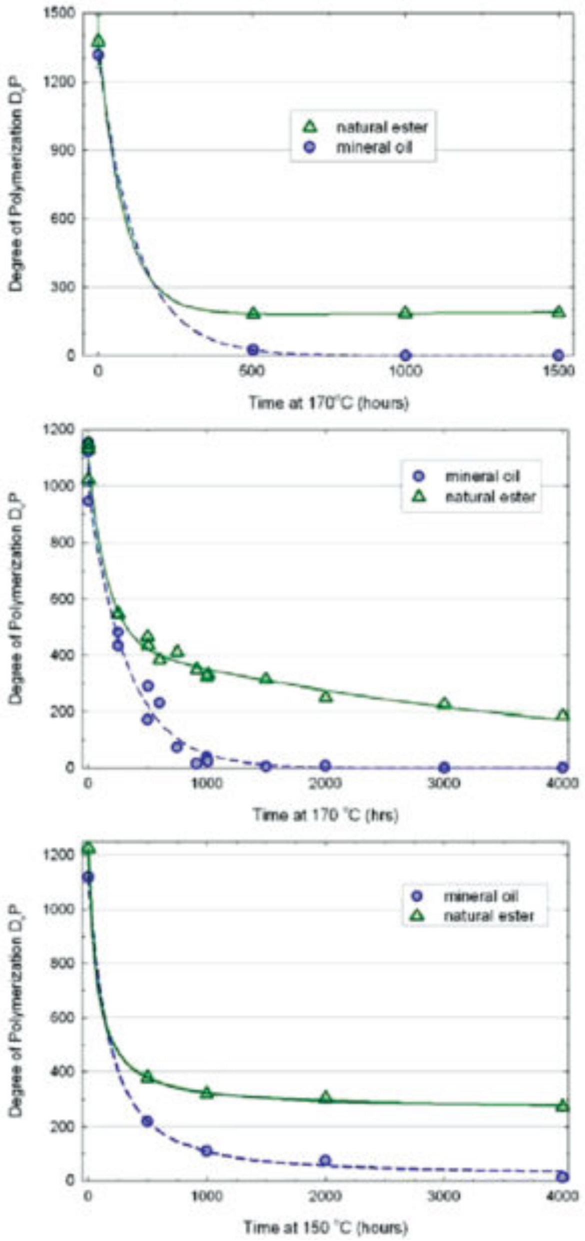

Fig. 6: Degree of polymerisation of insulation paper aged in sealed tubes with natural ester and mineral oil.

Once dissolved in the ester, water can hydrolyse the ester to form free fatty acids. These acids can then react with the paper itself in a chemical reaction called "transesterification", and act to provide a small amount of additional protection of the cellulose from hydrolytic attack. The cumulative effect is to slow the rate of paper aging.

The difference in aging rates translates into a 21°C higher permissible operating temperature for the natural ester/thermally upgraded Kraft paper system. Using the IEEE loading guide model [25], a hottest spot temperature rise of 86°C using natural ester will have the same insulation life as a hottest spot temperature rise of 65°C in mineral oil.

In Fig. 5, the top graph shows cotton/Kraft insulation paper at 170°C for 1500 hrs. Center graph shows thermally upgraded (treated) Kraft at 170°C for 4000 hrs. Bottom shows plain (untreated) Kraft paper insulation at 150°C for 4000 hrs. All insulation systems exhibit reduced rates of degradation in natural ester compared to those in mineral oil.

Thermal degradation of fluid

Accelerated aging studies using full-scale production transformers showed visually less fluid and component degradation in transformers using natural ester compared to identical transformers using mineral oil [2].

The same results were also seen in laboratory scale sealed tube aging systems. Fig. 7 shows the inside of the aging tubes after 4000 hours at 150°C. The tubes containing natural ester fluid remained clean. The tubes with mineral oil had large amounts of sludge and degradation products.

In Fig. 6, the top graph shows the degree of polymerisation (DvP) of cotton/Kraft insulation paper at 170°C for 1500 hrs. Center graph shows thermally upgraded (treated) Kraft at 170°C for 4000 hrs. Bottom shows plain (untreated) Kraft paper insulation at 150°C for 4000 hrs. All insulation systems exhibit reduced rates of degradation in natural ester compared to those in mineral oil.

Field performance

More than 10 000 distribution transformers using vegetable oil dielectric fluid, ranging from 10 kVA to 10 MVA, are in service. The successful application in distribution class equipment has led to application in power transformers.

Table 2 shows a partial list of medium power transformer installations. Fig. 8 shows a 200 MVA generator step-up transformer being retro-filled with natural ester fluid.

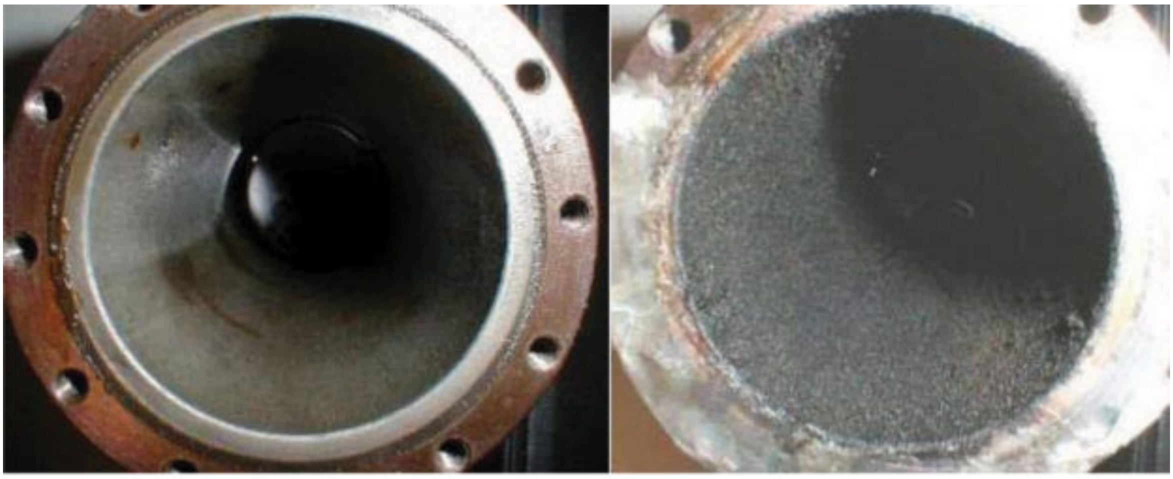

Fig. 7: Aging vessels after 4000 hours at 150°C. The steel cylinder containing the natural ester (a) was clean with slight discoloration. The cylinder containing mineral oil (b) was completely coated with degraded mineral oil sludge.

Changes in fluid properties

The natural ester fluids in an assortment of transformers are being monitored to track the changes in fluid properties under actual service conditions. These results compare well with the changes found during accelerated aging [26-29]. The natural ester fluids exhibit changes during aging similar to those changes seen in mineral oils.

As the fluids age, the dissipation factor and acid numbers increase. Interfacial tension and resistivity decrease. The baselines for change differ between mineral and vegetable oils, but the directions of change are the same.

These changes are used for diagnostic purposes in the same way as for mineral oil.

Dissolved gases

The dissolved gases in mineral oil are used to verify normal operation as well as help diagnose faults. As with mineral oil, the types of gases, their proportions, and gas generation rates are used by both IEC and IEEE as indications of abnormal conditions inside the transformer.

Arcing faults generate acetylene; partial discharge may appear as hydrogen; hydrocarbon gases can reveal a hot metal fault, and the amounts and ratio of carbon oxides could indicate overheated cellulose insulation.

Fig. 8: Generator step-up transformer, rated at 200 MVA and 161 kV, manufactured in 1966 and filled with mineral oil, was retro-filled in 2004 with natural ester fluid.

The number of faulted transformers using natural ester fluid and for which dissolved gas data are available is small. The examples we do have, combined with laboratory data from simulated faults, indicate that the interpretation of dissolved gas analysis in natural ester fluids will be done in much the same way as for mineral oil [25].

The combustible gas ratio methods do not appear to be reliable when directly applied to vegetable oils. Small differences in combustible gas solubilites in vegetable oils and the volumes of gases generated during different types of faults prevent the ratio methods from being applied as for mineral oil. Further work is needed to adapt the ratios to vegetable oils.

Conclusions

Natural ester (vegetable oil) dielectric fluids have advantages over mineral oil in terms of fire safety, environmental risk, and thermal performance. These high fire point fluids are self-extinguishing (non-propagating) and qualify in many applications as an equivalent safeguard to space separation, fire barriers, and extinguishment systems, all of which mitigate a fire but do not prevent it.

The thermal characteristics and interactions with cellulose insulation give longer insulation life or allow higher or extended overloads without abnormal loss of insulation life. Vegetable oils are commonly used as foodstuffs, can have little or no toxicity, and have environmental characteristics superior to those of mineral oil.
The natural vegetable oil ester dielectric fluids should be considered for use in applications where fire safety, environmental hazard, or improved insulation performance is needed.

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