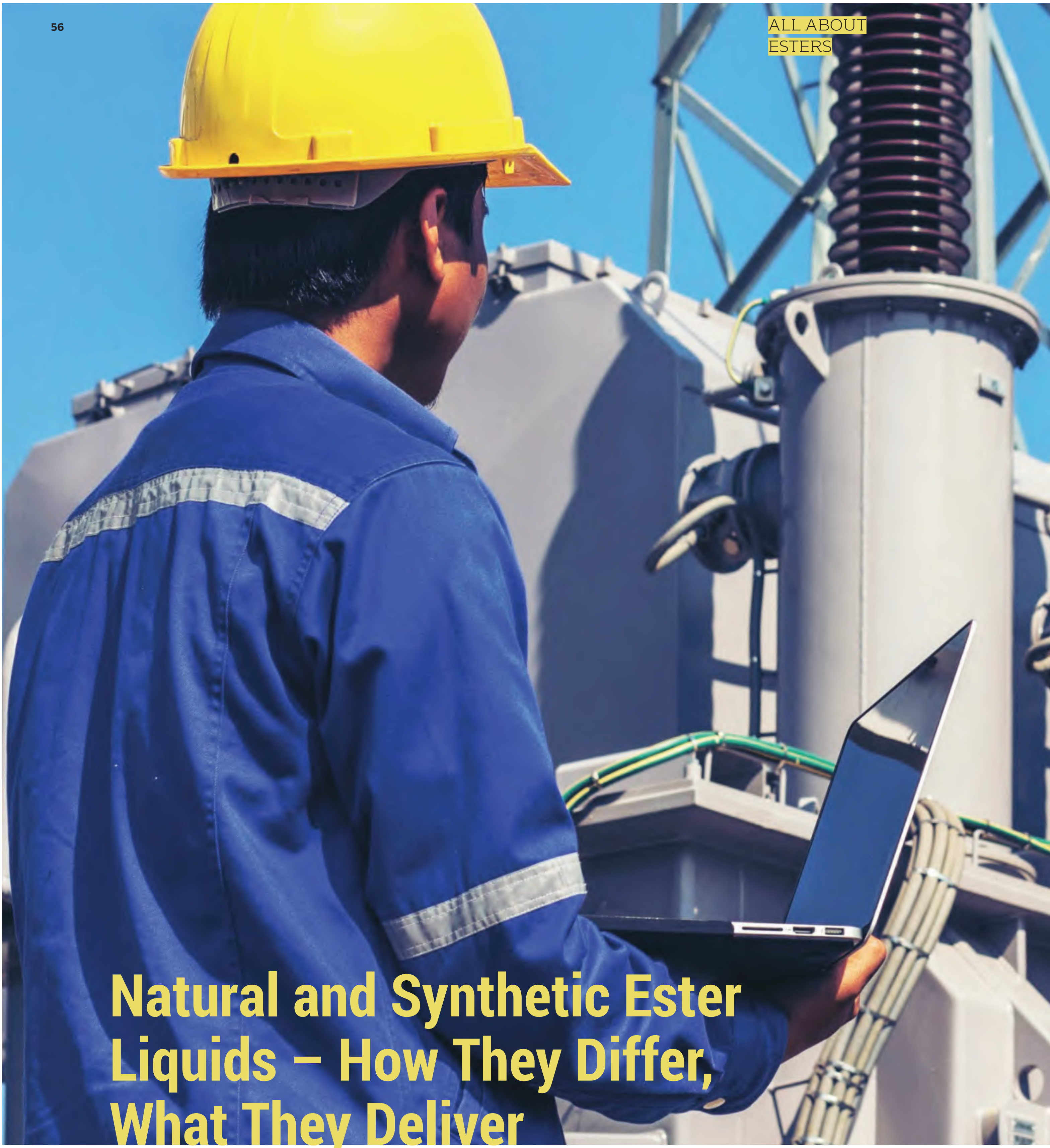

Natural and Synthetic Ester Liquids – How They Differ, What They Deliver

by **Jinesh Malde**
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A dielectric liquid is a material used in a transformer to enhance cooling efficiency of active parts and provide electrical insulation. Together, the dielectric liquid and the solid insulation (i.e. paper and pressboards), provide enhanced dielectric withstand strength of the transformer structure. The dielectric liquid also acts as an information carrier on issues related to internal faults within the tank and active parts. Currently, hydrocarbon based mineral oils represent the highest volume of dielectric liquids used in transformer applications. These oils are derived and refined from crude oil and achieve the desired properties

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Natural ester dielectric liquids are produced from vegetable oils and their properties are affected by the base vegetable oil from which they are made.

that meet most of the relevant standards. However, despite mineral oil being a good dielectric liquid, it is neither a K class liquid (fire point greater than 300°C), nor is it readily biodegradable (environmentally friendly). As such, over the past several decades, natural and synthetic esters have emerged to meet the K class requirements, are environmentally friendly and improve the life of the insulation system inside the transformer. This article provides information on differences between the various liquids, similarities between natural and synthetic esters and guidance on selection of the most appropriate liquid based on the application.

Differences Between the Dielectric Liquids

To define the differences between mineral oil and ester based dielectric liquids, it is worth looking at their chemical structures.

Mineral Oil

Figure 1 shows the basic chemical structure of mineral oil. The hydrocarbon compounds in mineral oil vary and can be categorized into paraffinic, iso-paraffinic, naphthenic, aromatic, and poly-aromatic. These compounds exist in mineral oil with different ratios and thus contribute to slight differences in properties such as flash and fire points, pour point, viscosity, and oxidation stability to name a few.

Ester Liquids

The basic building block of an ester is shown in Figure 2. It is comprised of carbon (C), oxygen (O), and hydrocarbon chains presented by R and R'. The single and double lines represent a single bond and a double bond respectively. Note that C=O double bonds behave differently from the C=C double bonds found in the R chains of natural esters.

Natural Ester

Natural ester dielectric liquids are produced from vegetable oils, which are manufactured from plant crops (soybean, canola/rapeseed, sunflower, etc.). The structure of natural esters is based on a glycerol backbone, to which are bonded 3 naturally occurring fatty acids as shown in Figure 3. Plants produce these esters as part of their natural growth cycle and contain different amounts of double bonds in the fatty acid chain (i.e. R').

Figure 1. Mineral oil hydrocarbon structures [1]

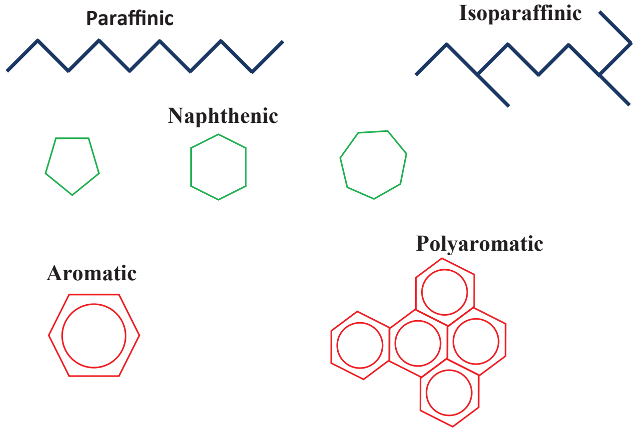
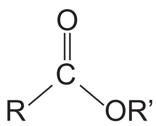
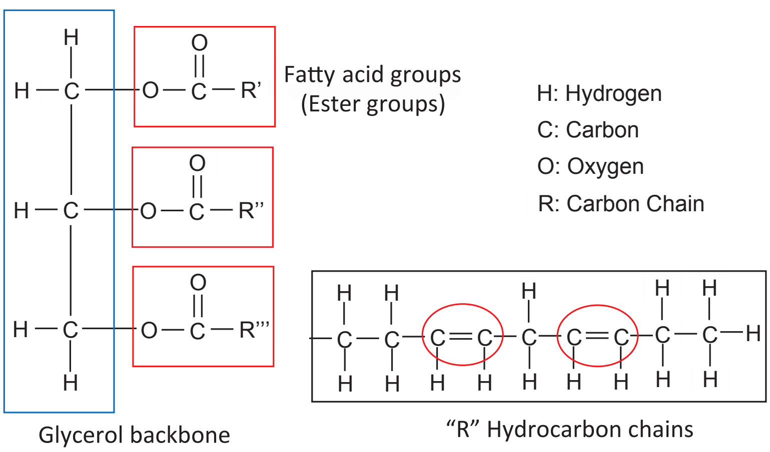


Figure 2. Basic building block of an ester



Natural esters should only be used in sealed systems where there would be no direct exposure to air for elongated periods of time.

Figure 3. Examples of a chemical structure of natural ester liquid



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Single and double bonds, saturation and oxidation stability

For the natural ester where all bonds in the 'R chain are single, the liquid is saturated and highly resistant to oxidation. Where double bonds are present, these can be broken as the liquid reacts with oxygen. Liquids which contain these double bonds are therefore referred to as unsaturated and need some degree of chemical stabilization to remain high performing in the presence of oxygen. Just as mineral oil dielectrics require inhibitors, natural ester dielectrics require anti-oxidant stabilizers for this reason and should only be used in sealed systems where there is no direct exposure to air for elongated periods of time.

Natural esters fall on a spectrum with respect to saturation. The spectrum is formally classified into mono, di- and tri- unsaturated (poly unsaturated) components (Table 1) which also carry the names oleic, linoleic and linolenic respectively [2]. While canola oil has a higher proportion of oleic content, this mono-unsaturated content is less susceptible to oxidation than the di-unsaturated linoleics and tri-unsaturated linolenics. Canola-derived esters therefore contain less of the more oxidation-prone fatty acids.

Figure 4 shows several vegetable-based oils with different ratios of poly-unsaturated, mono-unsaturated and saturated fatty acids. The higher the saturated fatty acid content, the higher the pour point of the liquid, which can limit the operational temperature of the transformer. By using specially formulated pour point suppressants, the pour point of the natural ester liquids can be improved.

Synthetic Esters

A synthetic ester dielectric liquid is designed using carefully selected acids and alcohols. A chemical reaction is created through esterification with heat to produce an ester and then any excess water is removed. The process is illustrated in Figure 5. Synthetic ester dielectric liquids are derived from chemicals and are usually the product of polyol alcohols (a molecule with more than one alcohol functional group)

Figure 4. Percentage of fatty acids in different base vegetable oils

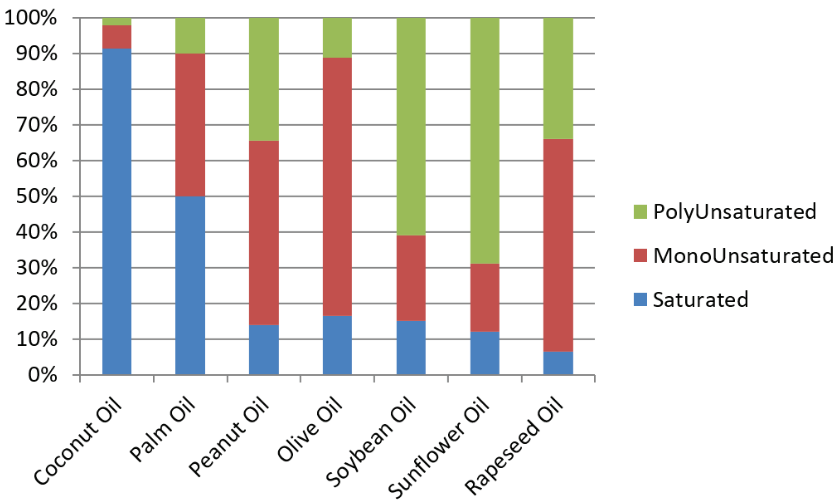


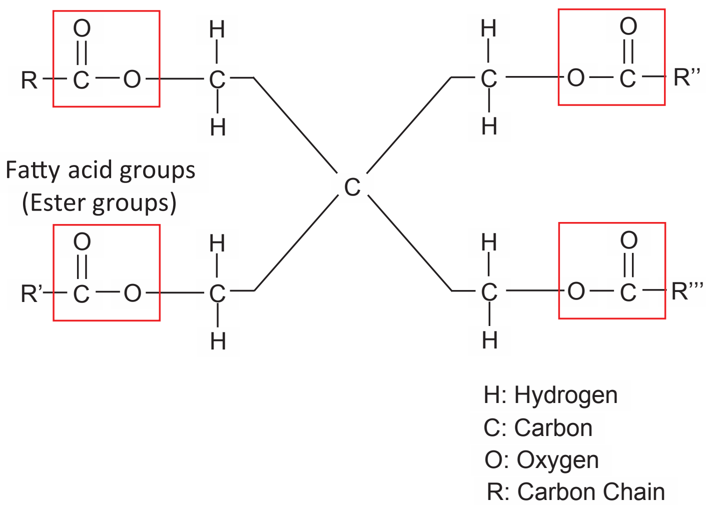
Table 1. Unsaturated fatty acid content in natural ester liquids.

Natural ester fluids	Less susceptible to oxidation	More susceptible to oxidation		Total
	Mono-unsaturated	**Di-unsaturated**	**Tri-unsaturated**	
	Oleic	Linoleic	Linolenic	
Soybean	24%	54%	7%	61%
Canola	62%	22%	10%	32%

Figure 5. Esterification process for synthetic esters

Acid + Alcohol + Heat → Ester + Water

Figure 6. Example of chemical structure of a synthetic ester with a central pentaerythritol hub with four ester groups



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Synthetic ester dielectric liquids are derived from carefully selected acids and alcohols through the chemical reaction of esterification.

with synthetic or natural carboxylic acids as shown in Figure 6. Chemically, synthetic esters consist of four ester groups where there is no double bond in the R chains between carbons (saturated bonds), which increases its oxidation and thermal stability.

Difference Between Natural and Synthetic Esters

The two fundamental differences in the physical properties of natural esters compared to synthetic ester liquids are oxidation stability and pour point.

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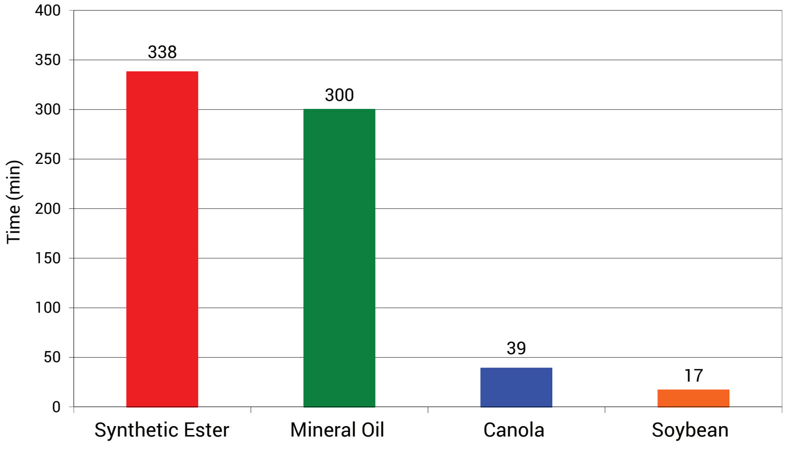
Oxidation Stability

Figure 7 shows test results for the different dielectric liquids following the ASTM D2112 pressurized vessel oxidation test method. The test is conducted in the presence of copper catalyst, pressurized at 90 psi with pure oxygen and heated to 140°C. The time is measured till the pressure drops to 65 psi due to pure oxygen consumption from the oxidation process. The longer the time, the better the oxidation stability.

Figure 7. Results of oxidation stability test according to ASTM D2112 test method



Oxidation stability is an important characteristic in the manufacturing, operation and maintenance of a transformer. If an insulating liquid oxidizes, the physical and chemical properties of the liquid change. In natural ester liquids, the viscosity of the liquid increases, the acid value increases, and the liquid starts to polymerize over time. The oxidation process in a transformer is a slow process that can be accelerated by an increase in temperature. In order to improve the oxidation stability of liquids, oxidation inhibitors are added which can prolong these changes to the chemical and physical properties of the liquid.

Pour Point

Another key difference between synthetic and natural esters is their pour point temperature. Pour point is defined as the temperature below which the liquid loses its ability to flow and pour down from a beaker. Table 2 shows the pour points of synthetic ester, canola based natural ester, and soybean based natural ester.

A lower pour point indicates better cold temperature performance of the transformer.

Comparison of Ester Liquids to Mineral Oil in Transformers

The chemical structures of ester liquids are more polar than mineral oil. This polarity has an effect on the moisture saturation limit, power factor and insulation resistance in a transformer. The gases generated (hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide and carbon dioxide) in ester liquids are the same as mineral oil, however the gassing behavior is different [3]. IEEE C57.155 has guidance on the gassing behavior of ester liquids. There are differences in the dielectric and thermal behavior of ester liquids compared to mineral oil. Leading transformer manufacturers are aware of these differences and address them when designing transformers. End users should be cautious in using the same limits set for mineral oil filled transformers as for an ester filled transformer in tests such as power factor, insulation resistance, and DGA.

Benefits of Using Esters in Transformers

As outlined earlier, the main reasons for adopting an ester as a transformer dielectric liquid include increased fire safety and better environmental protection. Additionally, esters have high moisture tolerance that can improve the life of the insulation system. These features are discussed as follows.

Table 2. Pour point for different types of esters

	Synthetic ester (MIDEL 7131)	Canola natural ester (MIDEL eN 1204)	Soybean natural ester (MIDEL eN 1215)
Pour point (ISO 3016)	-56 °C	-31 °C	-18 °C

Table 3. Fire classification of dielectric liquids according the IEC 61039:2008 based on fire point and net calorific value

Class	Fire point
O	≤300°C
K	>300°C
L	No measurable fire point

Class	Net calorific value
1	≥42 MJ/kg
2	≤42 MJ/kg and ≥32 MJ/kg
3	<32 MJ/kg

Liquid	Flash point ISO 2592	Fire point ISO 2592	Net calorific value	Classification to IEC 61039
Mineral Oil	160°C	170°C	46.0MJ/kg	O1
Synthetic Ester	275°C	316°C	31.6MJ/kg	K3
Natural Ester	316°C	360°C	37.5MJ/kg	K2

Fire Protection

Dielectric liquids are classified according to their Fire Point and Net Calorific Value, following the IEC 61039:2008 Standard "Classification of insulating liquids" [4]. Table 3 summarizes the classification.

K class liquids are recognized in the industry as "Less Flammable Liquids", which allows reduced separation distances between a transformer and its surroundings when it is installed indoor or outdoor. This is specifically mentioned in the IEC 61936 – 1, *"Power installations exceeding 1 kV a.c. – Part 1: Common rules"* [5] and FM Global Property Loss Prevention Data Sheets 5-4 [6]. As an example, the distances between a less flammable liquid insulated transformer with enhanced protection and an adjacent transformer or building can be reduced from 15.2 m in case of mineral oil down to 1.5 m in case of less flammable liquid in a transformer with enhanced protection, see table 3 in the IEC 61936-1 for more details [4].

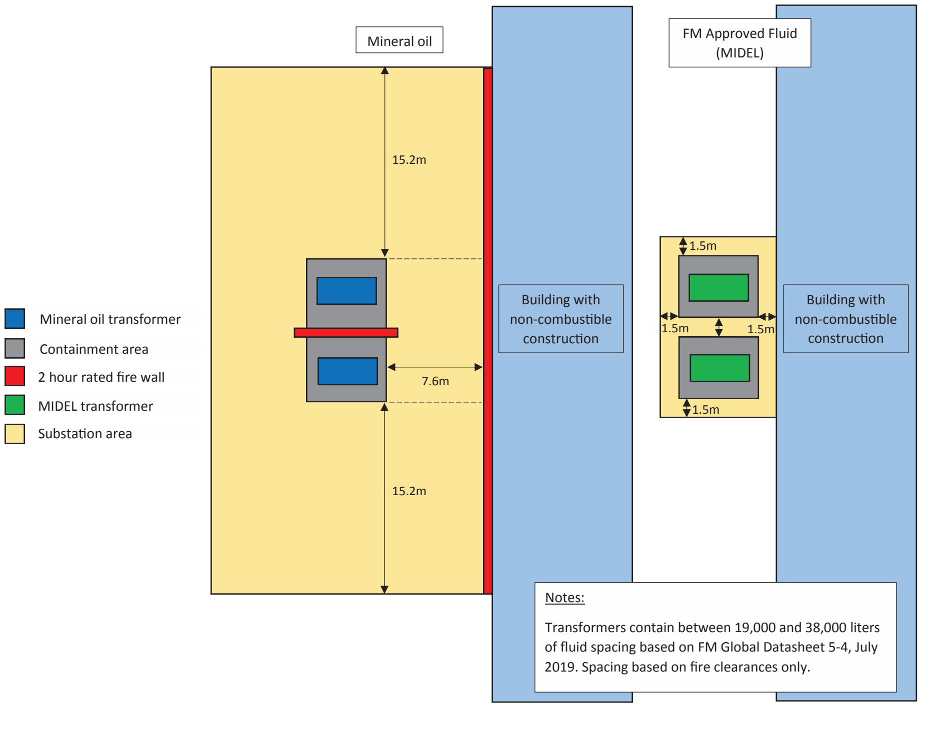
Figure 8 shows a visual demonstration of the benefits of using a less flammable liquid in a transformer. Savings can be achieved on space, concrete, and construction times following the FM Global guidelines [6].

Environmentally Friendly

Ester liquids are recognized as environmentally friendly since they are known as "readily biodegradable". Biodegradation is the process by which organic substances breakdown adequately enough for enzymes in soil or water to process them back to hydrogen and carbon (i.e. they become absorbed by the environment.). The biodegradation of ester dielectric liquids has been externally assessed by accredited laboratories using a standard test method developed by the Organization for Economic Cooperation and Development (OECD), a worldwide standard-setting body. To be classified as readily biodegradable a substance must satisfy the following criteria:

The main reasons for adopting an ester as a transformer dielectric liquid include increased fire safety and better environmental protection. Additionally, esters have high moisture tolerance that can improve the life of the insulation system.

Figure 8. Example of installation separation distances according to FM Global guidelines [6]



According to test method OECD 301B (test conducted over a 28-day period), in order for a product to be considered "readily biodegradable", a sample must achieve at least 60% degradation by day 28. Once a sample exceeds 10% biodegradation it must reach 60% within the next 10 days. For test materials that are not soluble in water, such as transformer liquids, measurements are taken of the oxygen consumed, or carbon dioxide produced, to determine the biodegradation percentage.

Figure 9 demonstrates that synthetic ester achieved 10% degradation by day 3, and by day 10 it achieved 61% degradation. On the 28th day, it reached 89% degradation, putting it comfortably in the "readily biodegradable" category. Similarly, soybean and canola based natural esters are superior in their biodegradation behavior; by day 10 they biodegrade to 85%.

Note that ester liquids will not biodegrade in a transformer. This is due to the fact that the conditions within the transformer are too hot and dry to sustain microbial life.

Moisture Tolerance
Due to the chemical structure, esters are able to tolerate more moisture while retaining higher breakdown voltage in comparison to mineral oil. This is well indicated with the plots shown in Figure 10. This provides advantages in locations of high humidity and remote transformers that are costly to check and monitor for leaks on the distribution network and thus save money in the field and generate better Total Cost of Ownership.

Esters have higher moisture saturation levels due to the free oxygen in the ester linkage which can attract and retain water molecules. In the ageing mechanism of the transformer, moisture is produced during the degradation of the cellulose material. The moisture generated attacks the cellulose chains further, increasing the rate of degradation. Because ester liquids hold more moisture than mineral oil, less becomes available to attack the cellulose chains and thus reduce the rate of degradation. The slower aging rate of cellulose in ester liquids is well documented in aging tests [7].

Application of Ester Liquids in Transformers

Natural ester and synthetic ester filled transformers have been used in distribution, power, and special transformers since the 1970s. As of today, the largest natural ester filled transformer is rated at 420 kV and the largest synthetic ester filled transformer is rated at 433 kV [8]. As these transformers are used more and more, it is important to understand what the strengths and limitations are of using the ester liquids based on application.

Ester liquids are recognized as environmentally friendly because they are “readily biodegradable”. However, they will not biodegrade in a transformer since the conditions within the transformer are too hot and dry to sustain microbial life.

Figure 9. Biodegradation results for synthetic ester and natural ester in reference to mineral oil.

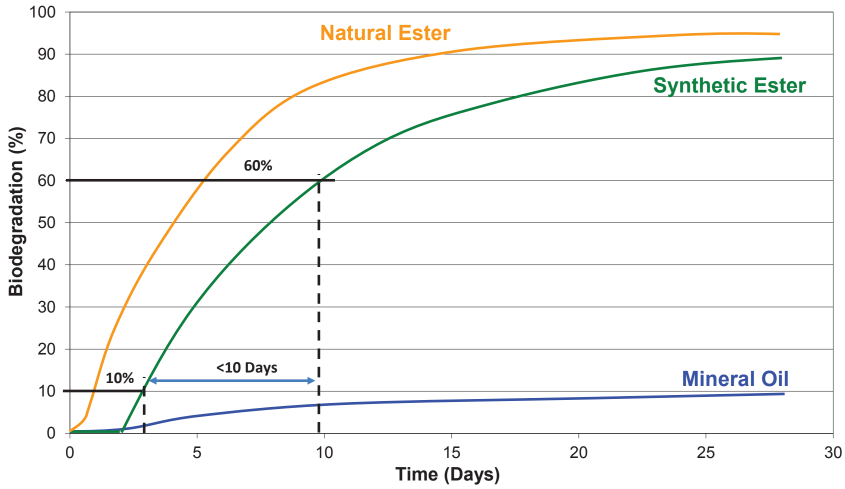
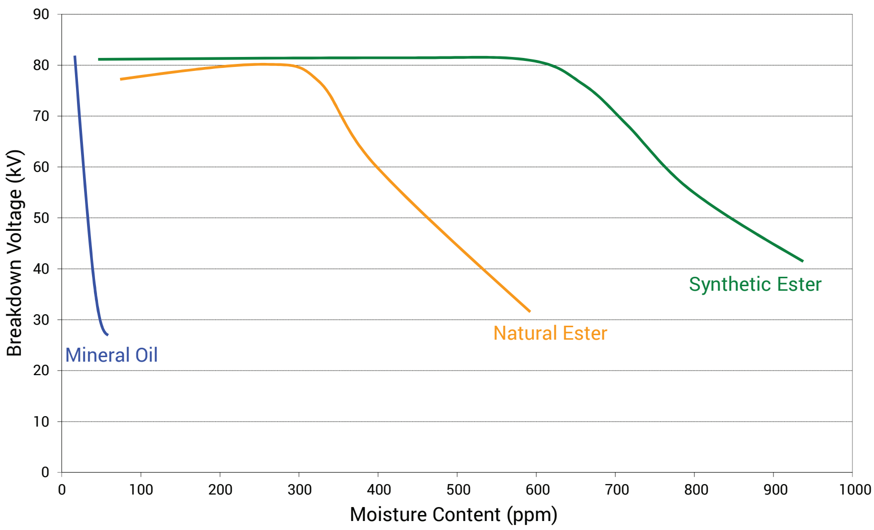


Figure 10. Breakdown voltage (kV) vs moisture content for different dielectric liquids. BDV is measured according to IEC 60156:2018 test method (2.5 mm gap) at 20°C.



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▼ **Breathing and non-breathing transformers**
Natural esters are not recommended for use in breathing transformers. Natural ester liquids are prone to oxidation and can solidify over time if used in breathing transformers causing cooling and dielectric issues. Synthetic esters on the other hand are perfectly suited for use both in breathing and non-breathing transformers. There have been instances where breathing transformers have been retrofitted for use with natural ester liquids. However, the long-term maintenance requirements need to be taken into consideration when retrofitting a breathing transformer.

▼ **Distribution transformer vs. power transformer**
Natural esters are perfectly suited foe sealed distribution transformers. They are a cost-effective solution that makes the transformers safer, provide an increased overload capability and are environmentally safer. Synthetic esters also work well for distribution transformers but are even more suited for power transformers than natural ester liquids. This is because they have the same benefits as natural ester in improving fire safety, environmental performance and insulation system life, but they can also be managed in a similar way to mineral oil. Because power transformers are more expensive, more attention is given to monitoring of the transformers to make sure that they operate under all circumstances. From a risk mitigation point of view, a synthetic ester can provide a better overall solution.

▼ **Operating conditions**
Transformers filled with ester liquids can work at a higher average winding rise (greater than 65°C rise). This is possible because ester liquids can operate at 90°C top liquid temperature rise compared to 65°C for mineral oil as per the IEEE C57.154 standard as the ageing rate of cellulose material in ester liquids is slower compared to mineral oil at similar operating temperatures. One thing to be mindful about at the higher operating temperatures is that in the event of a leak, the oxidation rate of insulating liquids increases as well. This would have to be taken into consideration with natural ester liquids as they have higher oxidation rate compared to mineral oil or synthetic ester liquids. In the case studies below, the 400 kV Highbury substation transformer is an excellent example of an innovative project that was designed to operate at high temperatures and the heat generated was captured and repurposed for another application.

▼ For cold temperature applications, transformer location, transformer loading profile, and what mechanical operations the transformer is subject to, need to be considered. Due to the difference from seed to seed for natural ester liquids, the proper selection needs to be made based on the conditions listed above. Soybean natural ester has a pour point of -18°C while canola natural ester has a pour point of -31°C. Synthetic esters, due to the pour point being below -50°C, are well suited in all cold temperature applications. If a transformer is operating at full load, the pour point of the transformer is not important, however if the transformer is lightly loaded, the cooling characteristics of the transformer would have to be analyzed to determine the effect on the hotspots of the transformer. The selection of a tap changer needs to be analyzed as a heater would have to be installed if the operating temperatures are below -18°C for synthetic ester and -10°C for natural ester liquids [9].

▼ **Retrofilling of transformers**
The use of ester liquids in retrofill applications is growing due to insurance, fire safety concerns and construction costs to existing transformer sites. Both natural and synthetic ester liquids have proven to be effective in retrofilling of existing transformers to 69 kV. Above this size, retrofilling decisions become design dependant due to the dielectric property differences between esters and mineral oils. Selection of using natural ester versus synthetic ester is dependent on the end users' needs and capability of handling maintenance requirements of the transformer with respect to oxidation.

K class liquids are recognized in the industry as "Less Flammable Liquids", which allows reduced separation distances between a transformer and its surroundings when it is installed indoor or outdoor (further reducing costs).

Figure 11. 28 MVA, 138 kV transformer filled with MIDEL eN1204 for a mine in Canada. (Photo courtesy of Northern Transformer)

Figure 12. 400 kV transformers with MIDEL 7131 synthetic ester for Highbury substation in London, U.K. (Photo courtesy of Siemens Transformers)

Photo: Shutterstock; MIDEL

Case Studies and Future Projects

The use of ester based dielectric liquids in transformer applications extend to over 40 years; starting when the synthetic ester MIDEL 7131 was first invented and used to retrofill existing furnace transformers to replace PCB oil at British Steel, in the U.K.

Some recent case studies include:

First canola natural ester filled transformer in North America rated at 138 kV

A 28 MVA transformer filled with canola natural ester was commissioned for use in a mine in Canada (Figure 11). The end user selected canola over soybean natural ester because the transformer was to be operational in ambient temperature below -25°C.

Highbury Substation, London, U.K.

Three 400 kV power transformers, filled with synthetic ester, were used to reduce the substation footprint in a highly confined location in London, U.K. The original substation had three old transformers filled with mineral oil and once the substation was due for refurbishment, the utility was restricted in using a limited space for the substation. Synthetic ester allowed reduced clearances between the transformers and adjacent objects/building and this saved considerable amounts on estate, concrete, and construction times without compromising on fire safety or on environmental protection.
On top of achieving the primary objectives from synthetic ester use, the utility desired to upgrade the project to extract the heat generated from the transformers from electric losses and heat a nearby school and residential building, in effect significantly reducing the carbon footprint of the substation. Figure 12 shows a picture of one of the transformers used in that substation enclosed with thermal jacket to control heat dissipation from the transformer to water heat exchanger of the substation.

Some of the upcoming projects with ester filled transformers include:

a) 400 kV natural and synthetic ester filled transformers in India
b) 420 kV canola natural ester filled transformer in Germany
c) Largest wind turbines rated at 12 MW will include transformers filled with synthetic ester
d) Several 230 – 345 kV synthetic ester filled power transformers for utilities in North America
e) 230 kV canola natural ester filled transformers in China
f) Several mines worldwide are retrofilling mineral oil filled transformers and purchasing new transformers filled with natural and synthetic ester liquids. The esters are also being specified instead of silicone liquid for new transformers because ester filled transformers are cheaper to manufacture and operate, easy to source and provide the benefits of less flammability as silicone liquid.
g) Larger use of natural and synthetic esters in indoor transformers, renewables, and industrial application
h) Research in use of synthetic ester liquid in transformer rated at 500 kVA and up
i) Research in use of synthetic esters in HVDC transformers

Conclusion

From their initial use and through the decades, there have been no reported fires due to the use of ester liquids in transformer fleets. Ester liquids allow for innovations to take place in transformers to make them – fit in smaller footprint, have better return on investment, environmentally friendly and most of all SAFER. Regarding the types of natural or synthetic esters to use in transformers, an end user can make a selection and decision based on the requirements of the project as the various liquids offer different options in each application.

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