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Eco-friendly ester liquid transformer designs

Ester liquids have been used in transformers for insulation and cooling purposes for over 20 years. These liquids greatly reduce environmental impact and significantly mitigate spillage and fire risks. Recent experience underlines the benefits of using ester liquids instead of traditional mineral oils.

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Since the 1990s, ester liquids have been gaining acceptance for transformer insulation and cooling →1, with application voltages now reaching 420 k. This shift from traditional mineral oils can be attributed to growing environmental awareness and the need to address the risks of tank rupture and fire, especially in crucial locations. Ester liquids lend themselves as a natural and safe, and almost obvious, solution, and they have related benefits such as smaller substation footprint and simplified oil containment design [1-2]. The 10 to 15 percent extra cost of ester-filled transformers is more than compensated for by the benefits it brings.

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Parameter	Unit	Envirotemp FR3	MIDEL 7131	Mineral oil
Density at 20 °C	g/ml	0.92	0.97	0.87
Kinematic viscosity at 100 °C	mm^2 /s	8	5.25	3
Kinematic viscosity at 40 °C	mm^2 /s	33	29	12
Kinematic viscosity at 0 °C	mm^2 /s	190	280	76
Thermal conductivity at 20 °C	W/m K	0.167	0.144	0.120
Pour point	°C	-21	-60	-60
Flash point	°C	315	275	160
Fire point	°C	355	317 ± 5	170
Relative permittivity	-	3.2	3.2	2.2
Classification of flammability	-	K	K	O
Breakdown voltage IEC 60159 2.5 mm	kV	73	> 75	> 70
Dielectric dissipation factor, Tan σ at 90 °C 50 Hz	-	0.005	< 0.008	< 0.002
Moisture saturation at ambient temperature	ppm	1,000	2,700	55

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01 As transformer insulation and coolants, ester liquids have many advantages over traditional oils.

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02 Comparison of different liquid characteristics.

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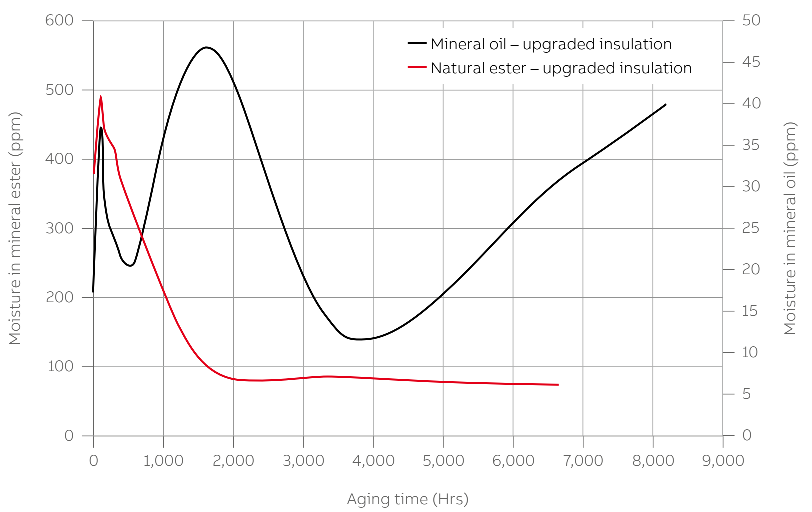
03 Moisture evolution in cellulose impregnated with natural ester and mineral oil at 130 °C.

In recent years, much progress has been made in ester-filled transformer applications, especially in the realms of:

- Eco-efficiency and safety
- Life extension – slower aging of insulation and longer lifetime
- Overloadability – flexibility in handling the load or minimizing footprint for mobility

Eco-efficiency and safety

The major safety and environmental concerns of transformers are catastrophic failure and oil spill. Small leaks can occur due to handling errors (eg, overfilling) but more serious leakages happen when a unit ruptures. Leakages can also lead to fires: of the around 1 percent of failures that necessitate major repair or scrapping [3], one-tenth result in a transformer fire.



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This seemingly low incidence rate conceals a significant risk as, on top of danger to workers and reputational loss, the average cost of replacement, clean-up and lost revenue is about $3 million, and individual cases have been known to incur costs of up to $86 million [4].

In any of the abovementioned situations, cooling and insulation fluid biodegradability, and high flash and fire point, improve operator safety, while reducing the impact and cost of cleanup.

Natural ester liquids are classified (see, eg, standard EC 61039) as non-toxic and readily biodegradable substances. Therefore, spills are characterized as nonhazardous.

If a transformer protection system is slow to react to a low-impedance fault, the high-energy internal arc generated can produce gases that lead to overpressure and tank rupture, thus allowing the ingress of oxygen to create a fire-prone environment [2]. For such failures, the most important parameters of the liquid used are its flash and fire point values. Compared with mineral oil, ester liquids have much higher flash and fire point temperatures →2. They meet the US National Electric Code (NEC) definition of less flammable dielectric liquids and are recognized as such by both FM Global and Underwriters Laboratories (UL), both independent product safety certification organizations. The byproducts of the combustion of natural esters are much less toxic than those of mineral oils, further reducing their overall impact on the environment.

Hydro plants that are located close to sensitive waters, for example, can benefit from the reduced environmental threat provided by ester-filled transformers.

	IEEE C57.154-2012		IEC60076-14	
	Mineral oil	Ester fluid	Mineral oil†	Ester fluid
Maximum continuous temperature rise limits for transformers with high-temperature insulation systems				
Minimum required high-temperature solid insulation thermal class	120	140	120	140
Top liquid temperature rise, (°C)	65	90	60	90
Average winding temperature rise, (°C)	65	85	75	95
Hottest spot temperature rise, (°C)	80	100	90	110
Suggested maximum overload limits for transformers with high-temperature insulation systems				
Maximum top liquid temperature with normal life expectancy (°C)	105	130	105	130
Maximum top liquid temperature with loading above nameplate rating (°C)	110	140	115	140
Maximum solid insulation hottest spot temperature with normal life expectancy (°C)	120	140	115	140
Maximum solid insulation hottest spot temperature with planned loading beyond nameplate rating (°C)	130	150	130	150
Maximum solid insulation hottest spot temperature with long-term emergency loading (°C)	140	160	140	160

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†For semi-hybrid insulation winding

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04 Maximum continuous temperature rise limits and suggested overload temperature limits for 120- and 140-class insulated transformers.

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05 138 kV compact mobile substation filled with a natural ester insulating liquid, in transit.

Between 2002 and 2016, ABB delivered 14 transformers with powers ranging from 16 to 40 MVA to the Warmian-Masurian region of Poland, well-known for its many nature reserves and lakes, and for being part of the EU Natura 2000 project. The choice of synthetic ester liquid Midel 7131 contributed to the protection of the landscape by obviating the need for oil containment and fire suppression systems.

Life extension – slower aging of insulation and longer lifetime

The lifetime of a power transformer is defined by the decay rate of its cellulose insulation. This decay increases with increasing oxygen and water content in the paper and the surrounding insulating medium.

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Insulation systems composed of ester liquids and cellulose materials have been shown to operate with lower moisture content in the insulation system and endure higher temperatures than those composed of mineral oil and cellulose materials, making them an ideal choice [5].

There are three factors that contribute to the lower aging rate and longer lifetime of ester-filled transformers:

- The moisture content in the mineral-oil-filled system increases with time, while that of the ester-filled system declines. An ester-filled cellulose insulation system operates with lower cellulose insulation moisture content than one filled with mineral oil →3.
- The solubility of water in ester liquids is several times higher than in mineral oil at typical transformer operating temperatures. This means more water is drawn out of the paper into the ester liquid.
- Cellulose polymers change when aged in natural ester liquids. The chemical reaction of water generated during the cellulose aging process with natural esters produces free fatty acids that attach to the cellulose structure through a reaction called trans-esterification, thus forming a barrier to water ingress, leading to a decline in the rate of deterioration of the cellulose insulation [5].

The practical result of the combined effect of all these phenomena is that cellulose insulation has a 20 °C thermal advantage when aged in ester liquids [5-6]. Specifically, for the same life expectancy, cellulose impregnated with ester liquids can be designed with a 20 °C higher hottest spot temperature than one with mineral oil.

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06 200 MVA/420 kV liquid-ester unit.

Overloadability – flexibility in load handling or minimizing footprint for mobility.
In a typical transformer design, the insulation system limits the highest temperature at which the conductors and metallic parts can operate. For a conventional system with mineral oil and thermally upgraded cellulose insulation, the highest temperature allowed is 105 °C for the oil and 120 °C for the conductor →4. Higher MVA supplied for the same footprint would mean higher temperatures in the transformer, which shortens its lifetime. To achieve higher MVA in the same or smaller footprint, the transformer would need to be designed using high-temperature insulation materials. Such materials, like ester liquids and ester-liquid impregnated cellulose, allow operation at higher temperatures without appreciable deterioration of the insulation system. Also, there should be no additional risk of failure from operating the transformer at higher temperatures.

For transformers insulated with thermally upgraded cellulose and ester liquid, the limit for the top oil temperature is 130 °C and the hotspot temperature under normal cyclical loading can be as high as 140 °C. The only limiting factors will be transformer components such as tap changers or bushings, which will also have to sustain much higher temperatures.

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Consequently, low- and medium-power transformers with ester liquids can be overloaded continuously by an average of 25 percent without negative impact on their lifetime. In combination with Aramid insulation – a high-temperature insulation paper material that can be used up to 200 °C – the overloadability of such transformers can be even higher without appreciable loss of life. This combination leads to the ultimate value proposition for end users: transformers with the same performance but with a much smaller footprint.

For example, instead of using two 30 MVA conventional transformers to meet a station capacity of 60 MVA, two 20 MVA ester liquid insulated transformers (with their additional overload capability) could be applied to meet the load and contingency requirements for the station. Also, these lower-rated transformers use less core steel and therefore will have lower no-load losses. The higher thermal performance of ester-liquid-insulated transformers can be used to advantage in mobile transformer applications →5, offshore applications and industrial production applications.

A global trend
In comparison to mineral oil, ester liquids have cost, operation and safety advantages in specific applications. They require careful design, production process considerations and compatible material and accessories selection [7]. When such considerations are made, ester liquids can be used in high- voltage power transformers →6. ABB has delivered more than 200 ester-filled power transformers.

Globally, environmental requirements are increasingly part of the business decision process. One major goal is to retain as much value as possible from resources, products, parts and materials to create a system that allows for long life, optimal reuse, refurbishment, remanufacturing and recycling. ABB's eco-efficient power transformers can help do this. ●

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