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State of the Art Review On Managing Vegetable Oil Filled Transformers

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ABSTRACT

Ten years have passed since the Utilities began using the vegetable oil based dielectric in their power transformers. Some advantages to using vegetable oil are that their environment impact is reduced if a spillage occurs, the higher flash and fire points assist with overall safety which can result in lower substation upgrade costs, and interactions between the fluid and cellulose have been identified to extend insulation life. They are >95% biobased, providing a very high degree of sustainability.

A power transformer is expected to last for decades. The insulating liquid should be tested at various stages of the transformer's life to maintain safe and reliable operation. Compared to standard mineral oil, there are some differences in the behaviour of vegetable oils which need to be taken into account when managing vegetable oil filled transformers. In this article we cover best industry practice to maintain a reliable transformer fleet, based on the findings of extensive research from both the University of Queensland and Monash University. Specifically, we will focus on oil quality measurements and their meaning, dissolved gas analysis, oil interactions with paper insulation, and dielectric response methods. The focus of this paper is to cover the key points applicable to the asset maintenance engineer.

Case studies on Utility transformers filled with vegetable oil will be included to communicate the measurement values expected for normally operating units. By the end of this paper the reader will have an overview of the practical considerations of using vegetable oil.

KEYWORDS

Vegetable Oil, Transformer Health Management, Oil Quality, Measurement Techniques, Dissolved Gases, Water

INTRODUCTION

Vegetable oil based dielectrics have been available since the mid-90s, and used in power transformers since the mid-00s [1], [2]. Transformers are expected to operate, with minimal intervention, for decades. When purchasing new technologies Utilities must consider the overall life cycle, and the resources required for support. In this article we review vegetable oil filled transformers, to help the Utilities understand what is normal, and what they should be monitoring.

Admittedly this article draws heavily on our experience with the Envirotemp™ FR3™ insulating liquid, which has a soy oil base. No bias is intended to one particular product, none of our sponsoring Utilities have had experience in using any other type of vegetable oil in a transformer.

TRANSFORMERS INVESTIGATED

Three transformers, all filled with soy based insulating liquid, have been thoroughly investigated over the years during industry funded projects to support attaining best asset management practice. Two transformers are based in the state of New South Wales in Australia, and another is based in the UK near London. The NSW transformers are located in Thredbo and in Sydney. The relative advantages of studying these transformers include:

- The Thredbo transformer started operating in 2005, and is one of the first power transformers installed in Australia using vegetable oil.
- The Sydney transformer was fitted with an extensive online monitoring suite, providing comprehensive data is available for analysis.
- The UK transformer is part of a pair, where its sister unit was filled with mineral oil. These two units share the load nearly evenly. This permits comparing the use of the two types of dielectric coolants.

In addition, the Utility which operates the Thredbo transformer has another dozen units filled with vegetable oil. These were not used in our investigations, although some data is available, particularly on dissolved gases.

A description of the environments in which these transformers operate is given below.

Thredbo Transformer

The 10-16 MVA Thredbo transformer, shown in Figure 1, has been operating in a rural environment since 2005. It supplies a ski resort where the load increases significantly during the southern winter. The minimum likely ambient temperature must be considered. Although the internal thermal losses of the transformer will heat the oil preventing it from freezing, if the transformer is de-energized this internal heat will gradually dissipate. The Australian Bureau of Meteorology has monitored ambient temperatures at Thredbo since 1969. The ambient temperature has not fallen below -13 °C during this period [2], which is still above the pour point of this fluid (-18 °C). Thus, it would be an extremely unlikely event for the temperature to fall below the pour point of this fluid. Temperatures in parts of North America can fall much further, so Rapp investigated the behaviour of ester oils near their pour point [3]. Rapp froze then thawed an ester finding that its dielectric strength did not change. If a Utility operates a vegetable oil transformer in a very cold environment they should have a procedure in place to thaw a solidified ester.

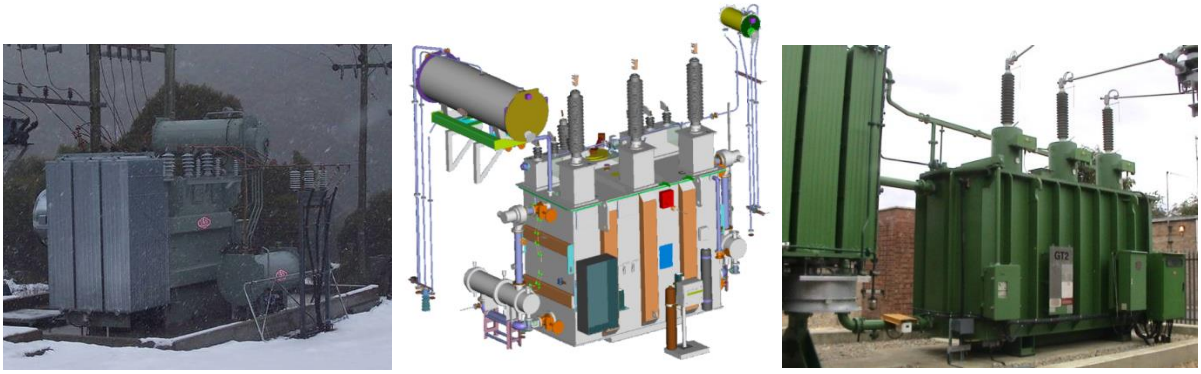

Figure 1: Vegetable oil filled transformers, Left – Thredbo, Centre – Sydney, Right – London.

Two Sydney transformers

The 50 MVA transformers were manufactured for an underground substation in the centre of the city, their design is shown in Figure 1. They were designed to replace two of the existing mineral oil filled transformers which were approaching the end of their operating life. The Utility was attracted to the higher fire point of a vegetable oil. The transformers were fitted with a comprehensive monitoring system, which recorded data every minute from the various sensors mounted around the transformer, i.e., load current, winding temperature measured by eight fibre optic probes, oil temperature and water content measured by four Vaisala probes, oil temperature and cooling water temperature recorded by resistance temperature detectors, and ambient temperature and relative humidity recorded by a Vaisala probe within the substation. The advantage of such a system is that the regular recording of data allows for accurate trends over time to be drawn. The temperature rise limits were the same as those given in IEC 60076 for a mineral oil filled transformer [5]. The transformer was water cooled, using two heat exchangers to increase the overall reliability of the cooling system. During normal operation only one of these heat exchangers is operative at any given time. The heat exchanger ratings were such as to ensure that adequate cooling would be provided, even if the exchangers were to be coated with salts deposited by water over many years.

Two UK transformers

Two 90 MVA transformers, of the same design, were manufactured for a British Utility in 2006. They are shown in Figure 1. One of them was filled with the FR3 vegetable oil while the other was filled with standard mineral oil. The transformers operate as a pair where the load is nearly equally shared. The advantage of studying these two transformers is that this has given a unique opportunity to compare the operation of two fluids in nearly identical use. One practical point of using transformers filled with a vegetable oil is that efforts should be made to prevent unintentional mixing with mineral oil. FR3 fluid has a fire point around 200 °C higher than that of mineral oil [6]. Per standards worldwide, to be eligible as a less-flammable insulating liquid, the minimum fire point is 300 ºC. However, this high fire point can fall below the less-flammable required minimum when the content of mineral oil mixed with FR3 exceeds 8%. The Utility has minimized the risk of mixing by colour coding the transformers.

MAINTAINING VEGETABLE OIL FILLED TRANSFORMERS

In this section different measurement techniques, and their analysis, are reviewed. Studies have indicated that paper heated in vegetable oil ages slower than in mineral oil [7]. Their theories proposed include:

- A reaction between the water and vegetable oil triglyceride consuming the water, which generates a fatty acid, and so the overall water content of the insulation falls.
- The fatty acid reacts directly with the insulating paper (trans-esterification of cellulose), helping prevent degradation of the paper (scissoring of cellulose chains). Because a by-product of cellulose degradation reactions is water, moisture generation is also reduced.

These theories involve the generation of fatty acids under accelerated life tests. In our investigations no change in acid content was observed. Therefore, we were unable to determine whether these life extending interactions have been occurred so far. This is not unexpected as the units were new when installed and not heavily loaded.

Accelerated Ageing of Oil

Tests were performed to support understanding of the degradation mechanisms. Two cases were considered, both sealed and unsealed to the atmosphere, the setup is shown in Figure 2. Oxidation in the unsealed case was further promoted by both bubbling oxygen gas through the oil, and using a copper catalyst. In both cases the oil was heated to, and maintained at, 110 ^{0}C. For the sealed case it is significant that even after one year of heating the vegetable oil was still usable, when taking into consideration limits set by the IEEE standard [8]. The dielectric dissipation factor of the oil was slightly below the IEEE recommended limit of 3%, and its breakdown voltage was still high, 70 kV (Breakdown voltage was measured according to IEC 60156 with a 2.5 mm electrode gap, brass 36 mm diameter VDE electrodes and a 0.5 kV/s voltage ramp rate) .

The results for this ageing investigation will be compared to operating transformer data below in the relevant section.

Figure 2: Vessel used to age vegetable oil. Left – Oxygen was bubbled through oil. Right – A conical flask conservator was attached to the vessel, and the headspace within the conical flask was filled with dry argon gas to minimise ingress of oxygen.

Oil Quality Measurements and Oil Ageing

In general the same oil quality tests as used for mineral oil are appropriate, however, in some cases modifications are required which are given in [6]. The chemical by-products of ageing, which affect viscosity, are precipitated by mineral oil forming sludge and other insoluble compounds [10]. One test not regularly used on mineral oil is for kinematic viscosity, because it does not change significantly during ageing. That is because sludge formed by oxidation tends to be insolvent in oil, and precipitated out of the oil. However, in contrast the viscosity of a vegetable oil will increase as it is exposed to oxygen over time [11]. However, for vegetable oil these oxidation by-products stay dissolved because vegetable oil by-products are less carbonaceous (mostly polymerized oil). Consequently the viscosity of the vegetable oil increases if exposed to excessive oxygen over a period of time. Our small scale accelerated oxidations studies show that as a vegetable oil polymerized, it will first form a gel and when fully polymerized it becomes virtually solid. However, in transformer applications, the application is limited to sealed transformer designs, so the exposure to oxygen is very limited. Also because the volume of insulating liquid in the transformer is measured in hundreds or thousands of litres, the ratio of exposure to oxygen in even a free breathing tank is extremely small relative to the ratio in our tests. This infers that as long as the Utility periodically checks the fluid, even if it is only a visual inspection, polymerization will not unexpectedly and spontaneously occur even in free breathing transformers.

Dielectric dissipation factor

Oxidation reactions cause the polarity of an oil to increase. A variety of compounds are created, some of which react further forming acids. Short chained acids are particularly detrimental because they accelerate the ageing of cellulose [12]. The DDF is a measurement of the polarity of the molecules in the oil.

The DDF of a vegetable oil must not be directly compared to that of a mineral oil because the polarity of the molecules (triglycerides) in a vegetable oil is inherently slightly higher. In mineral oil, a rise in DDF indicates that the intermediate chemicals, which go on to form acids, are being generated. However, the higher DDF of a vegetable oil is caused by its internal ester linkages, not by these intermediate species. If oxidation occurs a vegetable oil will also increase its acidity, and so its DDF will rise. Therefore, a condition monitoring regime should focus on the rate of change in DDF, not its absolute value. Table 1 shows the DDFs for the vegetable oil filled transformers, measured according to IEC 60247 [13]. Samples of oil were also taken from the Sydney transformers for DDF measurement according to another standard, IEC 61620 [14], at different temperatures. These results are shown in Figure 3, and allow a user to compare measurements taken at different temperatures. To aid understanding the significance of these DDF levels the results from the 1 year ageing test are also plotted, using the same IEC standard, in Figure 3; the DDF measurements from these transformers are very low in comparison to the levels reached by the end of the accelerated ageing.

Table 1: Dielectric Dissipation Factors for Vegetable Oil Transformers.

	Thredbo	Sydney A	Sydney A	Sydney A	Sydney A	Luton FR3	Luton FR3	LutonFR3
Time after manufacture (years)	2	0	1/2	2	4	3	5	5
DDF (%) IEC 60247	0.26 @ 25°C 7.4 @ 90°C	0.27 @ 25°C	0.42 @ 30°C 3.6 @ 90°C	5.0 @ 90°C	5.0 @ 90°C	0.28 @ 25°C	0.31 @ 25°C	0.25 @ 25°C

The results of the sealed accelerated ageing experiment were used to plot a graph of DDF versus time, in Figure 4. It can be seen that the rise in DDF, at these levels, is exponential. The DDF of the vegetable oil remained low for around a quarter of the ageing time, than it took three quarters of the ageing time to reach the level recommended by the IEEE, 3%, which triggers “prompt additional investigation” being required [8]. The vegetable oil filled transformers all had DDFs around 0.002 – 0.003 placing their DDF within the first quarter of the vegetable oil’s life. At present no significant ageing has been observed to have occurred of the vegetable oil.

Dissolved Gas Analysis

The Envirotemp FR3 dielectric has been frequently observed to generate ethane and hydrogen under non-fault conditions [15], [16]. Some of the components of vegetable oil, in particular linolenic acid, are known to create ethane by reacting with oxygen [17]. From the online data for the Sydney transformer, Figure 5, ethane levels are seen to increase over the first month of its energization [18]. However, ethane levels are static after six months. The transformer was sent to Sydney in several sections. Thus, the vegetable oil would have probably dissolved some oxygen from the air during installation. This oxygen then reacted with the vegetable oil creating ethane. A possible usage of ethane is that it could be used as an indicator for failed transformer sealing when oxygen is diffusing throughout the insulation. The advantage of this indicator is that an early warning can be obtained before the oil quality is affected. An observation noted by Hanson is that glass syringes filled with vegetable oil should not be exposed to the sun because the resultant ethane generated may lead to false conclusions being drawn [19].

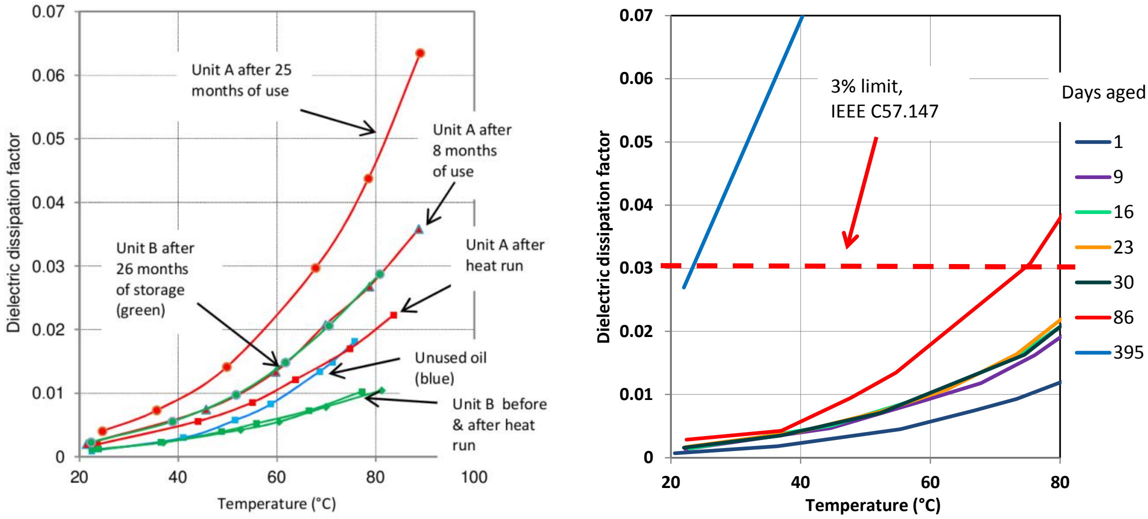

Figure 3: Left – DDF measurements, as function of temperature, for two Sydney transformers. Right – DDF measurements during accelerated ageing given for comparison. Both sets of measurements were performed according to [14].

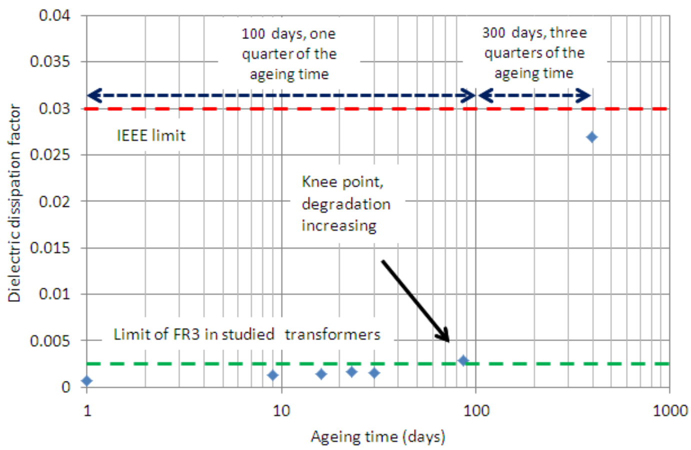

Figure 4: Showing how oil DDF changes over time, and approaches the IEEE recommended limit of 3% [8].

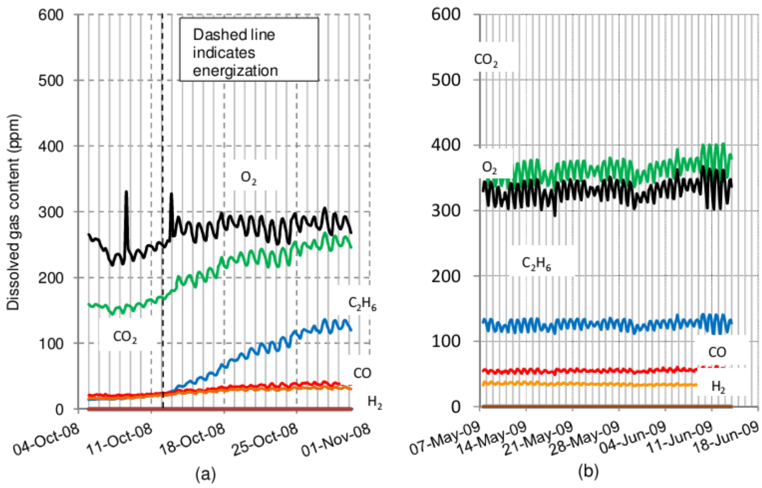

Figure 5: Plot of gases dissolved in vegetable oil of Sydney transformer unit A. Left - shows the change in gases around the time of energization. Right – the gases after a six month settle in period.

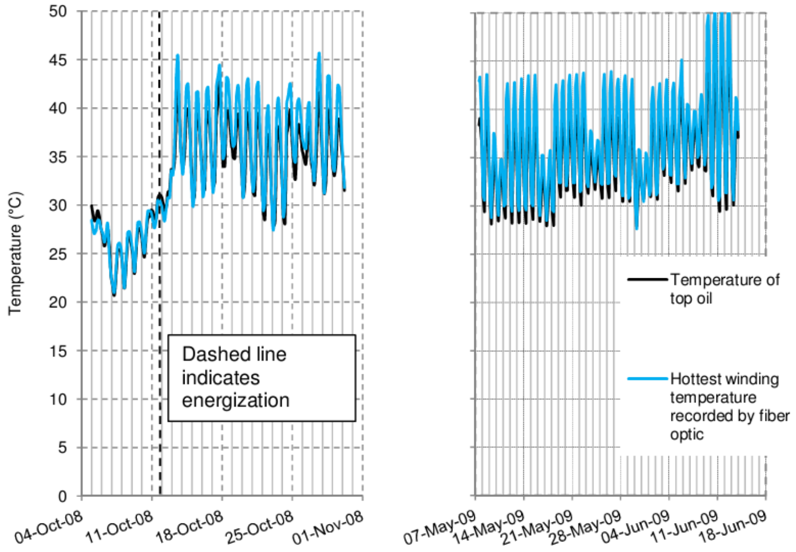

Figure 6: Temperature of oil at top of transformer tank.

Temperature, as shown in Figure 6, can be seen to have a sizable effect on the dissolved gas concentration. A tool can be developed to help the engineer compensate the gas concentration result for temperature by recalculating the gas concentration at the instantaneous measured temperature and then plotting these two parameters together. The measurements shown in Figure 5 were all taken at 25 ^{0}C. Figure 7 shows the recalculation for the Sydney transformer. If the gases deviate from this concentration vs. temperature profile, then their concentrations are changing. Duval published a method to determine faults from a three gas ratio [20], which was then adjusted for use with this vegetable oil [15]. This method uses a ratio of methane, ethylene and acetylene to determine a fault. None of the studied transformers had concentrations of gas present which would indicate a fault, the gases used for the ratio all had levels in the single digits of ppm. The dissolved gas content measured during the accelerated ageing experiments, both sealed and free breathing, is suitably high for analysis. Plotting these measurements on the appropriate Duval triangle, Figure 8, shows that most of these points lie in the T1 zone, thermal faults of temperature less than 300 ^{0}C. The temperature range, below 300 ^{0}C, is correct. However, 110 ^{0}C may not necessarily indicate a fault because a transformer could operate at this temperature during overload conditions. One point lies in outside of the zone in T2, which indicates a higher fault temperature. This has been caused by a reduction in methane concentration whereas the ethylene concentration did not change. The temperature of the free breathing system was returned to that of ambient before the sample was taken for DGA. Ethylene is more soluble in oil than methane is, thus when the temperature was lowered the methane escaped before ethylene was lost. The levels of ethane for 22 sampled transformers are given in Figure 8. Up to 300 ppm has been found in transformers, whose dissolved gas measurements are otherwise normal.

MEASURING TRANSFORMER WATER CONTENT AND ANALYSING RESULTS

A vegetable oil will dissolve approximately twenty times more water than mineral oil at a given temperature [23]. Limits for water in mineral oil should therefore not be directly used for vegetable oil insulation. For instance, the effect of water on lowering the dielectric strength of oil is more related to its percent saturation, rather than water concentration [24].

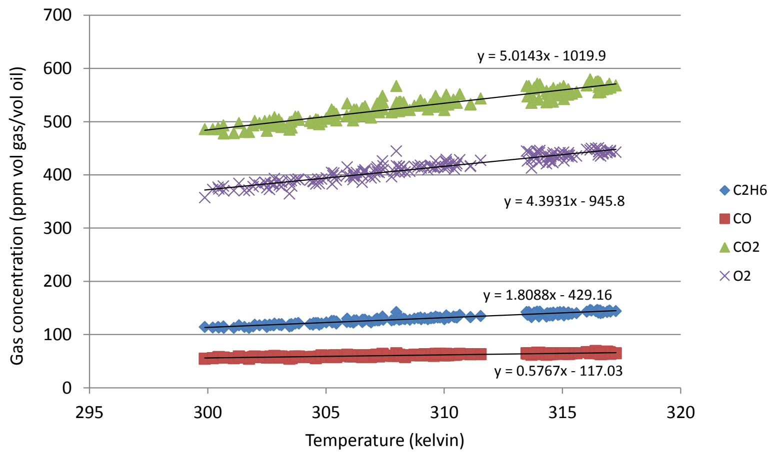

Figure 7: Gas concentration of vegetable oil as a function of temperature.

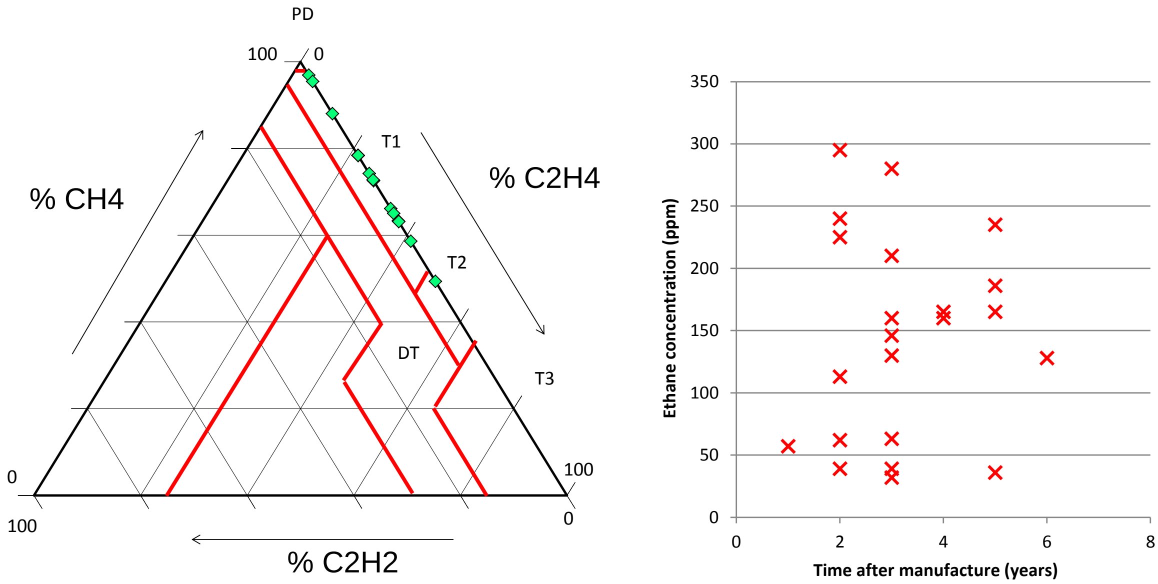

Figure 8: Left – Duval triangle analysis for fault gases from the accelerated ageing experiments, produced using a method sourced from Graham and Midgely [22]. Right – Levels of ethane from 22 vegetable oil containing transformers.

Some of the problems if the water content of an oil filled transformer reaches high levels include:

- Propensity for water bubbling to occur during overload temperatures increases, possibly leading to dielectric failure [25].
- Water accelerates paper ageing, reducing the operating life of the transformer [9], [12]. Thermal aging breakdown of paper also produces water, in a sense an auto-acceleratory process.

The water content of oil is usually expressed as either ppm (mass water/mass oil) or as water activity (vapour pressure of dissolved water/vapour pressure of pure water at that temperature). A Utility can measure either quantity, Karl Fischer titration for ppm or probe for water activity, and use a calculation to transfer between. Equation (1) can be used, where w is the water content in ppm by mass, Aw is the measured water activity, T is the temperature in kelvin, A and B are solubility coefficients specific to that type oil and its condition. Lewand recommends using A = 5.3318 and B = -684 [26], while our research found values of A = 6.00 and B = -881.39 [27]. Both sets of coefficients give similar results for calculated solubility.

$$w = A_w \times 10^{\left(A+\frac{B}{T}\right)} \qquad (1)$$

Oil water content for the studied transformers is given in Table 2 and in Figure 9 using a water activity probe. The oil water content tends to be between 10 and 30 ppm. At room temperature, based on the solubility of this vegetable oil being around 1000 ppm, this corresponds to approximately 0.01 – 0.03 water activity.

Table 2: Samples of natural ester water content, taken from transformer, as measured using Karl Fischer titration.

	Thredbo	Sydney A	Sydney A	Sydney A	Sydney A	Sydney B	Luton FR3	Luton FR3	LutonFR3
Time after manufacture (years)	2	0	1/2	2	4	2	3	5	5
Oil water content (ppm)	16	30	22	22	23	7	13	13	9

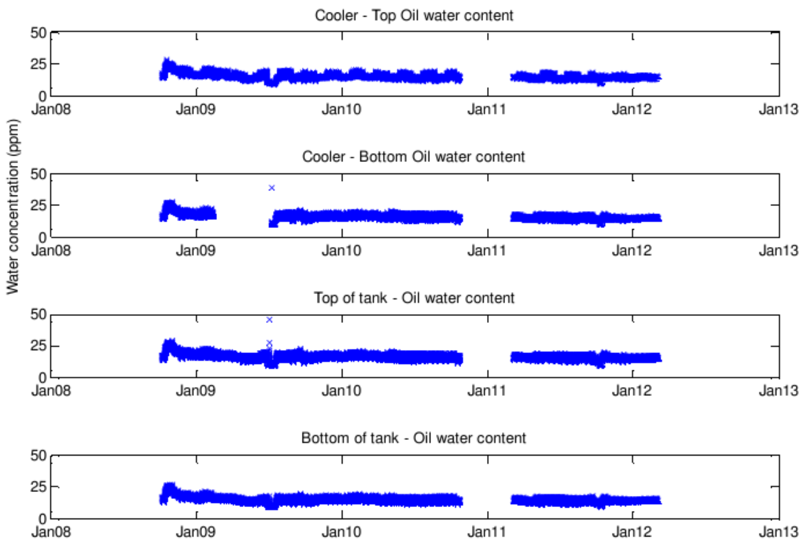

Figure 9: Oil water concentration calculated from water activity probe measurement.

When estimating the water content of paper insulation via the cellulosic isotherm method [28] the water activity data can be used to firstly calculate the vapour pressure of the water, then assuming thermodynamic equilibrium this vapour pressure is used to calculate the water content of paper insulation. The vapour pressure of the water dissolved in an ideal liquid can be calculated using (2), which is based on the Buck equation [29]. Equation (3) is based on work performed by Fessler [30], where the water content of paper, C, is calculated from vapour pressure and temperature. A full discussion on the advantages and disadvantages of this method is given in [31], in particular its inaccuracies compared to other models such as those by Langmuir or Brunaur-Emmett-Teller. In other work taking the long term averages for temperature and water activity was concluded to give a reasonable result [32], [33]. We believed the application of (3) to a vegetable oil is valid because (3) is fairly independent of the surrounding fluid medium. A discussion is given in the CIGRE brochure [31] on how a small difference exists depending on the fluid used, with a hypothesis that the fluid can block off the sites of the cellulose that water can adsorb to. We therefore tested the applicability of using (3) with the vegetable oil, by comparing the calculation with measurements using KF titration [27]. These measurements are shown in Table 3. Good agreement was found.

$$P_v = 6.1121 \times e^{\left(\frac{17.502 \times T}{240.97 + T}\right)} \times A_w \times 0.0009869 \quad (2)$$

$$C = 2.173 \times 10^{-7} \times P_v^{0.6685} \times e^{\frac{4725.6}{T}} \quad (3)$$

Table 3: Comparison of measured and calculated equilibrium water contents of paper and the studied vegetable oil.

Temperature (°C)	Water activity (p.u.)	Water content of paper (%)	
		Calculated using (3)	Measured using KF titration
22	0.033	1.7	1.2
22	0.083	3.2	2.3
49	0.039	1.4	0.9
48	0.086	2.4	2.1
76	0.042	1.1	0.7
76	0.086	1.7	1.6

Equations 2 & 3 were used to build a graph relating oil water content to that of the paper, shown in Figure 10. Both sets of oil solubility coefficients were used, the solid line is from Lewand's coefficients and the dashed line from Monash [27].

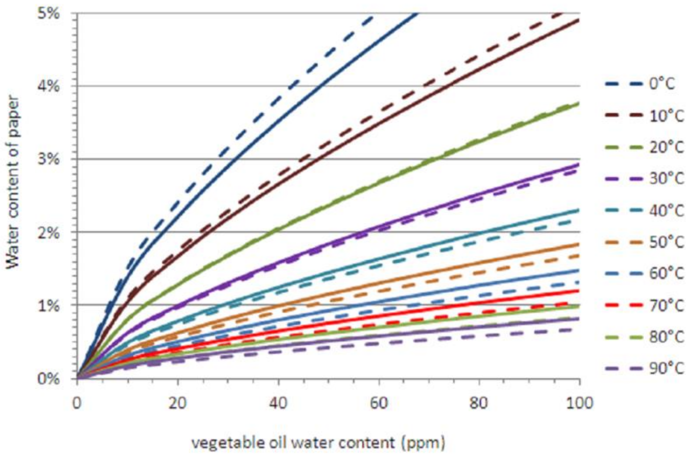

Figure 10: Equilibrium isotherms for vegetable oil and paper insulation.

A PRACTICAL CONSIDERATION OF TRANSFORMER MANAGEMENT – OPENING THE TANK

One practical consideration to managing a transformer is how to access the tank should either an inspection or mid life refurbishment be required. A vegetable oil can polymerize forming a thin film. Consequently, we investigated several practical problems which could be faced by a Utility. These were:

- The propensity for oil puddles, at the bottom of a drained tank, to solidify.
- The effect of leaving ancillary equipment, such as pumps, for long periods of time.
- Formation of gel on paper exposed to air at both ambient and elevated temperature.

Oil Skin Forming on a Volume of Vegetable Oil

In March 2010 an investigation began to determine the speed at which a small volume of vegetable oil solidifies at room temperature, under ambient laboratory conditions [34]. A 15 cm diameter Petri dish was filled with a vegetable oil to a 5 mm depth. This is similar to the depth of an oil puddle at the bottom of an emptied tank. After one month no changes were observed. It was noted that insects seemed to be attracted to the vegetable oil, falling inside the Petri dish and dying. This could be a problem for transformer maintenance if insects entered the unit and caused dielectric failure, possibly similar to a large particle. It took two years for a skin of gel to form on the surface of the oil. In the inspection one month before the skin had been observed the oil had been noted to be more viscous, however no skin was seen. Once the skin had begun to form, it grew relatively rapidly over the next month. This skin is shown in Figure 11.

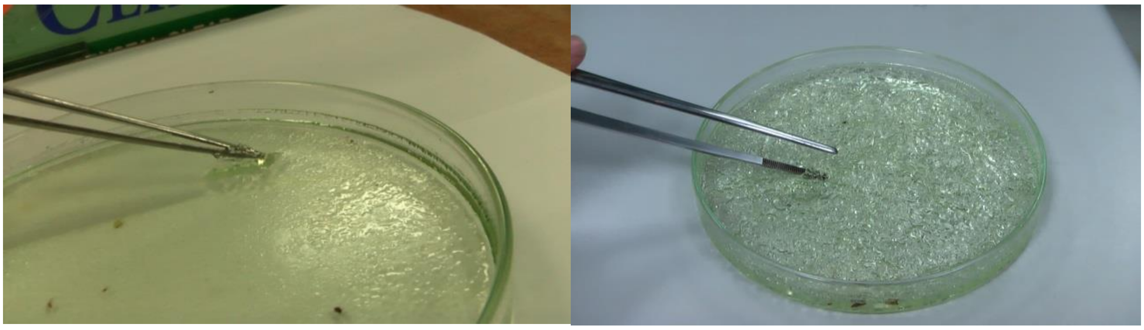

Figure 11: Left - skin on vegetable oil after two years and three months. Right - skin after two years and five months. Once the skin formed, it rapidly became thicker.

Since it took 2 years for a 5 mm deep pool of vegetable to gel it is concluded:

- Gelling is unlikely to form in oil puddles at the bottom of an empty tank, exposed to air, during transformer maintenance, because the tank will not be left open for this period of time.
- Ancillary equipment occasionally used to service a transformer on a regular basis, for instance external pumps, are unlikely to become clogged with gel unless left unused for several months. However, flushing the service equipment with mineral oil or synthetic esters is recommended if the vegetable oil thin film in the equipment is exposed to air and high ambient temperatures over an extended period of time.

Effect of Hot Air/Oil Circulation on Vegetable Oil and Impregnated Paper

Investigations were carried out to ascertain the effect of oxygen and temperature on a sample of vegetable oil. When a very small volume (<1 ml) is heated to 110 ^{0}C it forms a thin film (Figure 12). The results from the accelerated ageing tests indicates that a 1 litre volume of vegetable oil changes rapidly when oxygen is bubbled through at 110 ^{0}C. In this experiment the 3% IEEE recommended limit for DDF was reached after about twenty days, shown in Figure 12. Therefore, carrying out hot vegetable oil circulation in the presence of hot air is not recommended.

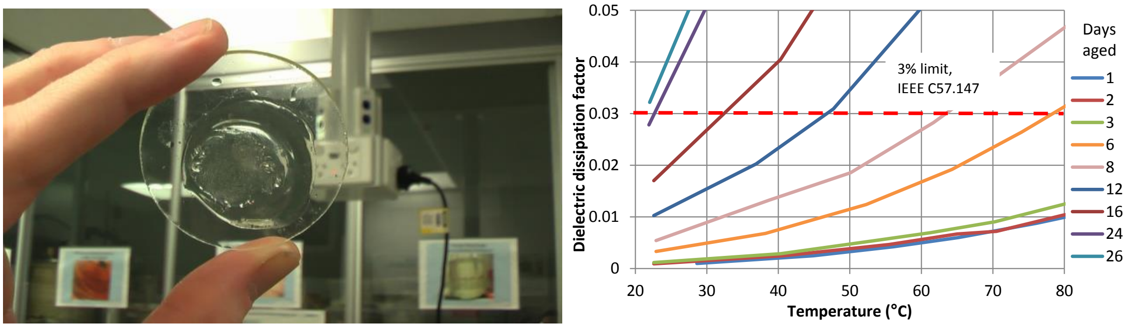

Figure 12: Left – A thin film of gelled vegetable oil, after heating at 110 °C for 1 day. Right – DDF of vegetable oil heated with oxygen, showing rapid ageing.

In order to determine whether hot air/oil circulation causes the vegetable oil to gel on the surface of the windings a piece of paper impregnated with the vegetable oil was heated in an air circulating oven. The oven was heated to, and maintained at, 110 °C. The strip of paper was clamped vertically, allowing for droplets of the oil to form at the bottom of the paper. Five hours into the heating we noticed that the vegetable oil had dried on the surface of the paper, similar to a varnish, shown in Figure 13. This layer was not noticeably a thin film, in that it could not be peeled off. Liquid vegetable oil had collected at the bottom of the paper and was forming a tacky substance, however had not gelled. This could mean that even if a vegetable oil within electrical equipment has not gelled, there may be a varnish-like coating on the windings. The paper was returned to the oven and heated overnight. The following morning we noted that the droplets of oil at the bottom of the paper had gelled. In comparison no varnish was observed on the oily paper left at room temperature. These results show that hot air should not be used to dry a vegetable oil filled transformer.

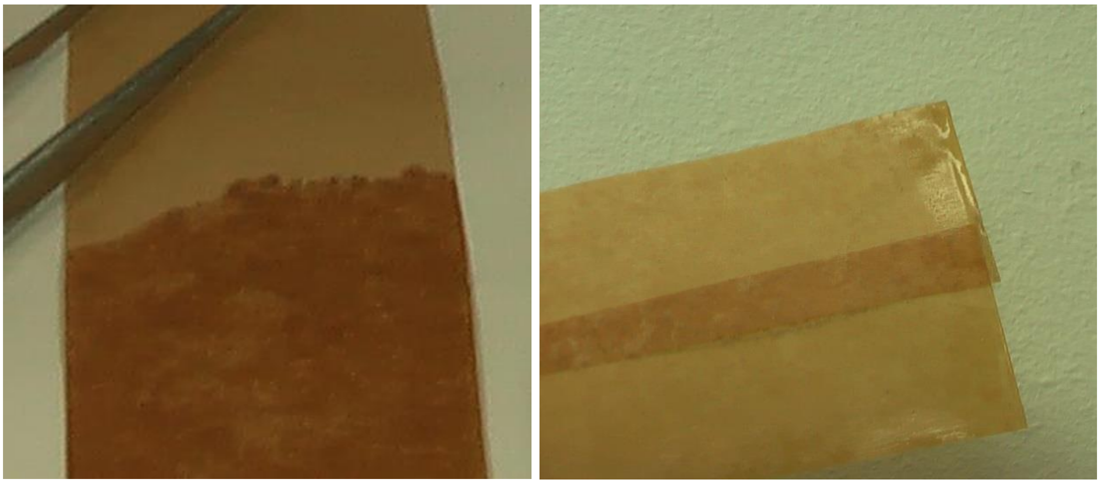

Figure 13: Varnish like substance on paper (left), gel on edge of paper (right)

CONCLUSION

In this article the main points on operating vegetable oil filled transformers have been addressed that a condition monitoring engineer needs to know in order to keep their transformer assets operating reliably.

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