The Essentials of Transformer Fluid Testing

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Dissolved gas analysis (DGA) has been a powerful tool for industry to detect and identify faults in oil filled transformers.

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Introduction

This article will be looking at the differences in analytical and diagnostic condition monitoring tools and fault identification techniques for transformers filled with natural and synthetic ester fluids in relation to the known mineral oil filled units. A reliable condition monitoring system for transformers, both distribution and power transformers, is of the utmost importance to ensure electrical reticulation system reliability.

In this article, we will focus on the chemical-based techniques for condition monitoring available in the industry.

We will look at the analytical tools for determination of moisture content, viscosity, acidity, DGA and furan content.

Moisture Analysis

According to IEC Std. 60814 we will apply the standard procedure for Karl Fischer Titration (KFT). An equilibrium chart is available for mineral oil that indicates the moisture content in paper (%) according to the result acquired by the KFT analysis. With this chart, the analyst can establish the approximate moisture content of the paper according to the actual KFT result and the temperature of the oil at sampling, which is due to an established equilibrium equation for this phenomenon. Ester fluids have a higher moisture solubility than typical mineral oil, and we cannot use the equilibrium conditions as set for mineral oils. As the polarity of natural ester fluids is higher than that of mineral oils, these fluids will admit higher amounts of water in solution before reaching saturation level

It should be noted that operating transformers experience dynamic temperature variations, therefore, moisture equilibrium conditions in transformers are hardly ever achieved – this is even more true for ester fluids as these display a higher viscosity.

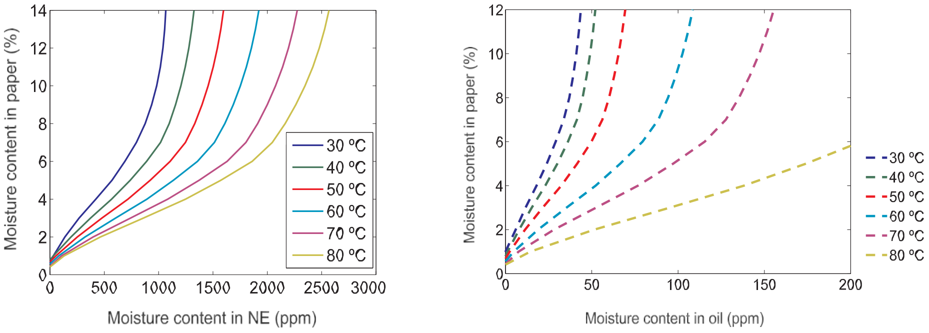


Figure 1.
Moisture content in oil (mg/kg): natural esters (left) and mineral oil (right) [1]

	Moisture content (ppm)					
	30 °C	**40 °C**	**50 °C**	**60 °C**	**70 °C**	**80 °C**
Mineral oil	38	58	80	119	171	228
Natural ester	575	699	837	1001	1182	1330

Table 1.
Moisture content of the two insulating fluids at RH 50% and variable temperature

Dissolved Gas Analysis

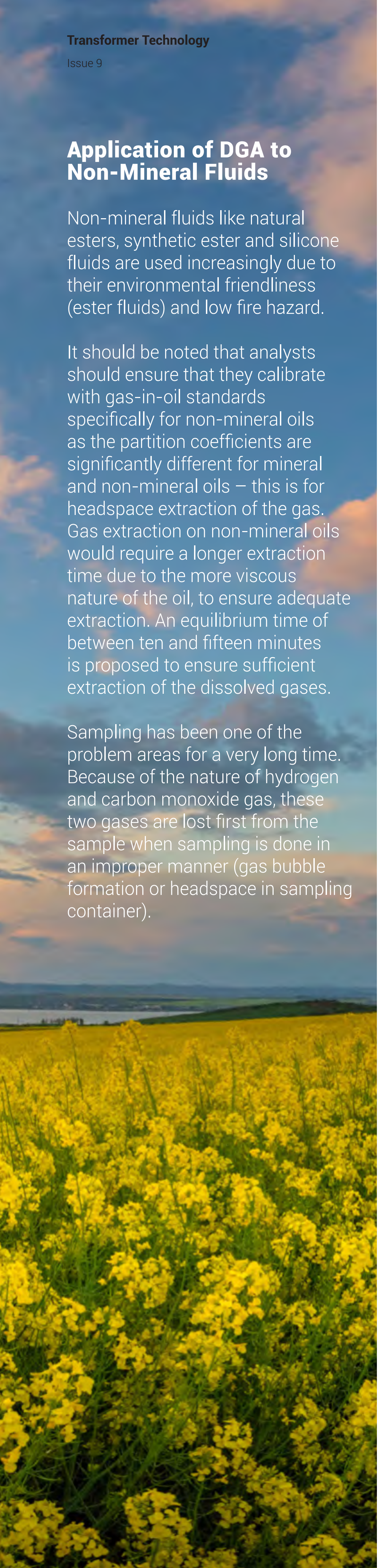
Dissolved gas analysis (DGA) has been a powerful tool for industry to detect and identify faults in oil filled transformers.

The objectives of DGA are a) to check that equipment is in a good condition, b) to monitor operating conditions of a transformer, and c) to prevent failure and their possible localization. DGA has mainly been used for transformers filled with mineral oil. Since the request for a more environmentally friendly, less flammable liquid to be used in transformers, a lot of research has gone into synthetic and natural ester fluids analysis. The research is done to determine if these types of fluids would be beneficial to the industry and the equipment they are purposed for. Ester fluids have been introduced to the transformer sector and are currently used in distribution transformers, bushings and tap-changers regardless of some limitations, such as higher cost, required protection from oil oxidation, very-low temperature operation, and full clean-up required by most national and regulatory bodies in case of a spill.

The chemical structure of esters or silicone fluids cannot be directly correlated to that of mineral oil as their chemical molecule construction is entirely different. The gassing of an insulating liquid under electrical discharge depends on the chemical composition of the fluid, electrical field stress, temperature, and time. The gassing tendency of natural esters is much lower than that of synthetic esters and mineral oils. This is most likely due to the amount of unsaturated, non-aromatic molecules as compared to mineral oils [2].

To ensure that the same level of monitoring is available to customers using ester fluids in distribution transformers, bushings or tap-changers, a group of industry leaders came together to set the guidelines and standards for analysis of ester fluids. The findings and recommendation have been published in Technical brochure D1/A2 – Advance in DGA interpretation [3]. This document addressed the need for diagnostic tools to clearly identify electrical and thermal stress conditions in operational equipment including transformers, bushings, and on-load tap-changers. The application of non-mineral fluids in power transformers poses a challenge as higher electrical and thermal stresses are inevitable, and a higher level of DGA monitoring would be required. More frequent DGA analysis in collaboration with on-line monitoring of gas formation are required. To ensure that the diagnostics are perfectly accurate and that the recommendations according to the oil analysis will give the true picture of the state of the equipment, interpretation of the key gas concentrations as well as ratios and what abnormalities this may indicate is of the utmost importance. This will ensure that any corrective actions recommended by the diagnostics will ensure reliability, accurate maintenance decisions and optimized lifetime for the equipment in question.

We will look at these standards and guidelines and compare them to the standard procedures and guidelines for mineral oils, pointing out some differences and similarities.



Application of DGA to Non-Mineral Fluids

Non-mineral fluids like natural esters, synthetic ester and silicone fluids are used increasingly due to their environmental friendliness (ester fluids) and low fire hazard.

It should be noted that analysts should ensure that they calibrate with gas-in-oil standards specifically for non-mineral oils as the partition coefficients are significantly different for mineral and non-mineral oils – this is for headspace extraction of the gas. Gas extraction on non-mineral oils would require a longer extraction time due to the more viscous nature of the oil, to ensure adequate extraction. An equilibrium time of between ten and fifteen minutes is proposed to ensure sufficient extraction of the dissolved gases.

Sampling has been one of the problem areas for a very long time. Because of the nature of hydrogen and carbon monoxide gas, these two gases are lost first from the sample when sampling is done in an improper manner (gas bubble formation or headspace in sampling container).

Identification of Faults in Non-Mineral Fluids

DGA interpretation methods for mineral oils are based on many cases of transformers in service where gas formation could be attributed to a specific type of fault detected by visual inspection. This is not the case for non-mineral fluids.

The same key gases are formed during the chemical breakdown processes of oil and paper in both mineral and non-mineral fluids – the ratios might slightly differ. The type and composition of gas formation depends on the degree of localized temperature rise or energy contained in a fault because the energy needed for scission of molecular bonds and their recombination into different gases is not similar. The interpretation of the DGA results also has many similarities although different Duval triangles and pentagons are used for mineral and non-mineral fluids, as the zone boundaries had to be adjusted for non-mineral oil data interpretation. It should be noted that there are different types of non-mineral fluids e.g. silicone fluid, natural ester, and synthetic ester. Natural and synthetic esters can be divided into different categories again, which complicates the whole analytical scene for these fluids, as you are not working with one specific molecule type, but a vast pool of different molecules. Each one of these fluids might act just somewhat differently in the same electrical and thermal stress conditions than the next one.

It should be noted that ester fluids generate more gases in total than mineral oil, but these are not dissolved in the oils.

This implies the need for comprehensive analytical monitoring, firstly of the new fluid that would be used in the equipment in order to establish baseline data, and then the interval monitoring of these units under different stress conditions to record the actual outcome of each type of natural and synthetic ester. All these fluids will behave slightly differently under electrical or thermal stress situations and not all the details on these reactions have been stipulated yet.

The appearance of "stray gassing" is higher in non-mineral oils and the relevant tools are provided to distinguish the "stray gassing" phenomenon from the more serious faults like carbonization of paper. This is particularly true for natural esters, which produce significant amounts of hydrogen and ethane, but mainly ethane gas at relatively low temperatures, between 90°C to 200°C [3], which is considered only mild overheating. The higher stray gassing tendency for FR3, a natural ester, has tentatively been related to the higher viscosity and/or additives in the oil. Silicone fluid, on the other hand, displays very little "stray gassing". Despite even higher viscosity, this fluid type produces only hydrogen when "stray gassing" and only from 180°C up to 220°C.

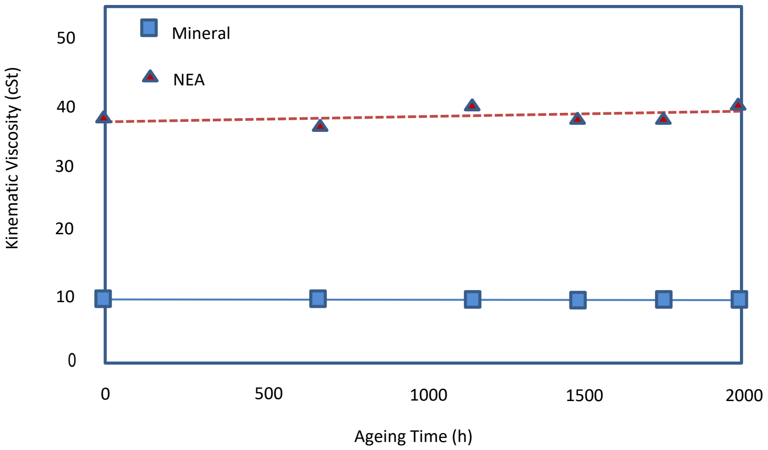


Figure 2.
Kinematic viscosity in relation to time for mineral oil and natural ester

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Typical Concentration of Key Gases in Non-Mineral Fluids

For electrical faults and especially for low energy discharges, the same main gases (hydrogen and ethylene) are created in relatively the same ratios, thus confirming the efficiency of key gas method for ester fluids. For thermal faults, and especially for stray gassing issues (low thermal faults), ethane associated with hydrogen constitutes the key gas of natural esters.

Considering the different gassing behavior of commercially available non-mineral insulation liquids (silicone and ester fluids) Duval Triangle 3 has been developed.

The typical concentration values in service for these key gases are lower than with mineral oils. It was found in experimental data that the IEC gas ratio method is not well adapted for natural esters, especially to define the discharges of low energy (D1) [4].

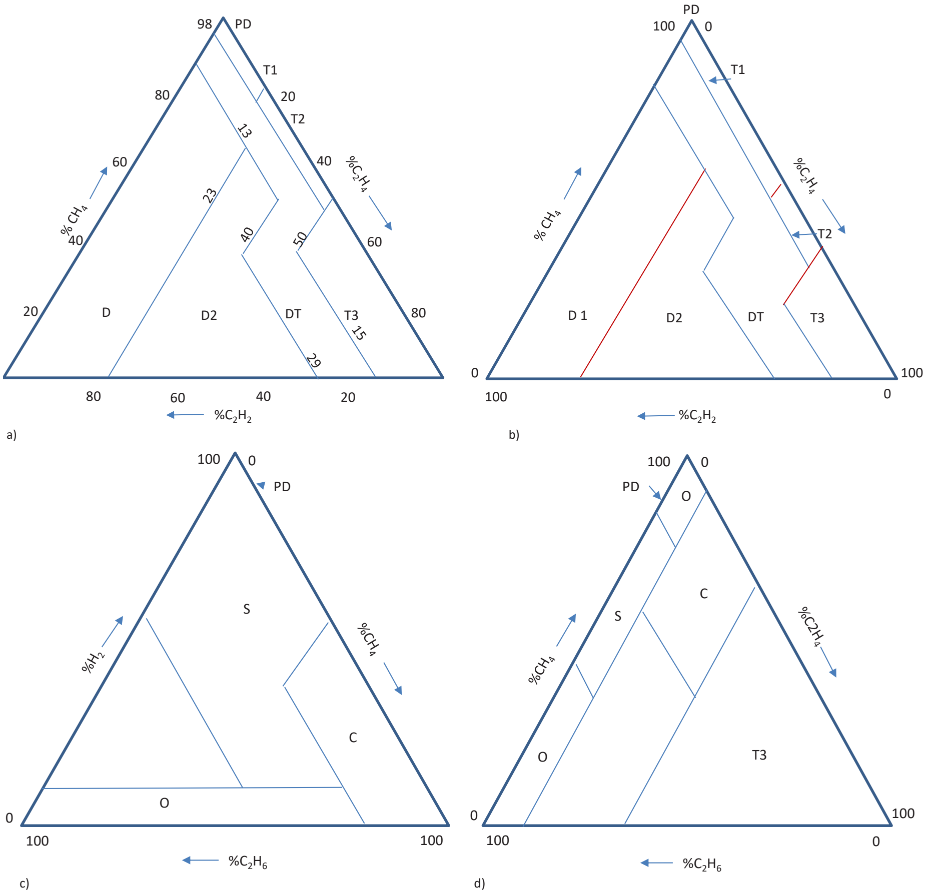


Figure 3.
Duval Triangle: (a) Triangle 1, (b) Triangle 3 for FR3, (c) Triangle 4, (d) Triangle 5

Oil Type / Gas	H_2	O_2	N_2	CH_4	CO	CO_2	C_2H_2	C_2H_4	C_2H_6	C_3H_6
Mineral	0.0504	0.172	0.091	0.423	0.125	1.1	1.25	1.81	2.88	9.64
FR3	0.0471	0.134	0.074	0.341	0.108	1.54	2.58	1.67	2.14	7.46
MIDEL	0.0479	0.152	0.091	0.378	0.13	2.08	4.26	1.85	2.2	7.67
Silicone	0.0869	0.267	0.155	0.58	0.189	1.63	2.04	2.18	3.1	9.91

Table 2.
Solubility/partition coefficients k of gases in mineral and non-mineral fluids at 20°C

Boundaries between zones	**Mineral oils**	**Silicone oil**	**Midel**	**FR 3**	**Bio Temp**
D1/D2	23	9	26	25	20
T1/T2	20	16	39	43	52
T2/T3	50	{46}	{68}	63	{82}

Table 3.
Fault zone boundaries for non-mineral fluids (when different from mineral oils) in % C_2H_4

The Duval pentagon is a graphical DGA interpretation technique which is based on the use of four main hydrocarbon gases: methane, ethane, ethylene, acetylene and hydrogen. Each summit in the pentagon corresponds to one gas. In this technique, relative percentages of each hydrocarbon gas are plotted on the axis between the center (0%) of the pentagon and the pentagon vertex (100%). The Duval Pentagon 1 allows identification of six basic electrical and thermal faults (PD, D1, D2, T1, T2 and T3); Pentagon 2 enables identification of three electrical (PD, D1, D2) and four advance thermal faults (T3-H thermal fault in the oil, C – Carbonization of paper, O – Overheating (<250°C) and S – stray gassing of oil).

The typical gas concentration values seem to be lower than for mineral oil, possibly because it takes higher temperatures to form these gases with such fluids, or because there is not enough data available so far to be really representative of their actual behavior in service. Most of the data available is experimental.

Furan Analysis

The thermal degradation of cellulose paper that is used in electrical equipment will lead to the formation of a class of heterocyclic compounds. These include 2-furfural-eldehyde (2-FAL), 2-acetylfuran (2-ACF), 2-furoic acid, 5-methyl-2-furfural (5-MEF), 2-furfuryl alcohol (2-FOL) and 5-hydroxymethyl-2-furfural (5-HMF).

IEC 61198 and ASTM D5837 are used to determine the presence of these chemical components in the transformer oil. This method allows for detecting trace quantities of these compounds in the parts per billion range. The furanic compounds dissolved in insulating oil are solely related to the degradation of paper insulation in the system. Cheim et al [5] have reported the existence of a linear relationship between DP value of cellulose paper insulation and 2-FAL concentration dissolved in mineral oil in logarithm scale.

Experimental data compared the decrease of the DP value of pressboard in both mineral oil and natural ester fluids. In Figure 5 (left) we notice that the average DP of pressboard decreases quite rapidly at the beginning and then the rate of decline is lower regardless of the type of oil used. This is due to the chemical features of the cellulose molecules in the pressboard and not the oil. The long chain cellulose polymer in new pressboard may contain weak links in the middle, which occur naturally in every 500 glucose monomer units. These links are weak and rapidly break under thermal stress, which accounts for the first drop in DP value. Amorphous regions break more easily than crystalline regions, and this phenomenon also supports the quick initial aging. Most water and acid produced during ageing reactions sit in the amorphous regions because of their greater permeability. The crystalline region, on the other hand, does not allow water and acid penetrations as readily.

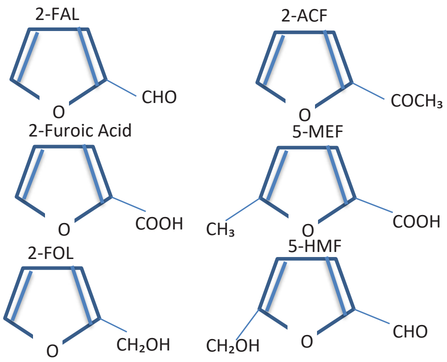
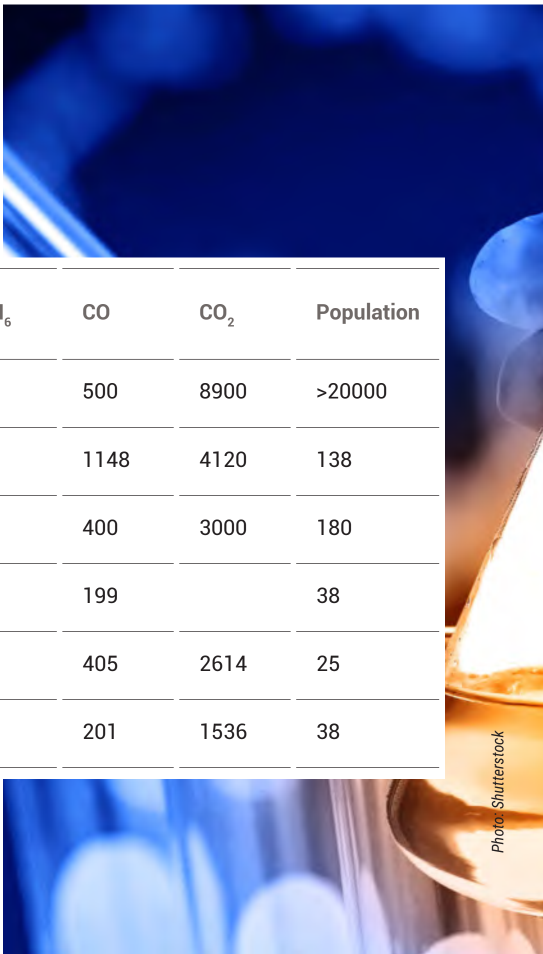


Figure 4.
Chemical structures of furanic compounds

Figure 5 (left) clearly indicates that the reduction in DP of pressboard insulation in the presence of natural esters is substantially lower than in those transformers filled with mineral oils. It should be noted that the initial moisture content for mineral oil and natural ester was nearly the same at the start of the experiment.

Oil Type	Network	Traction	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO	CO_2	Population
Mineral	X		100	80	170	3	55	500	8900	>20000
MIDEL (Ref 1)	X		37	68	70	1	50	1148	4120	138
FR3	X		35	12	12	1	20	400	3000	180
BioTemp	X		41	7	5	1	4	199		38
Silicones		X	25	28	1	1	0	405	2614	25
MIDEL (Ref 2)		X	21	7	9	2	2	201	1536	38

Table 4.
Examples of 90% typical concentration values observed in non-mineral oils



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The DP value decrease in natural ester filled units was negligibly small during the experimental period, and the DP was 100 to 150 higher than the DP of pressboard aged in mineral oil. According to these findings, natural esters show resistance to ageing of cellulose paper insulation.

It is clear from experimental data that a unit operating at 110°C should have a decrease in life expectancy of a factor of 27 due to the increase in moisture to about 2.2%, while that in natural ester with 2.4% moisture is only reduced by a factor of 15. This behavior pattern for pressboard can be applied to cellulose paper as they are of the same molecular structure.

Neutralization Number (Acidity Value)

In the case of mineral oils an increase in the acid value mainly gives an indication of the degree of deterioration of the oil under oxidizing conditions.

However, a rise in the neutralization number of synthetic and natural esters does not merely give an indication of the oxidizing conditions because hydrolytic degradation of esters also yields acids. Degradation of cellulose insulation releases water, and hydrolysis reactions in ester fluids in a transformer could become extensive with time. Synthetic esters mainly produce short chain acids and these acids accelerate the ageing process of paper insulation creating corrosion on copper conductors.

The hydrolysis reaction in natural esters produces long chain fatty acids and these are not harmful to the insulation system or other components of the system.

Different limiting values for neutralization values for different types of oil have been proposed. For example, the British standard EN 61203 proposes that for synthetic esters with a voltage rating of 35 kV or lower, the neutralization value should be less than 2 mgKOH/h, while acceptable maximum values in mineral and natural ester fluids of <69 kV should be 0.2mgKOH/g and 0.3 mgKOH/g, respectively. However, some studies have shown better ageing performance of cellulose material in natural esters with a higher acid level, therefore the proposed limiting neutralization value for natural esters is arguable.

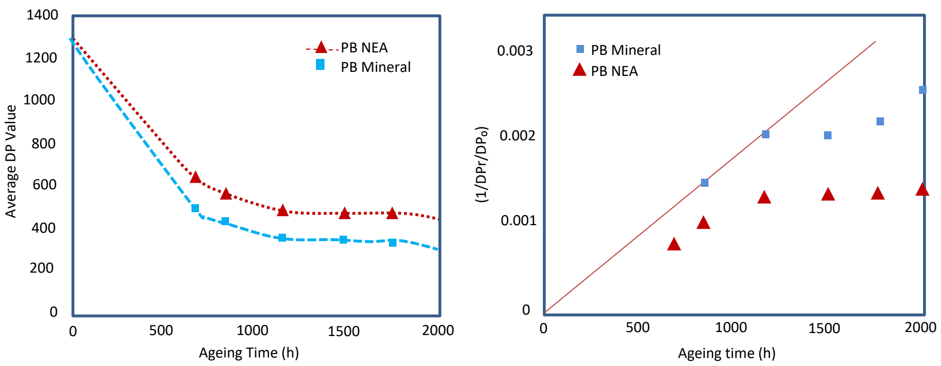

Figure 5.
Decrease of DP values of PB impregnated with mineral oil and NE (left), and 1/DPt´1/DP0 versus ageing time of PB (right)

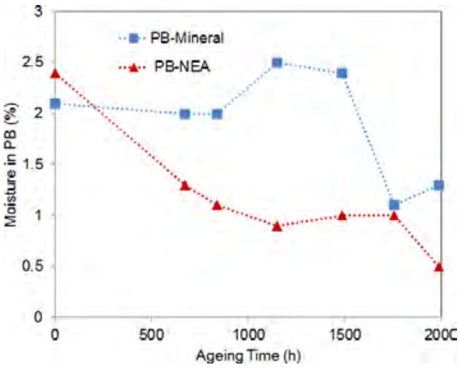

Figure 6.
Change of moisture in PB over aging

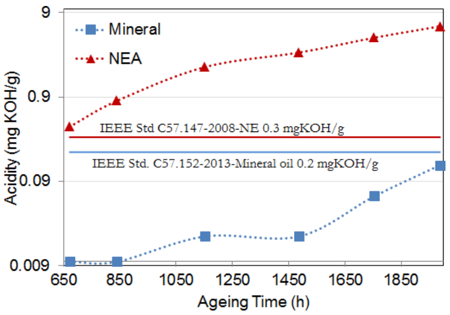

Figure 7.
Change of acidity over time

References

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