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Experiences in Service with New Insulating Liquids

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Experiences in service with new insulating liquids

Working Group A2-35

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Executive Summary

For the majority of transformer applications, mineral oil is an acceptable, cost-effective insulating fluid, and this situation is likely to continue well into the future. However, in applications where fire safety and protection of the environment are important considerations, transformers based on alternative fluids can be a more viable option.

The use of alternative fluids in transformers is not new technology; these fluids have been used for many years, mainly in distribution transformers. Lately there has been a clear trend to use these fluids at ever increasing voltages and power ratings, and now there are many examples of these fluids being used in high voltage and high power transformers.

It is clearly evident power grids worldwide are expanding, based upon existing technology and also important new renewable technologies which are rapidly emerging, to supply energy in the coming decades. Because of their many advantages, the family of alternative fluids will play an increasing role in the transformers of the future as part of these networks.

This Technical Brochure covers the in service experience of ***synthetic esters, natural esters and silicone fluids***. It is designed to give the reader an overview of the current knowledge about these fluids, the advantages they have to offer, and how they perform in service.

Topics covered include an overview of how the fluids are currently used, their properties, considerations impinged on transformer designing and manufacturing, testing regimes, handling precautions and reliability.

In summary, background knowledge on physical and chemical differences between the alternative fluids and mineral oil are given in chapter 2, whereas the researches and testings in laboratories on the electrical properties of alternative fluids are summarised in chapter 3. Various practical subjects for the use of alternative fluids in a transformer are then described in the chapters following-up.

As an important part of this study, the group commissioned an in-depth survey of industrial users of alternative fluids. Responses were received from key utilities, end users and transformer manufacturers from 12 major countries around the globe. The questionnaire was constructed so that individual company information would be protected, thus giving the companies the freedom to share the vital decision making information with the readers of this technical brochure.

A complete listing of IEC, IEEE and ASTM standards is comprehensively tabulated so that the reader should be in no doubt which standards apply to their fluid of choice.

The intention of this Technical Brochure is to give the reader sufficient background information to make an informed choice, or to follow up with their own research on topics which need further investigation. Last but not least, it was written by a team of over 20 experts from the field of transformers, drawn from fluid manufacturers, transformer manufacturers, university researchers, end users and utilities.

1 Introduction

Esters have been used as dielectric liquids since the invention of oil-filled transformers in the late 1880s. The earliest simple natural ester dielectrics were subsequently found to be incompatible with free breathing equipment, because of their chemistry, and were gradually replaced by mineral oils. Later, silicone fluids made an appearance, offering a high fire factor alternative. However, they were found to be environmentally questionable.

The electrical power transmission and distribution industry has for some time expressed a growing interest and need for environmentally friendly dielectric fluids, as viable alternatives to mineral oil and PCBs. However, in order for these fluids to have widespread appeal, they must also demonstrate that they are safe, economical, and offer a high standard of electrical performance over a long working life. Silicone and synthetic ester dielectrics have been successfully used for almost 40 years and continue to grow in popularity. In the last 10 years there has been a resurgence of usage in the use of natural ester dielectrics because of their obvious ‘green’ credentials.

To help understand the nature of alternative dielectric fluids and how they differ from mineral oil, this report attempts to explain the fundamental aspects of chemical, physical and dielectric properties of insulating liquids, and to summarise their in-service experiences of the alternative fluids to mineral oil. For the purposes of this brochure, the alternative fluids under discussion are natural esters, synthetic esters and silicone fluids.

2 Overview of the Current Application of Alternative Fluids[1,2,3,4,5]

Alternative fluids are now widely used in a variety of transformer applications, covering transformers for distribution, power and traction, but not yet including instrument transformers, as these have only recently been introduced as prototypes. Currently the knowledge database of alternative fluids is growing rapidly which may encourage end users to look at these fluids, as more and data become available.

Table 2.1 briefly summarizes the up-to-date distribution of the use of insulating liquids in the various applications.

Table 2.1: Use of insulating liquids

	Mineral oil	Silicone fluid	Synthetic ester	Vegetable oils (natural ester)
Power transformers	A	X	B	B
Traction transformers	A	A	A	X
Distribution transformers	A	A	A	A
Instrument transformers	A	X	X	X

(Key: A = Largely used, B= Used but less common, X = Currently not used)

2.1 Mineral oil

Mineral oil is the most commonly used insulating liquid for transformer applications, and years of experience with using mineral oils has led to the accumulation of a large knowledge database. However nowadays due to the environmental concerns, the use of a mineral oil is subject to additional requirements[6] :

The choice of a new mineral oil is guided by the IEC 60296 standard. In service evaluation of mineral oils is defined by the standard IEC 60422.

2.2 Silicone fluid

Silicone based liquids have been used by transformer manufacturers since the end of 1970’s[7], as an alternative to the PCB based liquids, mainly for fire safety applications.

As a highly stable and fire resistant fluid, silicone fluid is widely used in traction transformers and also in increasingly compact transformers where higher than normal operating temperatures are expected. In most cases, silicone liquid is used in conjunction with high temperature solid insulation. Silicone transformer fluids are also known to have an excellent oxidation resistance and can operate without forming copious amounts of degradation products or sludge[8]. Silicone fluids have a poor environmental property due to their resistance to biodegradation which may restrict their use in environmentally sensitive areas, and also their disposal may be problematic.

Silicone fluids are also used in distribution transformers because of their fire resistance and high thermal stability[9]. However because of their high viscosity reduces the fluid's capability to transfer heat, their use is somewhat restricted in applications where the addition of coolers or pumps is not possible.

To date, there are no power transformers filled with silicone liquids, except that Japan has recently developed a lower-viscosity silicone fluid for a power transformer 66kV/30MVA[10,11].

New silicone fluids are in accordance with the IEC 60836 and a maintenance guide is available as IEC 60944.

2.3 Synthetic ester

Synthetic esters are used mainly in distribution transformers and in transformers where fire safety and environmental protection are a prime concern. They are increasingly being used in power transformers and in transformers where demanding conditions are experienced, such as traction, trackside and wind farms[12].

They are commonly used where high temperatures are expected, and in this regard they can be used in combination with high temperature solid insulation such as aramid papers.

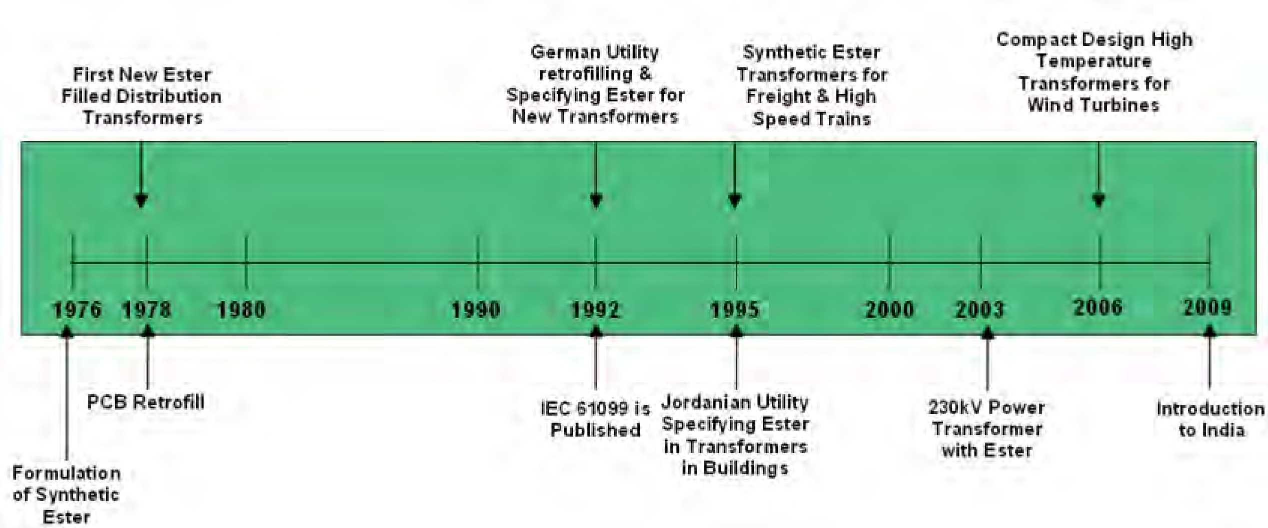


Figure 2.1 – Timeline of events in the development and application of synthetic ester dielectric fluids

Recent years have seen the application of synthetic ester liquids in power transformers, mainly for fire safety and environmental reasons[13,] but also for the reported benefits of the synthetic esters with regards to moisture absorption in cellulose[14].

Synthetic esters have been used extensively to retrofill existing mineral oil distribution transformers where the end user requires a higher degree of fire safety and environmental protection.

Unused synthetic esters are supplied in accordance with IEC 61099 and a maintenance guide is available as IEC 61203.

2.4 Natural esters

Since the beginning of the 1990's, because of increasing environmental concerns, companies started to develop vegetable oils as transformer fluids. These natural ester fluids have been commercially used since 1999[15,16,17], as shown in Figure 2.2.

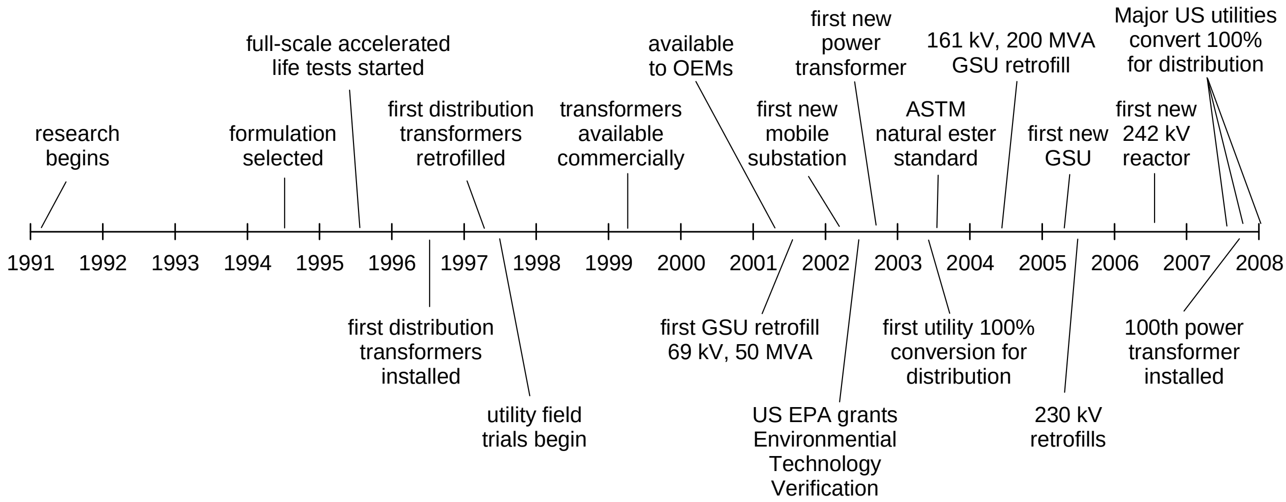


Figure 2.2 - Timeline of events in the development and application of natural ester dielectric fluids

Nowadays, natural esters are widely used in the distribution transformers. Figure 2.3 shows how their popularity in this market has increased.

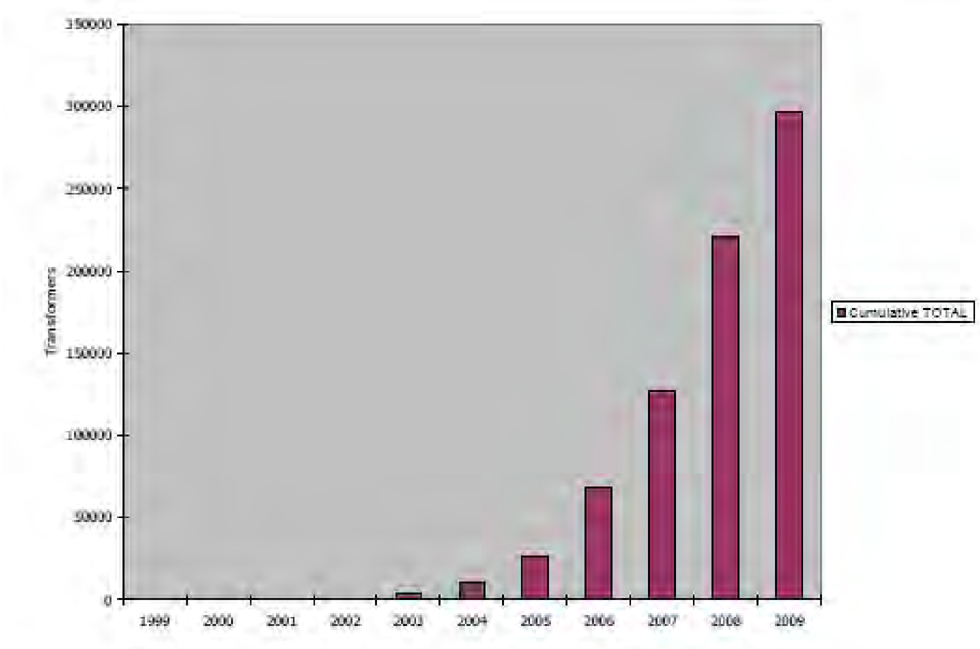


Figure 2.3 - Number of natural ester distribution transformers in service – worldwide

Laboratory studies have demonstrated that natural ester fluids also seem to have application in power transformers[18,19,20] coupled with the practical experience of over 200 power transformers up to 200 MVA and 242 kV being energized and operating globally.

An IEEE Guide C57.147 – "IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers" was published in 2008, and an ASTM Specification "ASTM D6871-03 (2008)" is available. The IEC is also developing its own unused natural ester standard.

3 Physical and Chemical Differences between the Alternative Fluids and Mineral Oil

3.1 Types of insulating fluids

For the purposes of this brochure, the alternative fluids under discussion are natural esters, synthetic esters and silicone fluids. In order to understand the properties of these fluids, it is first necessary to understand their chemical composition and how it compares to mineral oil.

3.1.1 Mineral oil

Mineral oil is a hydrocarbon mixture produced from the distillation of crude oil. Because of its wide availability, useful properties and low cost, mineral oil is the insulating liquid most commonly used in the transformer industry, and currently is the most common insulating liquid used for medium and large power transformers.

Mineral oil is a transparent, colorless liquid composed mainly of various types of hydrocarbons, including:

- straight chain alkanes
- branched alkanes
- cyclic paraffins
- aromatic hydrocarbons

There are two principal types of mineral oil used for transformers, produced as a result of different oil refining processes:

Paraffinic oil is derived from crude oil containing substantial quantities of naturally occurring n-paraffins. Paraffinic oil has a relatively high pour point and may require the inclusion of additives to reduce the pour point.

Naphthenic oil is derived from crude oil containing a very low level (or none) of naturally occurring n-paraffins. Naphthenic oil has a low pour point and requires no additives to reduce the pour point. Naphthenic oil provides better viscosity characteristics and longer life expectancy. Naphthenic oil has more polar characteristics than paraffinic oil.

Transformer oils contain inhibitors which delay the oxidation of oil. These inhibitors might be natural, as occur in uninhibited mineral oils, or synthetic and added, as in inhibited oils.

Uninhibited oils must be free of additives, either natural or synthetic, which are used to improve oxidation stability. This includes but is not limited to 2,6 di-tertiary-butyl phenol, 2,6 ditertiary-butyl paracresol, or metal deactivators such as benzotriazole and its derivatives. However in the US, the IEEE accept that < 0.08% inhibitor can be classified as uninhibited.

Inhibited oils are insulating oils which have been supplemented with either 2,6 ditertiary-butyl phenol or 2,6 ditertiary-butyl paracresol or any other specified and acceptable oxidation inhibitor.

New mineral oils are produced to be in accordance with the IEC 60296 or ASTM D3487. Since mineral oil has been used for such a long time, a large database of information is available to enable interpretation of changes to its characteristics and thus predict the possible malfunction of a transformer. IEC 60422 is a good tool to evaluate the quality of insulating oils in operational transformers.

3.1.2 Silicone fluid

Silicones (more accurately called polymerized siloxanes or polysiloxanes) are mixed inorganic-organic polymers with the chemical formula $[R_2SiO]_n$, where R = organic groups such as methyl, ethyl, and phenyl. These materials consist of an inorganic silicon-oxygen backbone (...-Si-O-Si-O-Si-O-...) with organic side groups attached to the silicon atoms.

In some cases organic side groups can be used to link two or more of these -Si-O- backbones together. By varying the -Si-O- chain lengths, side groups, and crosslinking, silicones can be synthesized with a wide variety of properties and compositions.

The most common example is poly(dimethylsiloxane) or PDMS. This polymer has a repeating $(CH_3)_2SiO$ unit, as shown in Figure 3.1, and this is the silicone fluid used in transformers.

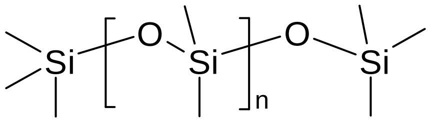


Figure 3.1 - Silicone fluid as used for transformers

The raw materials for the manufacture of this type of silicone are sand and methanol. The intermediates produced during the manufacture are all internally recycled back into the process.

This fluid has the advantage of having a high thermal and oxidation stability, but conversely biodegrades to a very small extent over a long period.

New silicone fluids are produced in accordance with IEC 60836. The published in-service maintenance guide is IEC 60944.

Lower viscosity silicone fluids have also been developed and are employed mainly in Japan. These fluids are produced in the same way as the standard silicone fluids with the same basic chemical structure, but the length of the polymer chains are shorter. This has the effect of reducing the viscosity of the product.

3.1.3 Esters – an introduction

The term ‘ester’ comes from the chemical linkage which is formed from the reaction of an alcohol and a fatty acid.

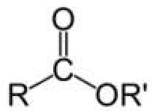


Figure 3.2 - The ester linkage

In Figure 3.2 O represents oxygen, C represents carbon, R and R’ represent carbon chains, which may be the same or different. The single line represents a single bond, and a double line represents a double bond. Note that C=O double bonds behave differently from the C=C double bonds found in the chains of natural esters.

As the name implies, the ester linkage occurs in both natural and synthetic esters, but does not occur in mineral or silicone oils.

3.1.3.1 Synthetic ester fluid

Synthetic esters are derived from chemicals. They are usually the product of a polyol (a molecule with more than one alcohol functional group) with synthetic or natural carboxylic acids to give structures where several acid groups (usually 2, 3 or 4) are bonded to a central polyol structure, such as those made from the tetra-alcohol pentaerythritol $C_5H_{12}O_4$. Importantly, the acids used are usually saturated (no C-C double bonds) in the chain, giving the synthetic esters a very stable chemical structure.

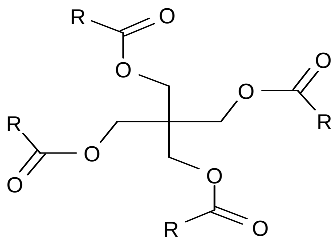


Figure 3.3 – Structure of synthetic ester

Synthetic esters offer the advantage of good oxidation and thermal stability as well as good biodegradability. Thus synthetic esters are particularly appreciated in applications where fire resistance is important and spillage/environmental concerns are critical.

New synthetic esters are produced in accordance with IEC 61099 and an in-service maintenance guide that is published as in IEC 61203.

3.1.3.2 Natural ester fluids

Natural esters are produced from vegetable oils, which are themselves manufactured from renewable (sustainable) plant crops.

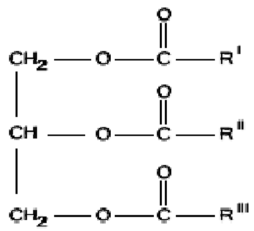


Figure 3.4 – Structure of natural ester

The structure of the natural esters is based on a glycerol backbone, to which 3 naturally occurring fatty acid groups are bonded. Again, these fatty acids may be the same or different. Plants produce these esters as part of their natural growth cycle. They are stored in the seeds, and can provide a valuable high calorific foodstuff when harvested.

Natural esters offer the advantage of high fire point as well as good biodegradability, but all types of natural esters suffer from not being as oxidation stable as other types of insulating liquids.

Although natural ester fluids can be produced from a wide variety of crop oils, natural esters for electrical applications are most commonly produced from soya, rapeseed and sunflower oil. This is due to factors such as availability, cost and having the desired performance characteristics. Other crop oils such as coconut oil have been used, but their use is not as widespread as the main crop oils and generally occurs in countries where these crops are common. It is possible that in the future as the popularity of natural esters grows, other crop oils might appear on the market.

The IEC is currently working towards standard for unused and in-service natural ester fluids. In the US, two guides are available: IEEE C57.147-2008 and ASTM D6871-03 (2008).

3.2 Comparison of properties of transformer fluids

An overview of the properties of the different types of insulating liquids is presented in Table 3.1, and the physical and electrical properties of the commercially available transformer fluids are given in Table 3.2.

Table 3.1 – Overview of properties of transformer insulating fluids

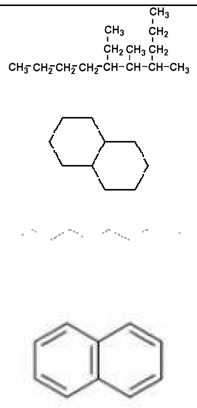
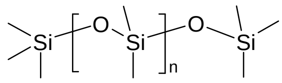
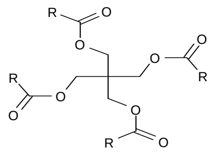
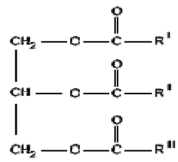
Name	Mineral oil	Silicone fluid	Synthetic ester	Natural ester
Type	Refined crude oil based distillate	Synthetic	Synthetic	Refined vegetable oil
Principal components	Complex mixture of hydrocarbons	di-alkyl silicone polymer	Pentaerythritol tetra ester	Plant based natural ester
Chemical structure				
Source	Purified from oil	Made from chemicals	Made from chemicals	Extracted from crops
Biodegradability	Slow to biodegrade	Very slow to biodegrade	Readily biodegradable	Readily biodegradable
Oxidation stability	Good stability	Excellent stability	Excellent stability	Generally oxidation susceptible
Water saturation at ambient (ppm)	55	220	2600	1100
Flash point, °C	160 - 170	>300	>250	> 300
Fire Point, °C	170 -180	>350	>300	>350
Fire Classification	O	K	K	K

Table 3.2 - Physical and electrical properties of insulating liquids

Data measured or calculated from suppliers' literature – note that other fluids are in development but it is not possible to include all in this table.

For test methods refer to fluids manufacturers' literature.

			Silicone fluids		**Synthetic ester**	**Natural esters**	
		Nynas	**Dow Corning**	**Shin-Etsu Chemical**	**M&I Materials**	**Cooper Industries**	**ABB**
	Units	**10 GBN Mineral oil**[21]	**561 Silicone oil**[22]	**KF-96-20 Lower viscosity fluid**[23, 24]	**MIDEL 7131**[25]	**FR3**[26]	**BIOTEMP**[27, 28, 37]
General Properties							
Density at 20°C	g/ml	0.88	0.96	0.956	0.97	0.92	0.91
Specific heat at 20°C	J/kg K	1860	1510	1600	1880	1883	1943
Thermal conductivity at 20°C	W/m K	0.126	0.151 (@ 50°C)	0.15 (@ 25°C)	0.144	0.167	0.160
Kinematic viscosity at 0°C	mm^2/s	37.5	86	32.8	240	207	276
Kinematic viscosity at 20°C	mm^2/s	22	54	22	70	78	97
Kinematic viscosity at 40°C	mm^2/s	9	39	15.3	28	36	42
Kinematic viscosity at 100°C	mm^2/s	2.6	15	6.7	5.25	8	9
Pour point	°C	-50	< -50	< -60	-60	-21	-15 to -20
Expansion coefficient	/°C	0.00075	0.00104	0.00104	0.00075	0.00074	0.00068
Flash point	°C	148	> 300	268	275	330	330
Fire point	°C	170	> 350	312	322	360	360
Autoignition temperature	°C	280	435		438		
Fire hazard classification to IEC 61100		O	K3	K3	K3	K2	K2
Biodegradability at 28 days							
- OECD 301F	%	N/A	N/A		> 89	>99	
- OECD 301D	%	< 10	< 5				
- OECD 301B	%					95 -100	(readily biodegradable)[1]
Gassing Tendency	µL/min	+5 ; Nitro 10CX = 30			29.2	-79.2	-50
RBOT Test	minutes	300			421	17	197
Chemical Properties							
Neutralisation value	mg KOH/g	< 0.01	< 0.01	< 0.01	< 0.03	0.022	< 0.03
Net calorific value	MJ/kg	46	28		31.6		36.9
Electrical Properties							
Breakdown Strength IEC 60156 2.5mm	kV	> 70	50	70	> 75	56 (ASTM 1816)	>75
Dielectric dissipation factor at 90°C		< 0.002	< 0.001	< 0.001	< 0.006	0.005	0.014
Permittivity at 20°C		2.2	2.7 (@ 25°C)	2.46 (@ 90°C)	3.2	3.2	3.2

[1] BIOTEMP biodegradability has been measured at 97-99% according to the 21 day test method CEC L-33-A-94[44]

3.2.1 Comparison of viscosities

The viscosity of a fluid is one of the key parameters in determining the cooling capability of the fluid from the perspective of designing transformers. The following graphs show both the logarithmic and linear plot of viscosity versus temperature for the commonly used transformer fluids.

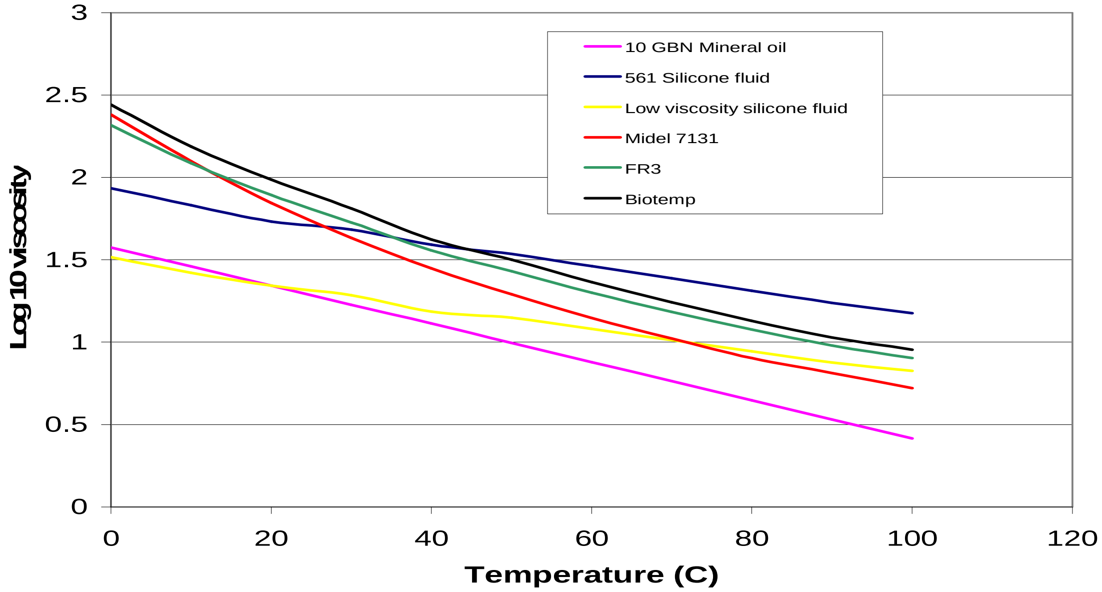


Figure 3.5 – Log $_{10}$ (viscosity) vs temperature

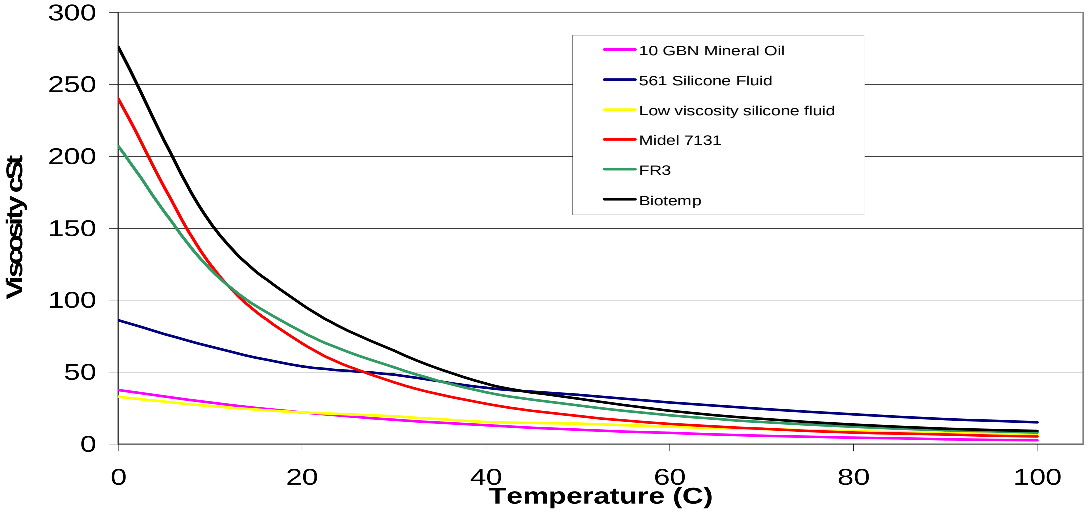


Figure 3.6 – Comparative viscosities with varying temperature

From Figures 3.5 and 3.6, it can be seen that except the low viscosity silicone fluid, all the rest of above mentioned alternative fluids are more viscous than mineral oil over a wide temperature range; however the differences diminish with increasing temperature. Viscosity of fluids represents resistance to flow; since an insulating liquid also acts as the thermal coolant, a higher viscosity may slow the flow of fluid in the winding ducts, and increase the operating temperature of a transformer. The flow rate at nominal ratings is important as at temperatures of > 80^{o}C, cellulose degradation becomes an issue. In addition, a higher viscosity also needs to be considered during liquid impregnation of the cellulose solid insulation in the transformer manufacturing process. Specific design rules may improve the cooling efficiency

3.2.2 Comparison of moisture tolerance

Water is a very polar molecule and polar molecules tend to be most strongly attracted to other polar molecules. In this context the term ‘polar’ refers to regions of a substance which have different attractions, like the poles of a magnet.

Mineral oil is not polar, and silicone oil only slightly more so. The ester linkages present in both natural and synthetic esters make these fluids ‘polar’, and like tiny magnets, these linkages are able to attract water molecules in a way that mineral and silicone oils can not.

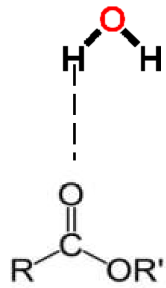


Figure 3.7 - How esters attract water molecules

Natural esters have 3 ester linkages per molecule, whilst synthetic esters may have 2-4 linkages per molecule. These differences become evident when we consider the amount of water that can dissolve in these fluids.

3.2.2.1 Solubility of water in fluids

Table 3.3 shows the water solubility of transformer fluids at room temperature, i.e. the total amount of moisture content which the fluid can hold without free water being deposited.

Table 3.3 - Solubility of water in fluids

	Ester linkages	Approx water saturation at 23°C (ppm)
Mineral oil	0	55
Silicone oil	0	220
Natural ester	3	1100
Synthetic ester	4	2600

The solubility of water in all these fluids increases with temperature. The logarithmic plot of the water solubility against temperature for the transformer fluids studied in this report is shown in Figure 3.8. Clearly the more polar esters are able to absorb more water across the temperature range[29,30].

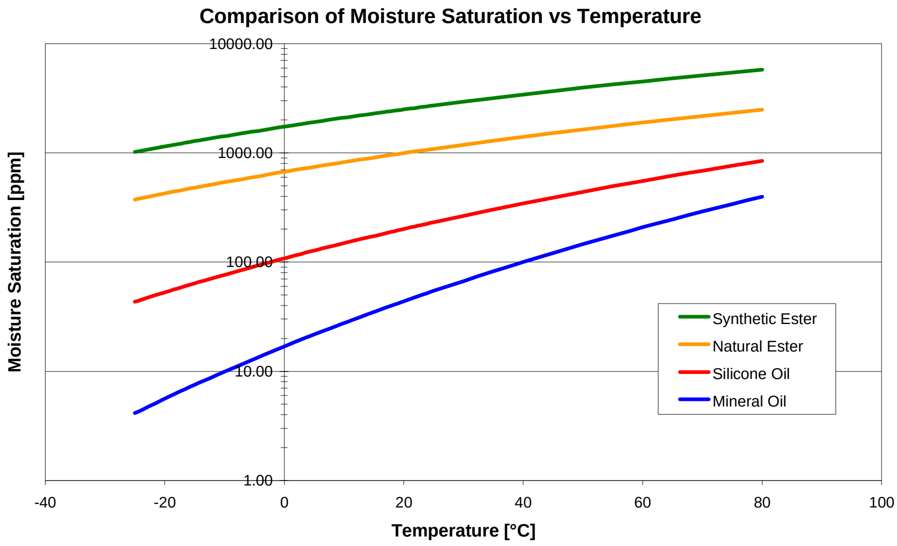


Figure 3.8 – How moisture saturation varies with temperature

As well as representing the water content of dielectric fluids by absolute ppm values of dissolved water, it is also useful to represent the water content by relative percentage of water saturation. The relative water saturation, W_{rel} of a fluid at a specific temperature is given as a percentage by the formula below where W_{abs} is the water content measured in ppm and W_{sat} is the water saturation limit at the temperature[31].

$$W_{rel} = \frac{W_{abs}}{W_{sat}} \times 100$$

3.3 Fire Safety

Fire safety is a key concern of today's users of insulating liquids, especially when considering their use in areas such as in subway tunnels or aboard ships. Equally this applies where they will be used in populated areas such as near offices, shops and in the workplace.

Insurance companies are increasingly aware of the fire potential of transformer fluids, and are encouraging end users to specify fire safe fluids, especially in areas where a fire originating from flammable transformer oil is potentially damaging as such

- Risk to human life
- Evacuation of surrounding area
- Down-time costs
- Transformer replacement time and cost
- Costly insurance claims

3.3.1 Fire classification for transformer fluids

The classification of insulating liquids is based upon Fire Point & Net Calorific Value according to the standard IEC 61100.

Table 3.4 – Fire classification of fluids

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

From a fire safety aspect, advantages of using the less flammable K class fluids are:

- Less costs for installation and maintenance safety equipment: “for electrotechnical equipment installed in areas of particular fire hazard (e.g. Buildings), less stringent measures are required in the case of less flammable liquids” IEC 60695-1-40 7.1
- No fire risk in event of major electrical fault; “even if spray ignites (..) the resulting pool of liquid rapidly ceases to burn” IEC 60695-1-40 7.1
- Low density, non toxic smoke

Silicone fluids and both natural and synthetic esters can offer a high degree of fire safety, due to their low fire susceptibility.

Table 3.5 - Fire properties of fluids

Fluid type	Flash point °C	Fire point °C	Class
Mineral oil	160 -170	170 -180	O
Silicone fluid	>300	>350	K3
Low viscosity silicone fluid	268	312	K3
Natural ester	>300	>350	K2
Synthetic ester	>250	>300	K3

3.4 Environmental safety

Environmental safety is determined with two basic criteria: biodegradability and low toxicity. In general fluids which possess a rapid biodegradation rate and can demonstrate low toxicity are classified as being ‘environmentally friendly’. These factors are important when considering the use of fluids in environmentally sensitive areas, such as water courses, to avoid contamination.

3.4.1 Biodegradability

The term ‘biodegradability’ reflects the extent which the fluid is metabolised by naturally occurring microbes in soil or water courses, in the event of a spillage or leak. Clearly it is an advantage if spilt fluids can quickly disappear naturally without the need to instigate expensive clean up measures.

To be classified as ***readily biodegradable*** a substance must satisfy both of the following criteria:

- 60% biodegradation must occur within 10 days of exceeding 10% degradation
- At least 60% degradation must occur by day 28 of the test

The OECD 301 series of tests for ready biodegradability has 6 main test methods covering all types of materials, solids and liquids, water soluble and non-water soluble. These are listed below, and the tests particularly applicable to transformer fluids (non water soluble, non volatile) are given in bold font.

- 301 A: DOC Die-Away
- **301 B: CO2 Evolution (Modified Sturm Test)**
- 301 C: MITI (I) (Ministry of International Trade and Industry, Japan)
- **301 D: Closed Bottle**
- 301 E: Modified OECD Screening
- **301 F: Manometric Respirometry**

Both natural and synthetic esters are officially classified as being ‘readily biodegradable’ [32,33,34] whilst mineral oils and silicone fluids are more resistant to biodegradation.

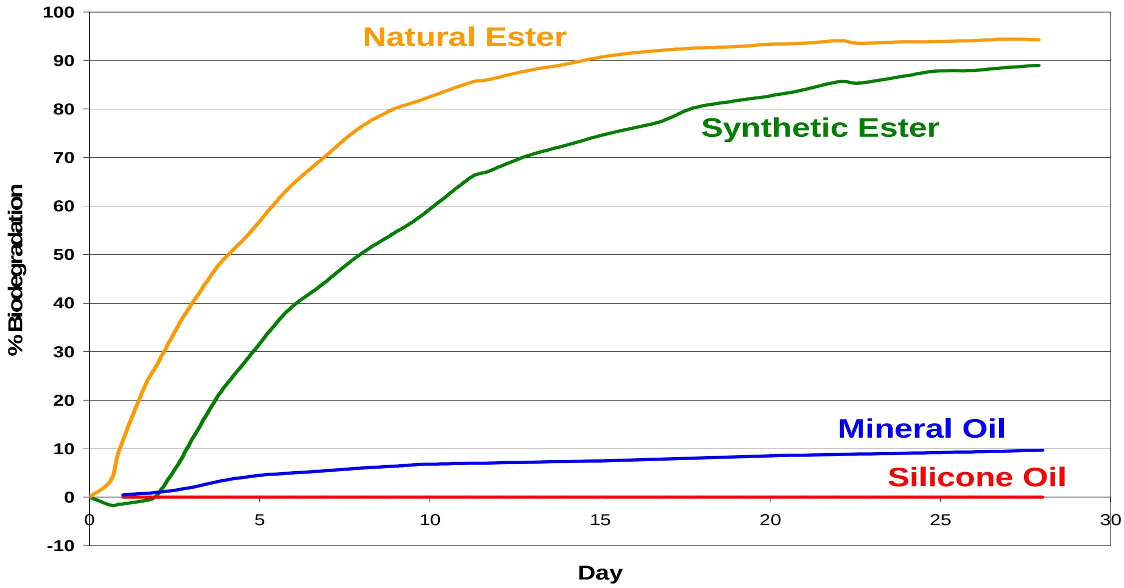


Figure 3.9 - Comparison of biodegradation rates

Silicone oils do not biodegrade quickly when tested by standard recognised methods, however studies have shown that in soil, the PDMS polymer can hydrolyze to small, water soluble siloxanols with the ultimate product being the monomeric dimethylsilanediol (DMSD)[35] . This hydrolysis is probably abiotic, because it can take months to years in wet soil, but only days as the soil dries. The hydrolysis product (DMSD) can then microbially degrade to CO_2 and inorganic silicate. If the silicone oil is mixed with waste treatment sludge the process will be slower and this is a likely route any effluent would take into the environment.

This means that the fate of silicone oils in the environment is more complex than just the biodegradability alone suggests. However the number of different factors which need to come into play to make silicone degrade in nature suggests that it should be considered less environmentally friendly than readily biodegradable fluids.

3.5 Oxidation stability of alternative fluids

The oxidation stability of alternative fluids for transformers is a key concern to end users. The relative stabilities of fluid to oxidation are as follows:

Silicone oil > synthetic ester > mineral oil > natural ester

Silicone oil: According to the manufacturer’s product information[36], silicones are chemically inert and have good oxidation resistance. There are two modes of degradation for silicone fluid: thermal breakdown and oxidation. Oxidation of silicone fluid will take place very slowly (in the presence of oxygen) at temperatures above 175°C (342°F). When it oxidizes, silicone fluid polymerizes, gradually increasing in viscosity until gelation occurs. This process takes place without the formation of objectionable acids or sludges. In addition, the dielectric properties of the longer-chain silicone molecules are similar to the dielectric properties of fresh silicone fluid.

Thermal breakdown of silicone fluid begins at temperatures above 230°C (450°F). At these temperatures the longer polymer chains will slowly begin to degrade to form more volatile cyclic silicone material.

Synthetic ester: Synthetic esters based on saturated acids and pentaerythritol oxidise only very slowly, at temperatures > 125°C, and darken as they do. Oxidation of synthetic esters does not produce sludge, but organic acids are produced.

Mineral oil: Mineral oil begins to volatilize and oxidize at temperatures above 105°C. Oxidation results in the formation of many degradation products, which include organic acids and sludge. These by-products may cause problems in a transformer by reducing the dielectric properties of the insulation and by corroding metals.

Natural esters: Natural esters are the most susceptible to oxidation of the alternative fluids. In simple terms natural esters are susceptible to oxidation because of their chemical structure. Natural esters have a structure based upon a glycerol backbone to which are attached 3 fatty acid groups as shown in Figure 3.4.

There are about 10 common fatty acids found in vegetable oils, and the exact composition of any natural ester depends upon the plant (crop) from which the oil is sourced, as shown in Table 3.6.

Table 3.6 - The fatty acid composition of common vegetable oils

Oil or Fat	Unsat./Sat. ratio	Saturated					Mono unsaturated	Poly unsaturated	
		Capric Acid C10:0	Lauric Acid C12:0	Myristic Acid C14:0	Palmitic Acid C16:0	Stearic Acid C18:0	Oleic Acid C18:1	Linoleic Acid (ω6) C18:2	Alpha Linolenic Acid (ω3) C18:3
Coconut Oil	0.1	6	47	18	9	3	6	2	-
Palm Oil	1.0	-	-	1	45	4	40	10	-
Peanut Oil	4.0	-	-	-	11	2	48	32	-
Olive Oil	4.6	-	-	-	13	3	71	10	1
Soybean Oil	5.7	-	-	-	11	4	24	54	7
Sesame Oil	6.6	-	-	-	9	4	41	45	-
Sunflower Oil	7.3	-	-	-	7	5	19	68	1
HO Sunflower Oil	10	-	-	-	3 - 5	3 - 6	75 - 85	8 -10	-
Safflower Oil	10.1	-	-	-	7	2	13	78	-
Rapeseed Oil	14.6				4	2	56	22	10
Canola Oil	15.7	-	-	-	4	2	62	22	10

Solid → Liquid

Oxidation stable → Oxidation unstable

A common feature of natural esters that are liquid at room temperature is that they contain C=C double bonds in the fatty acid side chains.

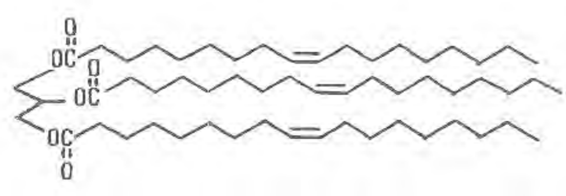


Figure 3.10 - Glyceryl tri-oleate

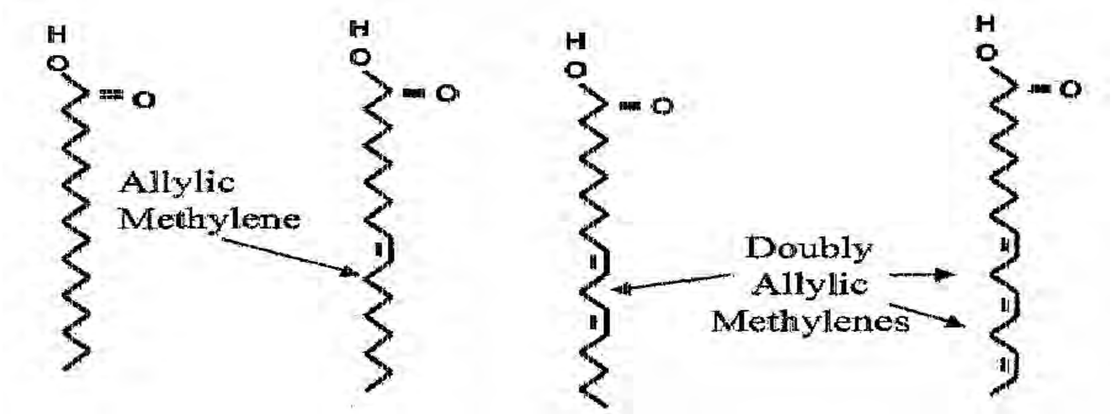


Figure 3.11 - Types of unsaturation found in natural ester fatty acid chains (Source: CARGILL)

These C=C double bonds and the carbon atoms next to the double bonds are the main sites for attack by oxygen (oxidation). In terms of oxidation stability, not all natural esters are the same, some are more oxidation stable than others.

There is a trade off between good cold flow characteristics and oxidation stability. In general the following bullets points apply

- In a natural ester, the more carbon – carbon double bonds that the molecules contains makes the oil more susceptible to oxidation.
- Fatty acid chains with 2 or 3 double bonds (di and poly unsaturated) are more susceptible to oxidation than chains with 1 double bond (monounsaturated).
- When natural esters oxidise, oxygen is consumed. This reacts with the oils to increase viscosity and eventually produce gels and/or smaller oxygen containing by-products such as alcohols, aldehydes, acids, and ketones.
- The oxidation process is irreversible and the gel is not the same as frozen natural ester.
- Viscosity of the oil increases as oxidation progresses.
- The oxidation is a free radical mechanism and is accelerated by trace metals, light and free radical initiators.
- Saturated vegetable oils (hydrogenated oils) have superior oxidation stability, but very high pour points (semi solid, e.g. like margarine).

3.5.1 Tests for oxidation stability

A simple test to measure and compare the rates of oil oxidation is the RBOT (Rotating Bomb Oxidation Test). In this test the oils are heated under oxygen under pressure. Because oxygen is consumed in the oxidation process, the object of the test is to measure the time taken for the initial oxygen pressure to drop to a preset level. This is a very severe test and is intended for rapid evaluation of the oxidation stability of inhibited mineral oils. More appropriate tests for natural esters are being investigated, but as yet there is no recognised standard test for these fluids[37].

3.5.1.1 RBOT Results

The RBOT test is carried out to ASTM D2112. The sample is aged in a pressurised vessel with water, a copper catalyst and oxygen at 95 psi and rotated in a bath at 140 °C. The test is complete when the pressure in the vessel has dropped substantially and the time is recorded. In the test the results of the fluids are recorded in minutes.

A comparison of the results with synthetic ester, mineral oil and natural ester fluid are presented in Figure 3.12 below.

This is quite a vigorous test, but it does allow the stability of different types of fluids to be compared easily.

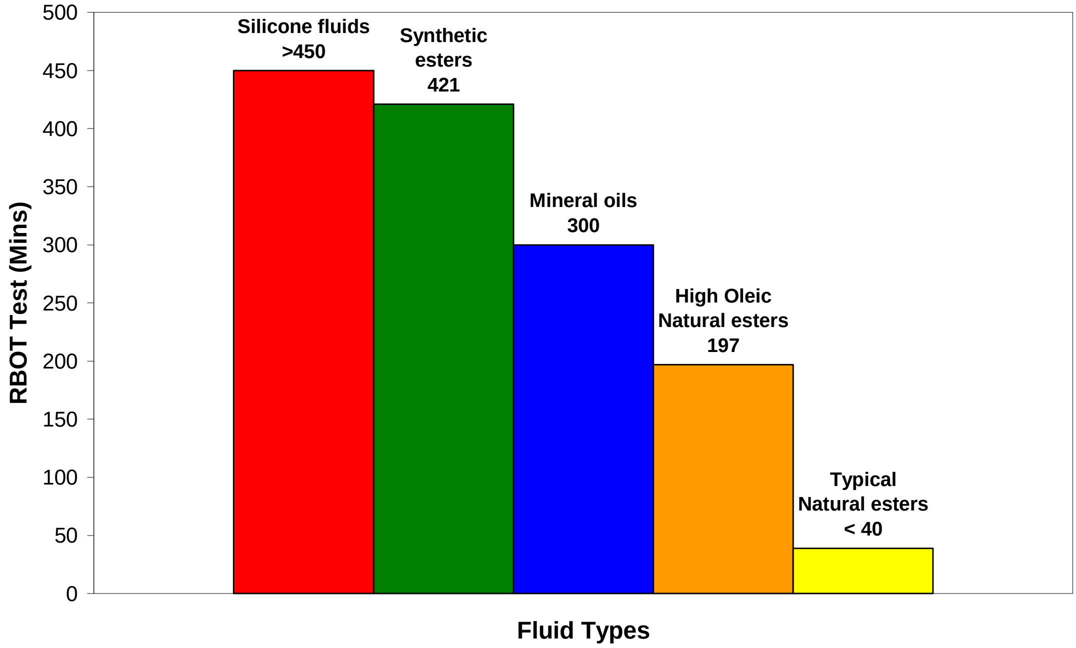


Figure 3.12 – RBOT test results for different dielectric fluid types

3.5.1.2 IEC 61125 Oxidation Stability

This standard was developed to measure the stability of unused mineral oils. There are three methods described under this standard. All methods use an elevated temperature with gas constantly bubbling through the oil and a copper catalyst. Method A uses oxygen as the gas, with a temperature of 100°C, method B uses oxygen at 120°C and method C uses air at 120°C. The results are reported in terms of total acid content of the fluid and total sludge content as a percentage of the weight of the fluid formed during the oxidation process.

The least vigorous of these methods, IEC 61125 Method C (using air and 120°C for 164 hr) is a useful tool for comparing the stability of a range of fluids. Currently, the reliability of this method is being tested via a round robin exercise for natural esters by two independent groups:

Cigre D1-01(investigating the oxidation stability of dielectric fluids) and IEC TC10 – PT05 are aiming to incorporate oxidation stability into the new IEC standard for natural esters. Both groups will report on their findings in the near future.

3.6 The miscibility of alternative fluids at ambient temperature

Both natural and synthetic esters are miscible with mineral oil in all proportions. It should also be noted that silicone oil is not miscible with ester fluids, and that even small amounts of silicone fluid contamination in ester fluids can cause foaming when filling a transformer under vacuum.

Table 3.7 Miscibility of alternative fluid with mineral oil at ambient temperature

(Note that this table applies only to unused oils)

	Mineral oil	Silicone oil	Natural ester	Synthetic ester
Mineral oil	X	Miscible	Miscible in all proportions	Miscible in all proportions
Silicone oil	Miscible	X	Not miscible	Not miscible
Natural ester	Miscible in all proportions	Not miscible	X	Miscible in all proportions
Synthetic ester	Miscible in all proportions	Not miscible	Miscible in all proportions	X

Although silicone fluid is miscible with mineral oil, even small quantities of silicone liquid can cause excessive foaming in mineral insulating oil. To avoid such contamination, the use of the same pipelines and pumps is not recommended. Note that although mineral oil is miscible with alternative fluids, mixing with excessive amounts of mineral oil may compromise the properties of the alternative fluid, such as fire point.

4 Electrical Properties of Alternative Fluids

Transformers filled with alternative fluids need to withstand the same ac, lightning and switching impulse voltages as the conventional mineral oil filled transformers. Most of the tests on alternative fluids and alternative fluid impregnated cellulose insulation systems, carried out in laboratories, attempted to do direct comparison of breakdown voltages and discharge characteristics between alternative fluids and mineral oil.

4.1 AC breakdown voltage

4.1.1 AC breakdown voltage of alternative fluids

A variety of standard test methods are applicable for measuring AC breakdown voltage of insulating fluids, where a small volume of oil sample is subjected to an almost homogenous electric field. This test is mainly used by utilities or transformer manufacturers to carry out quality check of insulating fluids.

A selection of results obtained for alternative fluids in comparison to mineral oil are presented in Table 4.1 below.

Table 4.1 – Comparison of AC breakdown voltages of insulating fluids

Test	Mineral Oil	Synthetic Ester	Natural Ester	Silicone Oil	Low Viscosity Silicone Oil
IEC 60156 2.5mm	>70 kV[38]	>75 kV[39]	> 75 kV[40]	50 kV[41]	70 kV
ASTM 1816 1mm	-	-	37 kV[42]	-	-
ASTM 1816 2mm	60 kV	-	76 kV[43]	-	-
ASTM D877	55 kV	43 kV	46 kV[44]	43 kV[45]	-

The modern insulating liquid testers all tend to have a very sensitive current detecting and limiting device, this means that the breakdown voltage of a fluid is related to the existence of weak links between the electrodes which incept the micro-discharge; this also means that the breakdown brings minimum damage to the oil sample and the consecutive breakdown events can be treated as independent to one and another. Typically the breakdown voltage which is quoted is the mean of a number of tests; in the case of IEC 60156 the mean of six breakdowns on the same oil sample is taken. Besides the mean breakdown voltage value, the standard deviation can also be used to indicate the scattering of the ac breakdown results.

Since most of the alternative fluids are more viscous than mineral oil, the standing time before carrying out the tests and the stirring time between two consecutive tests must be longer to allow gas bubbles to disperse.

Care must be taken when using the AC breakdown voltage to indicate the fluid's ability to withstand ac electrical stress. It is well known that the ac breakdown voltage is extremely sensitive to the impurities existing in a transformer fluid, such as the presence of excessive moisture, particulates, and air or gas bubbles. Consequently the measured AC breakdown voltage of an insulating fluid mostly represents the oil quality rather than oil characteristic itself.

4.1.2 Effect on AC breakdown voltage with increasing moisture

Moisture can have two main forms of existence in insulating liquids; dissolved or free water. Polar fluids tend to form hydrogen bonds with water molecules so that water can dissolve easily. This is why polar fluids have significantly more water tolerance. On the other hand, non-polar mineral oil and slightly polar silicone oil is particularly sensitive to the absolute moisture content[46]. Figure 4.1 shows the breakdown voltage at ambient temperature of synthetic ester, natural ester, silicone and mineral oil with increasing moisture levels. It clearly illustrates that even small amounts of water in mineral oil cause a rapid deterioration in breakdown voltage. In contrast, both types of esters maintain high breakdown voltages even with significantly larger amounts of dissolved moisture[47]. It should also be noted that, without the competition of μm cellulose fibre particles which are much more polar in terms of molecular structure, filtered clean insulating liquids are able to bond a certain amount of water molecules and maintain AC breakdown voltage unchanged with increasing moisture levels.

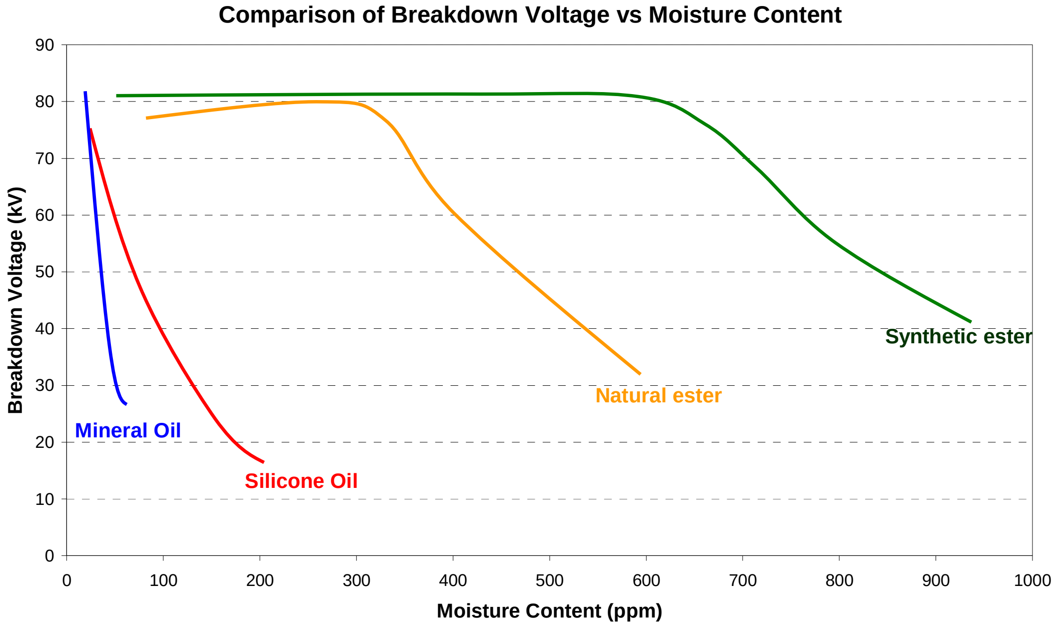


Figure 4.1 – Effect of absolute moisture content on AC breakdown strength of clean fluids

Figure 4.2 shows the results of breakdown voltage versus relative water saturation levels for three different natural esters, a synthetic ester, silicone fluid and mineral oil[48]. These fluids were tested as delivered, without any pre-test conditioning. Relative water saturation levels are calculated as in section 3.2.2. It can be seen that the AC breakdown behaviour with regards to relative moisture level of all the fluids is very similar. Note that the oil samples to generate Figure 4.2 may not be filtered clean oil therefore the moisture combined particle effect may affect the shape of the curve for breakdown voltage versus relative moisture level, which looks differently from the one in Figure 4.1. With micrometer size cellulose fibre particles attracting water molecules and combining together, the ac breakdown voltage will decrease with increased relative moisture level.

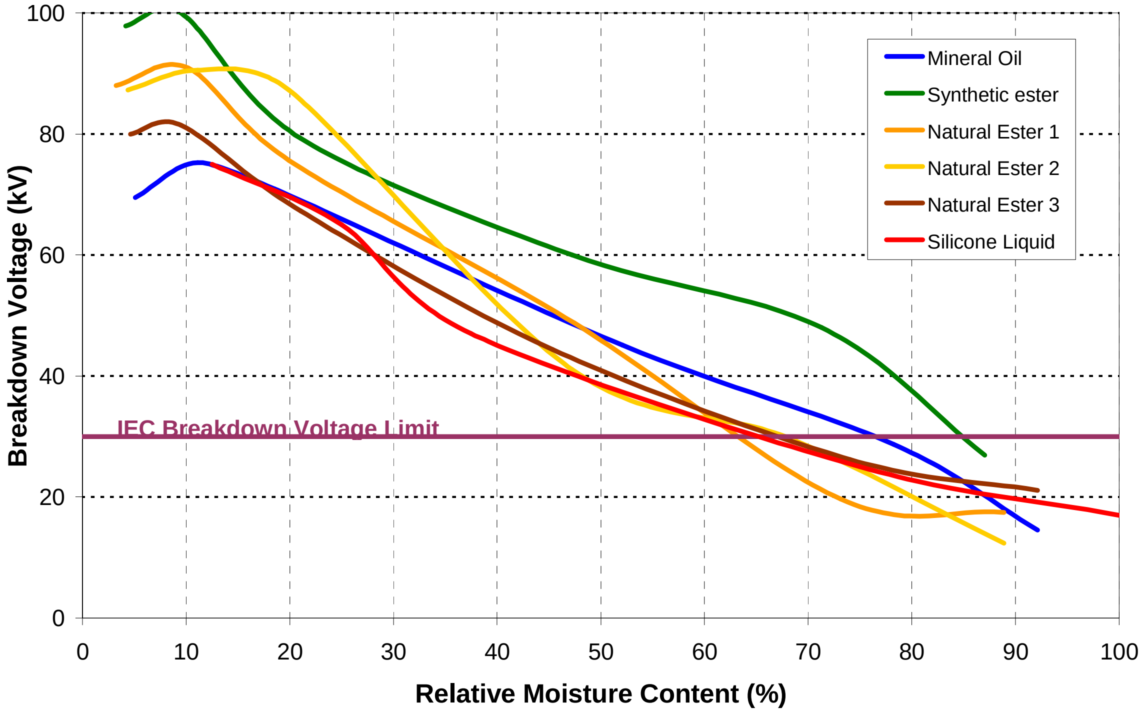


Figure 4.2 – Effect of relative moisture content on AC breakdown strength of fluids

(Data Source:- synthetic ester, natural esters and mineral oil from Prof Stefan Tenbohlen, University of Stuttgart; silicone fluid added from published data)[43]

To verify this effect of particle and moisture combination, test results on filtered clean fluids versus relative moisture content level are shown in Figure 4.3. New mineral oil, one synthetic ester and one natural ester fluid were tested and the samples were filtered to meet with CIGRE "clean" insulating liquid specification – every 100 ml liquid have less than 200 particles of > 5µm diameter size. 40 ac breakdown tests are carried out using ASTM 1816 VDE electrodes and 1 mm oil gap distance. The message shown here is that new and clean fluids with a relative moisture content level below 30%, can hold water in the dissolved form without affecting the ac breakdown voltage.

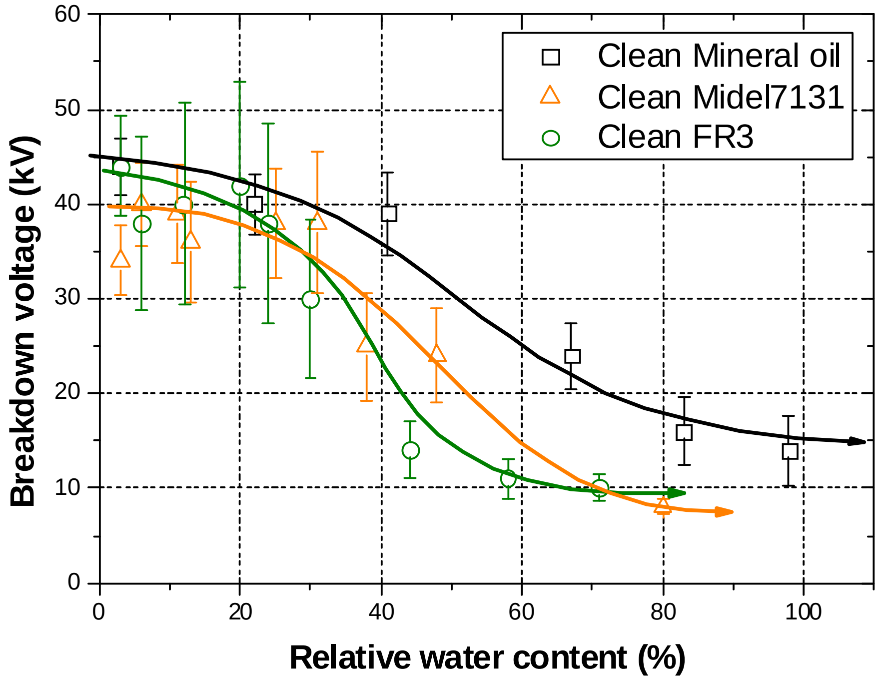


Figure 4.3 – Effect of relative moisture content on AC breakdown strength of clean fluids

(Data Source:- synthetic ester, natural esters and mineral oil from Prof Zhongdong Wang, University of Manchester)[49]

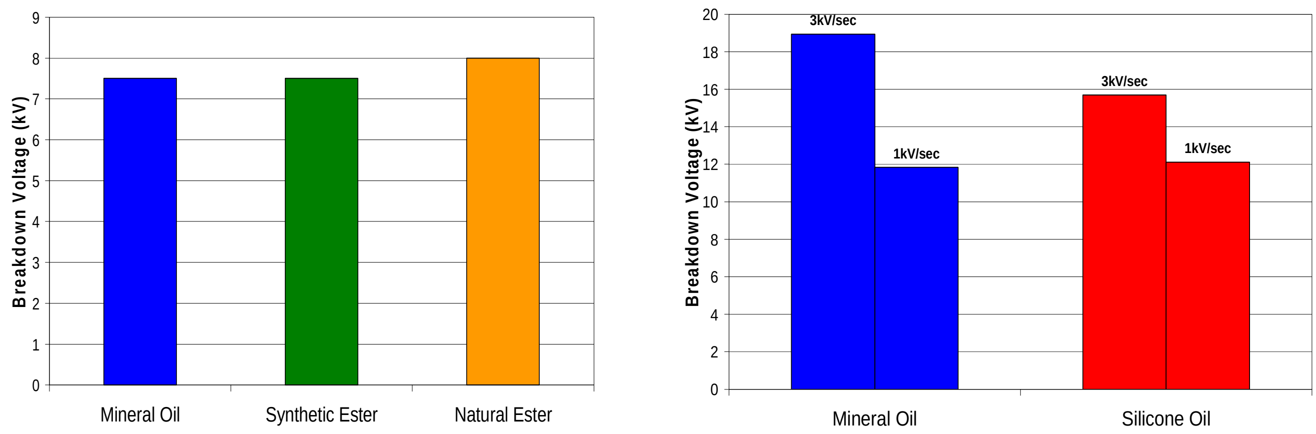
4.1.3 AC breakdown voltage of impregnated cellulose

Transformer cellulose insulation, either in the form of paper or pressboard, is a composite insulation system where the pores between cellulose fibres are filled with the fluid. Cellulose fibres have higher dielectric strength than insulating fluids and a breakdown of fluid impregnated cellulose is normally regarded as being initiated by the discharge in the fluid filled pores.

For fully impregnated 90µm Kraft paper by ester and mineral oil, their AC withstand voltages[50] are given in Figure 4.4.a, while the AC withstand voltages for 0.254mm Kraft paper impregnated by silicone and mineral oil[51] are given in Figure 4.4.b.

Using sphere to plane electrodes and 1kV/s rate of voltage rise, the comparison of breakdown voltage of impregnated Kraft paper by silicone, esters and mineral oil demonstrates that they perform similarly to one and another.

With a higher voltage rise of 3kV/s, the mineral oil gave a higher breakdown voltage than silicone fluid impregnated Kraft paper. It is speculated that with rapid increase of applied voltage, the different degrees of energy released by discharges of fluid in cellulose pores will create different damage of cellulose fibres and ultimately determine the breakdown voltage level of cellulose.



a. 90µm Kraft paper (1kV/sec) b. 0.254mm Kraft paper

Figure 4.4 – Breakdown voltages of impregnated Kraft paper

All the AC test results mentioned above are in homogenous or semi-homogenous electric field, and the test results show that fluids and fluid impregnated cellulose behave similarly to mineral oil and mineral oil impregnated cellulose.

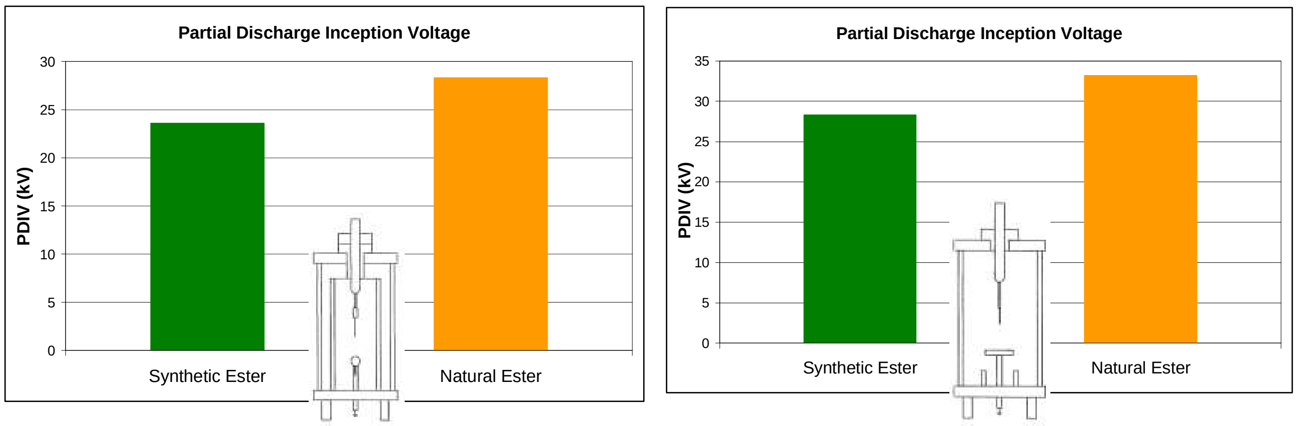
4.2 Partial discharge tests

For inhomogeneous field with relative large oil gaps, partial discharge tests are usually used, instead of AC breakdown tests.

4.2.1 Partial discharge inception voltage (PDIV)

Partial discharge behaviour has been studied in alternative fluids by a number of different institutions and work is still ongoing to characterise the behaviour of these fluids.

Using needle-to-sphere electrode with an oil gap distance of 50 mm[52, 53] the partial discharge inception voltages of a synthetic and a natural ester were determined following the procedure specified in IEC 1294. The inception voltage for PD activity greater than 100pC was recorded. Needle-to-plate electrode configuration was also used in the tests.



a. needle- sphere arrangement b. needle- plate arrangement

Figure 4.5 – Partial discharge inception voltages for ester fluids

The same tests have been carried out on mineral oil, and the conclusion was made that PDIV for mineral oil, synthetic and natural ester are similar.

The test method specified in IEC 61294 test guide suggests increasing the voltage in a steady speed of 1kV/s until the appearance of 100pC partial discharge. When considering partial discharge numbers per AC cycle might differ from one fluid to another, it is probably worth to take into consideration the partial discharge pattern of Q-N-Φ (PD magnitude - PD number - phase angle of PD occurrence) built in a specific period of time (normally 1 minute)[54] suggested using step voltage increase method 1kV/step and 1 minute holding time at each voltage step to record the PD pattern, to accurately determine the PDIV of 100pC for different fluids. New dry mineral oil, one synthetic and one natural ester fluid were tested using this method, and the PDIV are given in Table 4.2 for the two test methods, one of which followed exactly the IEC 61294 method and the other the suggested modifying method. Note that the needle tip radius is 6.5μm.

Table 4.2 – Comparison of partial discharge inception voltages of insulating fluids

Oil Type	IEC1294 method (kV)	Suggested modified IEC 1294 method (kV)
Mineral oil	38.2	23.2
Natural ester oil	34.0	25.6
Synthetic ester oil	28.2	22.3

Partial discharge inception in silicone fluids has also been studied and found to be similar to mineral oils. Using a needle plane configuration the mean partial discharge inception field (maximum field near to the needle tip) for 10pC at 20mm gap spacing was found to be 351.8 kV/mm for mineral oil and 336.7 kV/mm for silicone[55]. In this study silicone fluid was found to form gelled polymer substances with exposure to long time high level partial discharges. The gel consists of cross-linked polymer structures of Si-CH_2-Si, Si-OH and Si-H. For this reason care must be taken when using silicone to ensure a PD free design, the gel substances which form could cause issues with cooling flow etc.

The cross comparison among results generated from different research groups on PDIV is, if not impossible, a difficult task to perform due to the following reasons:

- needle tip radii are varying without any accurate specifications, from 3μm to 100μm,
- various oil gap distances are used, from 20mm to 50mm,
- needle-to-plate or needle-to-sphere electrode configurations, making the field distribution varying across the gap,
- the maximum partial discharge value under PDIV is varying, from 10pc to 100pC,

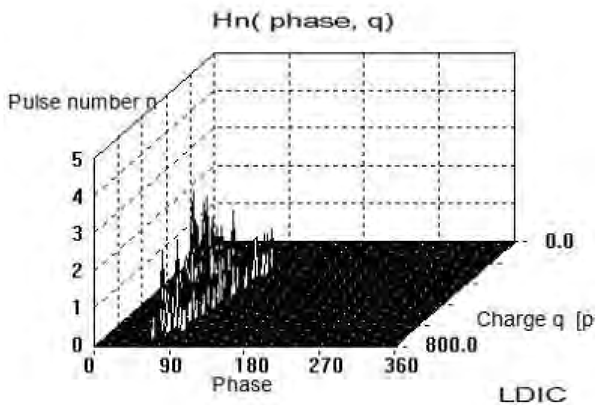
Nevertheless, PDIV test is to subject the insulating liquids to an extremely inhomogeneous electric field and to determine the condition under which the liquid ionisation happens. It is therefore one of the characterisation test for insulating liquids.

4.2.2 Partial discharge patterns

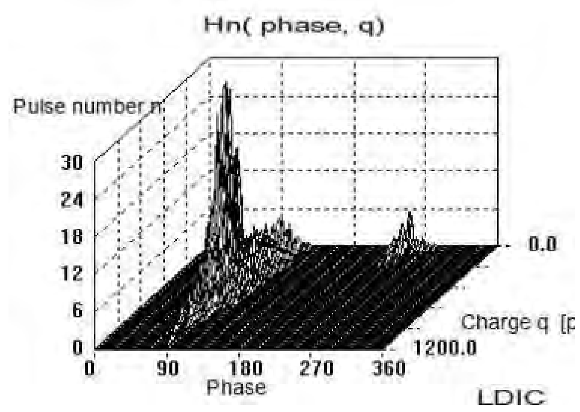
The recent researches carried out at the University of Manchester on partial discharges found that continuing to stress the insulating liquids beyond the PDIV voltage level, PD patterns for mineral oil and alternative fluids are significantly different.

These differences indicate that although the stress/voltage for alternative fluids to have an ionised discharge of 100pC is similar to that of mineral oil, the ionisation propagation will be greatly influenced by the insulating fluids.

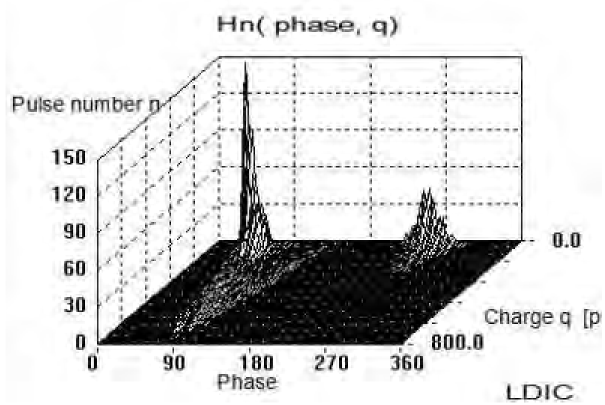
Figure 4.6 show the PD pattern observed under a voltage twice higher than the PDIV. The PD patterns for synthetic ester and natural ester have a significant amount of discharge activities in both positive and negative half cycles, while mineral oil tends to have it in only positive half cycles with less discharge magnitude.



a. Mineral oil



b. Synthetic Ester



c. Natural Ester

Figure 4.6 – Partial discharge inception voltages for ester fluids

(Data Source:- synthetic ester, natural esters and mineral oil from Prof Zhongdong Wang, University of Manchester)

4.3 Impulse breakdown voltage tests

Different from AC breakdown tests, impulse breakdown of insulating liquids is not greatly affected by moisture and particle impurities of the liquids therefore can be used to assess the dielectric characteristics of the insulating liquid itself.

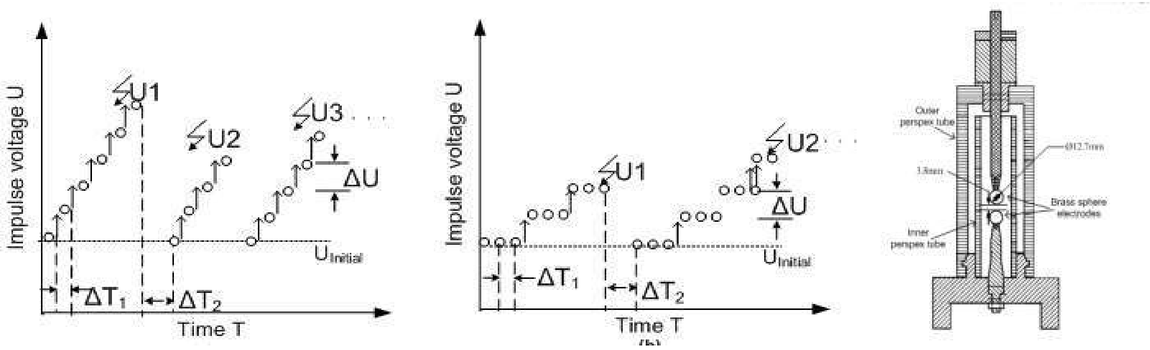
4.3.1 Impulse breakdown voltage of alternative fluids under homogenous field

There are two test standards widely used for impulse breakdown voltages of insulating liquids, a comparison between the two methods is shown in Table 4.3.

Table 4.3 – Comparison between ASTM and IEC impulse test methods

Property	ASTM D 3300	IEC 60897
Electrode type	Steel or brass; point-to-sphere or sphere-to-sphere	Steel; Point-to-sphere
Electrode gap (mm)	25.4 for point-to-sphere; 3.8 for sphere-to-sphere	25, 15, 10 depends on the expected voltage range
Voltage increasing method (kV)	Step by step, 3 shots per step Step voltage 5 or 10	Step by step, 1 shot per step Step voltage 5 or 10
Time interval between shots (s)	Minimum 30	Minimum 60
Results	5 breakdowns; 1 breakdown/sample	5 breakdowns; 1 breakdown/sample

Using sphere-to-sphere electrode configurations with a gap distance of 3.8mm, standard 1.2/50 µs lightning impulse voltages were applied with two different rising-voltage methods (1 shot/step or 3 shots/step) as shown in Figure 4.7, impulse breakdown voltages of mineral oil, one synthetic ester and one natural ester are shown in Table 4.4. All fluid samples under test are dry and clean filtered. It can be seen that 3shots/step test method is much more stringent and therefore produce lower impulse breakdown voltages for all fluids under tests. In general, ester fluids have lower impulse breakdown voltages than mineral oil. [56]



a. 1 shot/step rising-voltage method   b. 3shots/step rising-voltage method   c. test cell

Figure 4.7 – Impulse breakdown voltage test method and electrode configurations

Table 4.4 – Impulse breakdown voltages of alternative fluids

Fluid	Impulse breakdown voltage (kV)	
	1 shot/step	3shots/step
Mineral Oil	276.4	251.9
Synthetic Ester	258.0	205.0
Natural Ester	239.3	200.4
Silicone Oil	X	X

An impulse breakdown study was carried out by University of Salford in Manchester[57] to compare between Synthetic Ester (MIDEL® 7131), Silicone Oil and Mineral Oil. A comparison of the impulse breakdown of insulating liquids between spherical electrodes is shown in Table 4.5.

Table 4.5 – impulse breakdown voltages with spherical electrodes

Gap Size (mm)	Mean Stress (kV/mm)		
	Mineral Oil	MIDEL 7131	Silicone Oil
1.0	40.6	42.0	33.4
1.5	38.3	47.0	33.0
2.0	45.8	42.3	44.6
2.5	39.0	34.0	36.5

4.3.2 Impulse breakdown voltage of alternative fluids impregnated cellulose

Impulse breakdown tests on Kraft paper samples impregnated by mineral oil and ester fluids are given in Table 4.6, where Kraft paper of 0.93g/cm3 density and 0.128mm thickness were tested using plate-to-plate electrodes, following ASTM D3300 test standard. The paper results are consistent with the impulse breakdown voltages of alternative fluids, showing lower breakdown strength than that of mineral oil.

Table 4.6 – Impulse breakdown strengths of 0.128 mm Kraft paper

	Mineral Oil	MIDEL 7131	FR3
Breakdown voltage (kV)	49.6	42.0	46.6

Separate tests were carried out on mineral oil impregnated and silicone oil impregnated Aramid paper, using 1.2/50µs lightning impulse of positive polarity, 0.254mm thick Aramid paper was placed between sphere-to-ball electrodes, and the impulse breakdown voltages are shown in Table 4.7.

Table 4.7 – Impulse breakdown strengths of 0.254 mm Aramid paper

	Mineral Oil	Silicone
Breakdown voltage (kV)	30.5	31.6

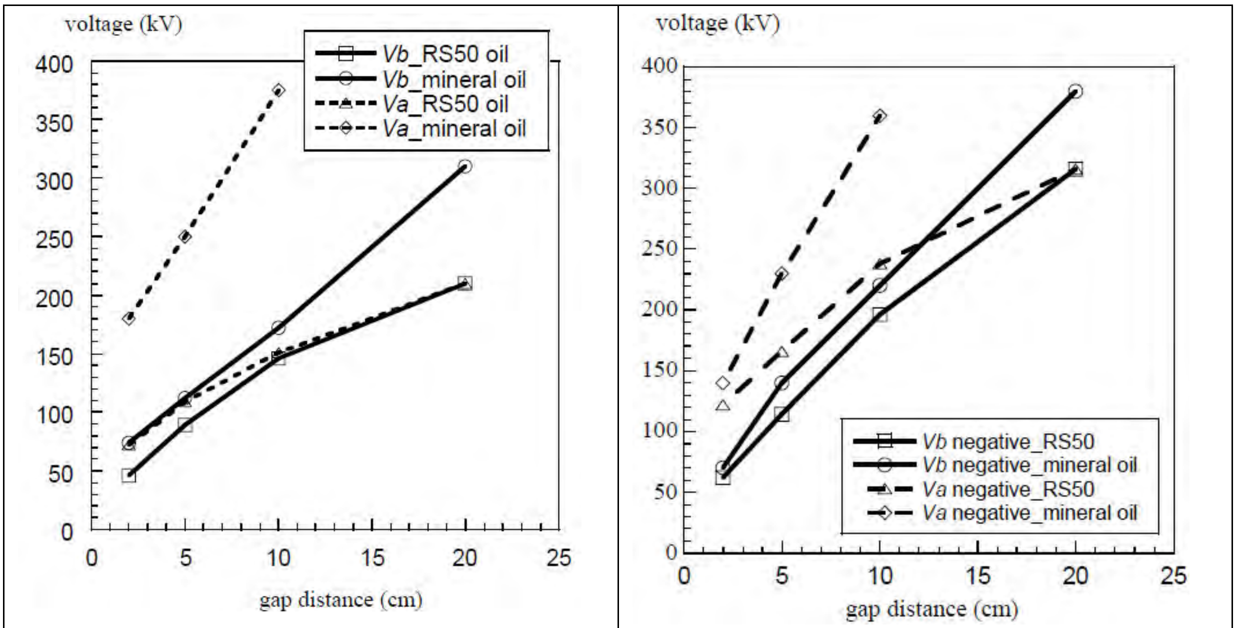
4.3.3 Impulse breakdown voltage of alternative fluids in long gaps

For the time being the only relevant method for testing dielectric performance of insulating liquids in relatively long gaps (25 mm maximum) is IEC 60897. The method applies lightning impulse on a needle sphere gap. It is the average breakdown voltage that is revealed. The applicability of this technique is described by[58].

During recent years considerable investigations have been done on pre-breakdown and breakdown in transformer mineral oils and other liquids, mainly in large point-plane gaps. Point anode (plate electrode is grounded, while positive lightning impulse is applied to the needle) often has a lower withstand voltage than point cathode conditions. In mineral oil, the propagation velocity of pre-breakdown “streamers” emanating from the point anode and propagating up to the plane to induce breakdown is typically 2 to 3 mm/µs. It remains remarkably stable over a very wide gap range, from mm gaps up to more than 20 cm. Increasing the voltage above the breakdown voltage, a steep increase of streamer velocity (up to more than 100 mm/µs) occurs at some critical voltage (“acceleration voltage”). The time to breakdown sharply drops accordingly. For mineral oils this acceleration, caused by a sudden change in the streamer propagation mechanism, occurs at about twice the breakdown voltage[59, 60], as depicted in figure 4.8a. Contrary to the IEC test method which uses 1.2/50 µs standard lightning impulse, the above mentioned observations have been made with long-tailed impulses to avoid quenching a propagating streamer. Solid insulation aligned parallel to the gap will increase the tendency of occurrence of fast mode streamers[61, 62].

Fast streamers are harmful, not only because they can propagate during short duration impulses such as lightning, but also because in identical impulse voltage conditions they can propagate over longer distances than slower ones.

Recent studies have revealed that new ester-oils arriving in the market behave quite differently than mineral oils[63, 64].. While for long mineral oil-insulated gaps the acceleration voltage is about twice as high as the breakdown voltage (figure 1a), fast streamers in the rapeseed oil occur at much lower voltages. Figure 4.8a, fast streamers of ester fluid in a 100 mm gap are seen at 140kV instead of 380 kV as for mineral oil. In turn, the propagation of fast streamers in rape-seed oil induces low values of the 50% breakdown voltage Vb, whereas in mineral oil breakdown in the same conditions is due to slow streamers and shows higher Vb values. Similar tendencies, although less pronounced, are also observed in negative polarity (Figure 4.8.b).



a: positive polarity

b: negative polarity

Figure 4.8: Breakdown voltage (Vb, 50% probability) and acceleration voltages (Va) for positive (a) and negative (b) voltages for mineral oil and a specific rape-seed based liquid. (Point-to-plane gap, fast rise time/long tail impulse)[65]

These phenomena are mainly related to liquids under inhomogeneous electric field of long gaps with needle-to-plate electrodes. For lower voltages (i.e. distribution level transformers) experience with new liquids appear to be good, however caution must be taken when considering exchanging mineral oils with new liquids for power transformers of the higher voltage levels. High voltage transformers tend to be more stressed than distribution transformers and long oil gaps tend to exist in high voltage transformers. In Cigre SC D1 a WG D1.31 “Dielectric Performance of insulating liquids for transformers” has been established to look into these issues.

5 How the use of alternative fluids impinges on equipment design

The use of alternative fluids had traditionally been restricted to distribution transformers. However, in the most recent years, the public’s increasing sensitivity on matters of safety and environmental responsibility, have led the transformer industry into considering the use of alternative fluids in power and special transformers. Extensive R&D as well as field trials has made the application possible and today there is a significant number of power transformers filled with alternative fluids[66, 67, 68, 69, 70, 71, 72].

The scope of this chapter is to examine how the use of alternative fluids influences transformer design. Comparisons with parameters already established for conventional mineral oil will be made, since mineral oil continues to be the industry preferred insulating liquid.

5.1 General

The distinction between distribution and power transformers is not clear or universally acceptable. In this document the following classification will be followed:

- **Distribution transformers**: up to 5MVA
- **Power transformers**: 5MVA and above
- **Special transformers and reactors**: traction transformers, rectifier transformers, furnace transformers, reactors etc.

Transformers are typically designed to have a life span of at least 30 years. The first challenge is therefore to design a transformer filled with an alternative fluid that will have, as a minimum, the same life span as a mineral oil filled unit, without the additional need of scheduled maintenance.

Silicone filled and synthetic ester filled transformers have been installed and operating since the 1970's and it is therefore just to assume that a transformer filled with alternative fluids can have a life span equal to a mineral oil filled unit. The oldest applications of natural ester filled transformers date back to 1994, and therefore have working life of at least 15 years so far. Monitoring of these transformers has demonstrated the suitability of the natural ester fluid for continued use. Accelerated ageing tests on prototype natural ester filled transformers indicate that their life span may surpass the life span of mineral oil filled units[73].

5.2 Transformer tank design

According to their tank design transformers may be classified as follows:

a. Sealed tank (hermetically sealed, rubber bag and gas blanket)
b. Free breathing tank – (with or without conservator)

The sealed type transformer has been the predominant design in USA since the 1960's and is nowadays becoming the trend worldwide. All types of alternative fluids are suitable for use with this design.

Hermetically sealed transformer technology is well known and has been applied for distribution transformers with expandable corrugated tank for a long time. Because of the much higher oil volume for power transformers and the vacuum stability of the tank a new concept has to be developed[74]. Expandable radiators are designed to take over the function of the expansion tank, but strong enough that the single sheets of the radiator remain effectively separated during the transformer operation. This strength is necessary to ensure natural air flow around the radiators for the cooling functionality. The hermetic concept with expansion radiators does not require any air drying system and therefore the maintenance expenditure for the transformer could be reduced.

The free breathing with conservator design had been favoured by most users worldwide for many decades. The expansion and contraction of the insulating fluid due to the variation of its temperature is compensated by the oil volume in the conservator, making this design simple and economical. Silicone fluids and synthetic esters fluids have been used successfully with the breathing - conservator design, mostly in transformer ratings below 1MVA. In order to be able to use natural ester fluids with this design, an adjustment must be made. As natural ester fluids are more susceptible to oxidation when in direct and continuous contact with air, a bladder or membrane must be fitted in the conservator tank in order to minimize the air exposure and prevent oxidation and consequently the increase in the viscosity of the natural ester fluid.

The use of flexible membranes or bladders is becoming increasingly common, especially in warm and humid climates, even for mineral oil filled units.

The free breathing tank is very common in the UK. Although silicone based fluids and synthetic ester fluids may be used with this design, it is considered preferable to fit a desiccant (silica gel) to the breather tube to avoid excessive moisture ingression in the transformer tank. It is worth commenting that mineral oil filled units are also commonly fitted with such devices for the same reasons. The natural ester fluids are typically not used with this design.

It is suggested that operation at high temperature requires “essentially oxygen-free applications where the oil preservation system effectively prevents the ingress of oxygen and moisture filled air into the tank”[75, 76]. To comply with this requirement, transformers with hybrid insulation system are designed with a conservator containing a rubber bag that avoids direct contact between the ambient air and the oil. Designs without conservators but with a nitrogen cushion above the free oil surface in the main tank, connected to a system that maintains a slightly positive pressure of gas-cushion are regularly used for power class transformers built according to ANSI/IEEE standards.

Designing an adequate transformer tank for each type referenced above depends on the properties of the insulating fluid. Parameters such as the coefficient of thermal expansion are critical for the calculation of a suitable tank. Coefficients of thermal expansion (/^{0}C) as published by liquids manufacturers are presented in Table 5.1.

Table 5.1 - Coefficient of thermal expansion of different alternative fluids

Mineral oil (*typical*)	**Synthetic Ester E200**	**Synthetic Ester Midel 7131**	**Natural Ester E-FR3**	**Natural Ester BIOTEMP**	**Silicone Oil Dow Corning 561**	**Low Viscosity Silicone Oil**
0,00075	0,00079	0,00075	0,00074	0,00068	0,00104	0,00104

5.3 Dielectric design

In a transformer, the fluid provides electrical insulation. The insulation capability is controlled by the complex solid/liquid insulation structures. Insulating liquid impregnates solid insulation (cellulose, wood, Nomex® etc.) and so drives away the air which presents a lower dielectric strength than the insulating liquid.

Breakdown voltage measures the effectiveness of the fluid as electrical insulator. This characteristic is very sensitive to the quality of the fluid, which can be influenced by the presence of impurities like humidity, particles and gases. However, this is not the only property that is taken into account to calculate the transformer’s dielectric design. Table 5.2 compares the basic electrical properties of several new unused alternative fluids.

Table 5.2 - Electrical properties of new/unused alternative fluids

	Mineral oil (*typical*)	**Synthetic Ester Midel 7131**	**Natural Ester BIOTEMP & FR3**	**Silicone Oil Dow Corning 561**	**Low Viscosity Silicone Oil**
Dielectric Strength ***Per IEC 60156***	>70 kV	>75 kV	>75 kV	50 kV	>70 kV
Relative Permittivity ***Per IEC 60247***	2.2	3.2	3.2	2.7	2.7
Dissipation Factor (At 90 C) ***Per IEC 60247***	<0.001	<0.006	<0.02	<0.002	<0.001

The dielectric strength of all alternative fluids conforms to the requirements established by IEC 60296 standard for unused mineral oil.

An important criterion in the dielectric system design is the interfacial strength of the solid material, (creep strength). EHV Weidmann creep design curves for 60 Hz and impulse are presented when natural ester fluid is compared to mineral oil[77].

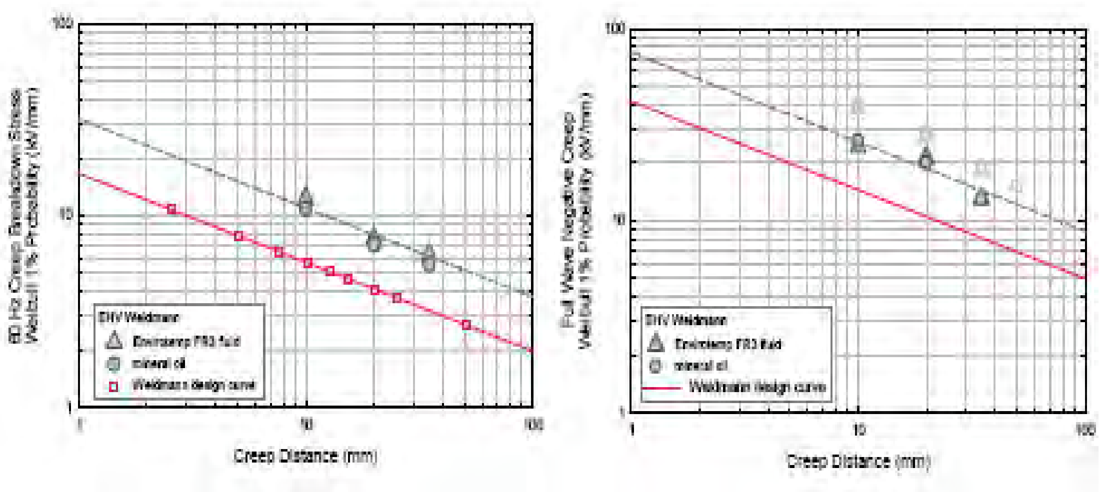


Figure 5.1: 60 Hz and impulse EHV Weidmann creep design curves for natural ester and mineral oil

Results indicate that the creep strength of pressboard in natural ester is as good as or better than the creep strength in mineral oil for AC and negative impulse.

It is noted that the relative permittivity of the ester fluids is significantly higher than that of conventional mineral oil and closer to that of commonly used Kraft paper (approx. 4.4). This leads to an interesting observation of T. Prevost[78]:

"The dielectric strength of solid insulation (Kraft insulation impregnated with dielectric fluid) is close to an order of magnitude higher than the fluid itself. Thus the weak material in the insulation structure is the fluid. By bringing the permittivity of the liquid and solid insulation closer together more of the dielectric stress will be distributed in the solid material. This will reduce the stress on the fluid, which typically sets the design clearance."

Esters have a relative permittivity that is closer to the solid insulation used in oil-immersed transformers and reactors. This has several effects on the dielectric design. The capacitances of the insulation structure change, causing different voltage distribution under transient conditions such as impulse application. This change was not found to be significant[79]. The distribution of voltage stress within the insulation structure also changed, such that for a given voltage distribution the voltage stress in the fluid was less for the ester than for the mineral oil. This is beneficial and allows higher levels of voltage withstand for certain electrode and insulation configuration.

5.4 Cooling design

The insulating liquid in a transformer must ensure the transfer of heat. This function is realised both by thermal conductivity and convection. The convection represents all of the properties (viscosity, specific heat, thermal expansion coefficient) which lead to the heat transfer by fluid displacement, whereas the conduction is realised within the fluid. The viscosity of the liquid is therefore a critical property as it affects its cooling performance. Other properties such as heat capacity and thermal conductivity play an important role in the calculations of an adequate transformer thermal design.

Table 5.3 presents a comparison between mineral oil and alternative fluids (data published by the manufacturers)[80, 81].

Table 5.3 - Mineral oil and alternative fluids thermal properties

	Mineral oil (*typical*)	**Synthetic Ester Midel 7131**	**Natural Ester BIOTEMP**	**Natural Ester E-FR3**	**Silicone Oil Dow Corning 561**	**Low Viscosity Silicone Oil**
Viscosity @ 40^0C (mm^2/s)	9	30	42	33	40	15.3
Viscosity @ 100^0C (mm^2/s)	2.5	5.25	9	8	18	6.7
Density @ 25°C ($kg/m^{3)}$	0.88	0.97	0.91	0.92	0.96	0.956 @ 20°C
Specific Heat @ 25°C (J/kgK)	1860	1880	1963	1880	1500	1600
Thermal Conductivity@ 25°C (W/mK)	0.126	0.144	0.17	0.17	0.15	0.15
Thermal Expansion Coefficient (1/ ^{0}C)	0.00075	0.00075	0.00068	0.00074	0.00104	0.00104

At the normal operating temperature of a transformer, the viscosity of ester fluid is higher than that of mineral oil, but lower than that of silicone oil. This reduces the fluid flow rate for a given dynamic head causing a higher temperature difference between top and bottom of the cooling device in distribution size transformers. This difference is even larger for power transformers.[82] This is significant for natural cooled transformers, as the mean oil temperature rise is controlled by the cooler capacity while top oil is controlled by the natural thermosyphonic fluid flow and is effectively summation of mean oil rise and half the top to bottom fluid rise. On the other hand, when the cooling system uses forced directed flow, the effect of changing to alternative fluids is minimal, providing that the correct rating pump is used to take into account the higher impedance to fluid flow by the higher viscosity. The net effect is that for naturally cooled transformers, the top oil and thus hot spot temperature rises will be higher with esters than with mineral oil.

1. Heat-run tests performed by different transformer manufacturers[82, 83, 84, 85], on transformers up to 5 MVA indicated the following for **natural ester filled transformers:** average temperature rise 1-3 K above identical mineral oil filled units.
2. Top oil temperature rise: 3 – 5 K higher for small transformers and higher for larger transformers
3. Bottom oil temperature rise: 1 – 2 K lower for small transformers and lower for larger transformers
4. Average winding temperature rise: 1 – 2 K higher for small transformers and higher for larger transformers
5. Winding hot – spot temperature rise: several degrees higher for small transformers and can be as much as 20 K for larger transformers

Test results have shown that the temperature differences between mineral oil – filled transformers and natural ester – filled transformers are higher for Larger transformers and also higher for ONAF than ONAN.

Comprehensive temperature measurements made on a 50 MVA Power transformer[82], have also shown that in ester – filled transformers, the core hot – spot rise and hot – spot rises of other structural parts of the transformer are several degrees higher than those in Mineral oil – filled transformers.

The higher viscosity of the natural ester fluids is partially compensated by the more favourable thermal conductivity. A distribution class transformer designed for operation with mineral oil, may be filled with natural ester assuming there is sufficient margin to handle the higher temperature rise or different temperature rise limits are agreed. The proper consideration of the fluid properties in the transformer design rules allows an adequate control of the winding and fluid temperatures in every transformer range.

For optimal design of ester fluid – filled power transformers, where the temperature rises are expected to be significantly higher, there is a need for proper thermal modelling to be made. It is essential for accurate design calculations and proper winding designs to be used. Because of the higher viscosity of the ester fluids, the thermal model should include detailed flow in each winding, effect of local thermal losses based on a detailed network model for local pressure balance, detailed flow – field and cooling capacity of radiators, and pressure head / drop path analysis for combining windings, tank volume, and radiators in a single model. All necessary thermo – physical processes, including effect of local pressure gradients within windings, must be considered[86].

- **For synthetic ester filled transformers:** analyses and measurements on models and completed transformers have shown that when good transformer design rules are followed and MIDEL® 7131 as cooling medium has been used, winding temperature increases only several degrees as compared to mineral oil units. The biggest unit up to now built with synthetic ester (MIDEL® 7131) is 135 MVA, 238/13.5 kV GSU transformer[87].

In the study of cooling efficiency of MIDEL® 7131 six fluid properties are needed to be taken into consideration on the whole temperature range of operation[88], as shown in Table 5.4.

Table 5.4 - Thermal properties of MIDEL® 7131 over temperature range applicable to transformers

T(°C)	Dynamic viscosity (mm^2/s)	Specific heat (J/kg°C)	Density (kg/m^3)	Thermal Condutivity (W/m°C)	Coeff. of thermal expansion (1/°C)
-30	4200	1783	1007	0.145	0.00072
-20	1400	1797	1000	0.145	0.00073
-10	430	1811	992	0.145	0.00074
0	240	1830	985	0.145	0.00074
10	125	1855	978	0.145	0.00075
20	70	1880	970	0.144	0.00075
30	43	1910	963	0.144	0.00076
40	28	1933	956	0.143	0.00077
50	19.5	1959	948	0.142	0.00077
60	14	1994	941	0.141	0.00078
70	10.5	2006	934	0.140	0.00078
80	8	2023	926	0.139	0.00079
90	6.5	2040	919	0.137	0.00079
100	5.25	2058	912	0.136	0.0008

- **For silicone oil filled transformers:** In the retrofill of mineral oil filled units some consideration should be given to resulting temperature rise performance. Depending on the transformer design it may be possible to see higher than original design rating temperatures of the fluid.

The fluid itself is unaffected by typical over-temperatures. However, the aging rate of conventional insulation materials, such as cellulose, could be affected by operation at temperatures higher than design limits. Designers can compensate for the higher temperatures by adjusting loading levels such that the design temperature rise is not exceeded or by adding external radiator fans to increase cooling of the fluid.

The heat transfer performance of silicone transformer fluid is highly dependent on the transformer design; some designs are better optimized to take the advantage of the heat transfer characteristics of the fluid. Layer winding vertical channels maximise the thermal siphoning effects produced by the high coefficient of expansion, while disc windings are more complex and can obstruct the vertical free flow of the fluid. Table 5.5 provides comparative fluid temperature rises of both mineral oil and silicone filled transformers in a test station. The transformers were tested both as-new and after retrofilling with silicone fluid[89].

Table 5.5 - Temperature versus load data for 50 kVA transformers

Tested as received with silicone 561® fluid							
Unit 1				Unit 2			
Load %	Amb °C	Top oil °C	Oil rise K	Load %	Amb °C	Top oil °C	Oil rise K
75	26	56	30	75	26	59	33
100	28	80	52	100	26	82	54
125	31	92	61	125	31	94	63
150	28	110	82	150	28	108	80
175	24	120	96	175	24	119	95
Retrofilled with mineral oil				Rerun with silicone 561® fluid			
Unit 1				Unit 2			
Load %	Amb °C	Top oil °C	Oil rise K	Load %	Amb °C	Top oil °C	Oil rise K
100	4	44	40	100	4	42	38
126	14	68	54	126	14	69	55
153	15	91	76				
175	30	103	73	175	30	105	75

Maximum temperature limits for various combinations of solid and liquid insulating materials are presented in Table 5.6[90]. These temperatures are intended to be upper limits and are highly dependent on specific design and application.

Table 5.6 - Insulation liquid temperature limits for transformers[91]

	Conventional insulation system with mineral oil	High-temperature homogeneous insulation system with ester liquid or equivalent[1]	High-temperature homogeneous insulation system with silicone liquid or equivalent[1]
Top liquid temperature rise over ambient temperature (K)	60	80	100
Top liquid temperature at maximum ambient (°C)	100	120	140
[1] Essentially oxygen free applications where the oil preservation system effectively prevents the ingress of oxygen and moisture filled air into the tank			

The limiting factors to be considered in determining the permissible maximum temperatures are:

- Free breathing units that introduce moisture and free oxygen into the transformer tank, which are major contributors to insulation aging;
- Aging of materials which may introduce moisture and free oxygen inside the transformer tank;
- Velocity of the liquid in the cooling ducts, since long exposure of the liquid to high-temperature will accelerate degradation;
- Accelerated ageing of the liquid and insulating materials due to catalytic action caused by the presence of bare copper and silver surfaces with generation of by-products, copper derivatives dissolved in insulating liquids and particles;
- Gas bubbles caused by overheated trapped liquid between the winding conductor and conductor covering.

5.5 Material compatibility

Material compatibility is an important factor for transformer design. By far, the most commonly used transformer fluid is conventional mineral oil. Consequently, the transformer industry typically uses materials which were found to be compatible with mineral oil but may however present incompatibilities with certain alternative fluids.

To date, no incompatibilities have been found between natural ester fluids and material typically used with conventional mineral oil. However, especially in the case of elastomer material (such as gasketing) it is acceptable that interaction takes place due to the wide variation in materials quality. Individual compatibility assessments are therefore recommended for such materials.

Some material may:

- swell slightly in mineral oil and shrink slightly in natural ester fluid
- soften a little in mineral oil and harden a little in natural ester fluid

Synthetic ester fluids: As a general rule, materials that are used in the manufacture of standard mineral oil filled transformers are compatible with MIDEL® 7131. However there are several materials which are considered incompatible or are recommended for use only in particular situations. For example[92]:

- neoprene rubber is an acceptable binder for cork but should not be used on its own,
- tank enamels based on natural resins, although resistant to Midel, may leach out acidity on ageing,
- zinc plated components are not recommended apart from small fasteners, chromate passivation will break down at normal operating temperature and should not be used,
- certain papers and pressboards may release dye into Midel,
- PVC may release plasticisers into Midel and after prolonged immersion become brittle.

Silicone oils transformer fluid has acceptable compatibility with most of the materials used in mineral oil filled transformers. A large number of materials have been tested for compatibility with silicone transformer fluid. Table 5.7 is a list of transformer materials of questionable compatibility[93],

Table 5.7 - Transformer materials of questionable compatibility with silicone oil (should be tested individually)

Material (plastic)	Condition after 30 days immersion
cellulose acetate butyrate	Stiffens
polyacetal	stiffen and crazes
polyethylene	stress cracks
linear polyethylene	some stress cracks
Polyvinyl chloride	shrinks and hardens

Care is needed to properly select seal and gasket materials. Some plasticizers can be leached from some rubber formulations by silicone fluids. Because of large number of formulations available, individual testing of each potential seal or gasket material is recommended. Table 5.8 is intended as a guide to the selection of seal and gasket materials.

Table 5.8 - Compatibility ratings with silicone oil for seal and gasket materials

Material	Not compatible	Compatible	Testing recommended
Natural rubber		√	
Fluorosilicone rubber		√	
Silicone rubber	√		
Neoprene			√
Teflon		√	
Viton		√	
Nitrile rubber			√
Buna-N	√		
Polypropylene			√
Hypalon	√		
S.B.R.			√
E.P.R.			√
Corprene			√

Silicone rubber and silicone transformer fluid are very similar materials. The fluid is absorbed readily into the rubber, causing swelling and loss of physical properties. Silicone rubber parts may be found in power transformer bushing seals, top-cover gaskets, tap-changers, instrumentations and other openings. If silicone rubber is found in a transformer it should be replaced with a seal material compatible with silicone oil.

5.6 Transformer accessories

5.6.1 Tap-changers

On-load tap-changers show many different electrode configurations. The insulating distances which can be found there may be homogeneous or highly inhomogeneous. In natural ester fluid short to long homogeneous shapes like "phase-to-phase" and "phase-to-ground" distances show a dielectric strength similar to mineral oil[94]. In contrast, inhomogeneous configurations show significantly reduced withstand voltages. For AC 74-77% of the values valid for mineral oil could be achieved, while for impulse voltage only 63-65% of the nominal values were confirmed as statistically safe[95]. This behaviour has been reported as typical for inhomogeneous gaps with a clearance of 50 – 100mm. where AC test voltages up to 190kV and impulse voltages up to 650 kV are applied.

Off-circuit tap-changers are not always located in the hottest top liquid zone. However, in case the tap-changer is located in liquid temperatures above the commonly used 100°C in conventional units, one should have special thermal, mechanical and dielectric considerations for the selection of these components. In the application of high-temperature operation the compatibility of contact materials needs to be considered.

When on-load tap-changers are going to be exposed to higher temperature than conventional the supplier of the on-load tap-changer should be informed at the enquiry and the contact stage. The supplier of the on-load tap-changer should also be informed if the insulating liquid of the transformer is different from conventional mineral oil.

5.6.2 Bushings

Special attention should be given to the gasket material selection. In case of higher operating temperature condenser body of conventional bushing might be damaged due to thermal runaway. Special high-temperature or over-sized bushings may be required.

Up to date no alternative fluid filled condenser bushing has been developed for power transformer applications, alternative oil filled transformers are forced to either use conventional mineral oil OIP bushing or to use RIP bushing for the 100% "green" option.

5.6.3 Buchholz Protection Relays

The fault gases that are generated in transformers using high-temperature insulation systems based on alternative fluids may differ from those in a conventional system. The protective relay therefore, should be compatible with the insulating liquid, its operating temperature and gases that may be developed. Information on gas generation level and fault severity is still desired and caution needs to be taken when setting up the alarm and triggering levels of the Buchholz relay.

5.6.4 Other accessories

All accessories should be thermally and chemically compatible with insulating fluid over the operational temperature range.

5.7 Conclusions

The use of alternative fluids in distribution and small power transformers does not impose major design modifications. Practical experience has demonstrated that the necessary adaptations can be made without significant burdening cost.

6 In-service testing for alternative fluids

There are several standards worldwide listing the many established in-service tests used to monitor the health of mineral oil transformers. This chapter reviews the in-service tests used for alternative fluids.

When deciding on the health of a fluid, it is useful to have as many different test results as practically possible, and the trending of results over a period of time is an additional tool for decision making. This holds true for all transformer fluids, not just mineral oil.

The limits for the individual tests and the applicability to particular equipment should be sought in the relevant standards as given in Table 6.1. Note that specific analytical methods may change with time, but the latest methods are to be found in the latest issue of the relevant standard. The list of standards applicable to alternative fluids can be found in Table 6.2.

There is no current IEC standard for natural ester fluids; hence the test methods currently used rely heavily upon the existing ASTM and IEEE standards/procedures for natural esters. The IEC is in the process of developing its own natural ester standard, and the reader is advised to check with the IEC concerning its availability.

Note also that the differences in the chemistry of the alternative fluids also may lead to different methods or solvents being used to determine the same parameter. Hence for example the solvents used with mineral oil may be different from those needed for alternative fluids. Also the acceptable limits for the test parameters will change, taking into account the properties of each fluid. For example the acceptable moisture limits in esters are far higher than for mineral oil.

The reader should also be aware that test methods and standards are being continually updated and modified, hence the latest test methods can only be sourced from the latest version of the relevant standard.

6.1 DGA with alternative fluids[96,97,98]

DGA has been used for many years as an effective and reliable tool to detect incipient faults in mineral oil-filled transformers. The information provided by DGA analysis is extremely important to the asset managers with electricity supply companies.

Fault gases are formed when sufficient energy breaks the chemical bonds to form reactive fragments. These fragments combine to form the range of fault gases. Although the chemical structures of mineral oil, ester fluids and silicone fluid are fundamentally different, they all contain similar bond types, for example C–H bonds, such that the types of fault gases are similar from each of the different fluids. For a given fault, the amounts and ratios of the gases may differ from fluid to fluid.

Cigre working group WG D1.01.15 is studying the issues surrounding DGA in alternative fluids. Their report, expected to be published in 2010, centres on the use of the Duval triangle with modified diagnosis boundaries to take into account the differences in gas production of the various fluids.

6.2 On line DGA monitoring of alternative fluids[99,100,101]

On-line DGA monitoring has been accepted as an efficient means for early stage fault diagnoses, and the on-line DGA devices have been widely used in mineral oil filled transformers for years. Cigre working group TF D1.01.15 has done extensive investigations into the accuracy of various commercial on-line devices used with alternative fluids. Its report on the subject is now available through Cigre publications[102].

Table 6.1 - List of Alternative fluid testing methods

(Key: Most commonly used IEC method, Most commonly used ASTM method, Not quoted but generally used)

Properties	Mineral Oil[103]	Synthetic ester[104]	Natural ester[105]	Silicone fluid[106]
Acidity	IEC 62021-1/ IEC 62021-2 ASTM D974	IEC 62021-1/ IEC 62021-2	ASTM D974	IEC 62021-1
Appearance	ISO 2049	ISO 2049	ASTM D1524	Visual , ISO 2049
Breakdown voltage	IEC 60156 ASTM D1816	IEC 60156	ASTM D877 ASTM D1816	IEC 60156
Colour	ISO2049 ISO 2211 ASTM D1500	ISO 2211	ASTM D1500	ISO 2211
Corrosive sulphur	IEC 62535 ASTM D1275		ASTM D1275	
Dielectric Dissipation Factor (DDF)	IEC 60247 / IEC 61620 ASTM D924	IEC 60247	ASTM D924	IEC 60247
Density	ISO 3675 / ISO 12185 ASTM D1298	ISO 3675	ASTM D1298	ISO 3675
DGA analysis	IEC 60567		ASTM D2945 ASTM D3284 ASTMD3612	
Fire point	ISO 2592 ASTM D92	ISO 2592	ASTM D92	ISO 2592
Flash point	ISO 2719 ISO 2592 ASTM D92	ISO 2719 / ISO 2592	ASTM D92	ISO 2719 / ISO 2592
Furanic compounds	IEC 61198 ASTM D5837			
Gassing tendency	IEC 60628 ASTM D2300	IEC 60628	ASTM D2300	IEC 60628

Properties	Mineral oil	Synthetic ester	Natural ester	Silicone Fluid
Interfacial tension	ISO 6295 ASTM D971		ASTM 971	ASTM 971
Kinematic viscosity	ISO 3104 ASTM D445	ISO 3104	ASTM D445	ISO 3104
Kinematic viscosity at low T°	IEC 61868			
Lightning Impulse breakdown	(IEC 60897) ASTM D3300		ASTM D3300	
Oxidation stability	IEC 61125 IEC 62036 ASTM D2112 ASTM D2440	IEC 61125		
PCB content	IEC 61619 ASTM D4059		ASTM D 4059	
Permittivity	IEC 60247 ASTM D924	IEC 60247	ASTM D924	IEC 60247
Pour point	ISO 3016 ASTM D97	ISO 3016	ASTM D97	ISO 3016
Refractive index	ISO 5661	ISO 5661		ISO 5661
Resistivity	IEC 60247	IEC 60247	ASTM D1169	IEC 60247
Specific heat	ASTM D2766		ASTM D2766	
Stray gassing	CIGRE Brochure n°296			
Thermal conductivity	ASTM D2717		ASTM D2717	
Thermal expansion coef.	ASTM D1903		ASTM D1903	
Visual examination	ASTM D1524		ASTM D1524	
Water content	IEC 60814 ASTM D1533	IEC 60814	ASTM D1533	IEC 60814

Table 6.2 - Standards applicable to alternative fluids

Standard	Transformer fluids			
	Mineral oil	**Synthetic ester**	**Natural ester**	**Silicone oil**
IEC	**60296 (Ed. 3) - 2003** "Fluids for Electrotechnical Applications - Unused Mineral Insulating Oils for Transformers and Switchgear"	**61099 (Ed. 1) - 1992** "Specifications for unused synthetic organic esters for electrical purposes"	The IEC is currently working towards this standard	**IEC 60836 (Ed. 2) - 2005** "Specifications for Unused Silicone Insulating Liquids for Electrotechnical Purposes"
	60422 (Ed. 3) - 2005 "Mineral Insulating Oils in Electrical Equipment - Supervision and Maintenance Guidance"	**61203 (Ed. 1) - 1992** "Synthetic organic esters for electrical purposes - Guide for maintenance of transformer esters in equipment"		**IEC 60944 (Ed. 1) - 1988** "Guide for Acceptance of Silicone Transformer Fluid and its Maintenance in Transformers"
	60599 (Ed. 2.1) - 2007 "Mineral Oil-Impregnated Electrical Equipment In Service - Guide to the Interpretation of Dissolved and Free Gases Analysis"	**60599?**	**60599?**	**60599?**
IEEE	**C57.106-2006** "Guide for Acceptance and Maintenance of Insulating Oil in Equipment"	/	**C57.147-2008** "Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers"	**C57.111-1989** "Guide for Acceptance of Silicone Insulating Fluid and Its Maintenance in Transformers"
	C57.104-2009 "Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers"	/	/	**C57.146-2005** "Guide for the Interpretation of Gases Generated in Silicone-Immersed Transformers"
	C57.140-2006 "Guide for Evaluation and Reconditioning of Liquid Immersed Power Transformers"	**C57.140-2006?**	**C57.140-2006?**	**C57.140-2006?**
ASTM	**D 3487 - 08** "Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus"	/	**D 6871 - 03** "Standard Specification for Natural (Vegetable Oil) Ester Fluids Used in Electrical Apparatus	**D 4652 - 05** "Standard Specification for Silicone Fluid Used for Electrical Insulation"
	/	/	/	**D 2225 - 04** "Standard Test Methods for Silicone Fluids Used for Electrical Insulation"
	D 3455 - 02 "Standard Test Methods for Compatibility of Construction Material with Electrical Insulating Oil of Petroleum Origin"	**D 3455?** (because petroleum origin….)	/	**D5282 - 05** "Standard Test Methods for Compatibility of Construction Material with Silicone Fluid Used for Electrical Insulation"

7 Handling precautions

In general, alternative fluids are considered non flammable and non toxic. The actual handling recommendations for each particular fluid will be supplied by the fluid manufacturer.

There is a list of considerations that users should consider:

- Storing more than one liquid – flushing of lines and pumps to prevent contamination
- Storage in cold climates – what is required
- Spillage and containment
- Whether the manufacturer recommends a nitrogen atmosphere
- Materials compatibility
- Pumping rates (to prevent the build up of static charge)
- Handling precautions
- Fire characteristics
- Local regulations and attention to the volume being handled/stored
- Disposal at end of life

Anyone interested in using a particular fluid should refer to the manufacturer's data sheets or contact the company. All responsible fluid manufacturers will be please to help with concerns about the handling of their fluids.

7.1 Containment Measures

Local regulations and insurance companies usually determine the containment requirements for transformers. Certain insurance companies have identified reduced containment requirements for alternative fluids, these are mainly due to the less flammable rating of the fluids, but there are further reductions in requirements for biodegradable fluids.

7.2 UBA Classification

The Umwelt Bundes Amt (UBA) in Germany evaluates chemicals and gives them a water hazard rating, either being non-water hazardous or based on three hazard levels. Classification is carried out on the basis of the Administrative Regulation on the Classification of Substances Hazardous to Waters into Water Hazard Classes (Verwaltungssvorschrift wassergefährdende Stoffe, VwVws) and the ratings are shown in the table below

Table 7.1 – UBA Classifications

Classification	UBA Description
nwg	Non hazardous to water
Hazard Class 1	Low Hazard to Waters
Hazard Class 2	Hazard to Waters
Hazard Class 3	Severe Hazard to Waters

Table 7.2 - The UBA classification for various transformer fluids is in the table below[107]

Fluid	CAS Number	UBA Classification
Synthetic Esters	865203-73-2	nwg
Natural Esters	68956-68-3	nwg
Silicone Oils	63148-62-9	1
Low viscosity Silicone Oils	63148-62-9	1
Mineral Oils	Variety	1

8 Retrofilling

8.1 Introduction

The term retrofilling refers to the process of removing the insulating liquid of an existing working transformer and replacing it with a new liquid. Usually the fluid being replaced is mineral oil in distribution class transformers. Retrofilling of power transformers requires qualified engineering assessment as there would probably need to be design considerations to accommodate the differences between mineral oil and other fluids.

8.2 Reasons why retrofilling is done[108, 109, 110, 111, 112, 113, 114, 115]

- Although mineral oil is a commonly used transformer fluid, there are many reasons why the end user may wish to consider retrofilling with another fluid:
- **Fire safety** - Alternative fluids have much higher flash and fire points than mineral oil. Replacing mineral oil will greatly enhance fire safety, especially in populated or sensitive areas. The cost of retrofilling for fire safety reasons is often less than the cost of installing or upgrading fire safety systems for insurance purposes.
- **Environmental concerns -** Both natural and synthetic esters are officially classified as readily biodegradable and are considered to be much more environmentally friendly that mineral oil. Replacing mineral oil will greatly reduce the environmental impact in the event of a spillage.
- **Moisture tolerance** - Ester fluids are much more tolerant of moisture ingress than mineral oil. Hence in areas prone to wet conditions, retrofilling transformers with ester fluids will lead to increased reliability.
- **Corrosive sulphur** - Corrosive sulphur problems are linked to the use of mineral oil. Alternative fluids do not suffer with this problem. Retrofilling transformers where corrosive sulphur compounds have been detected in mineral oil, but before the transformer has shown signs of copper corrosion is likely to prevent further damage. However, it should however be stressed that alternative fluids will not correct the effect of corrosion that has already occurred, nor are they able to restore transformers that have failed due to corrosive sulphur problems.
- **Prolonging solid insulation longevity** - There is now a body of literature which explains that cellulose insulation last longer in ester fluids than mineral oil. In part this effect may be explained by the esters' ability to retain moisture. Replacing mineral oil by an ester fluid will shift the position of the equilibrium of moisture between paper and fluid, such that the fluid will draw moisture into itself. This should not cause problems with electrical safety as these fluids are more moisture tolerant. The attraction for asset managers is that this may delay the purchase of a new transformer.

Before starting a retrofilling, it is strongly recommended that the warranty on the transformer is checked to see if it will be affected.

8.3 Fluid Miscibility

When considering retrofilling, it is important to check whether the old and new fluids are miscible. Retrofilling is recommended when both fluids are miscible as this makes the flushing procedure to remove the old oil more effective and prevents unusual electrical stresses at the fluid interfaces. Although not typically recommended for immiscible fluids, e.g. replacing silicone fluid with ester fluid, it is possible, but in these cases much greater care would need to be taken.

Table 8.1 lists fluid miscibility which is reproduced here again for convenience.

Table 8.1 - Miscibility of alternative fluid with mineral oil at ambient temperature

(Note that this table applies only to unused oils)

	Mineral oil	Silicone oil	Natural ester	Synthetic ester
Mineral oil	X	Miscible	Miscible in all proportions	Miscible in all proportions
Silicone oil	Miscible	X	Not miscible	Not miscible
Natural ester	Miscible in all proportions	Not miscible	X	Miscible in all proportions
Synthetic ester	Miscible in all proportions	Not miscible	Miscible in all proportions	X

8.4 Materials compatibility

When changing fluids it is necessary to check whether the new fluid is compatible with the other materials in the transformer e.g. gaskets, seals, paints etc. This should be done by consulting the fluid manufacturer or by using appropriate data sheets.

8.5 General description of the retrofiling procedure

The actual procedure to be followed must be done in accordance with the recommendations of the transformer manufacturer and fluid supplier. The procedure needs to be carried out by a qualified engineer.

A simple general description of the retrofilling process is given as follows:

a. De-energization of the unit, grounding of equipment, testing oil sampling etc, must be performed in accordance to the transformer manufacturer or the User's standard procedures.

b. Draining of transformer oil

c. Flushing with heated replacement fluid (heated fluid recommended)

d. Draining of residual "flushing" fluid

e. Replacement of aged or damaged seals and gaskets

f. Filling of the transformer with heated new fluid, preferably under partial vacuum

g. Standing time to allow any trapped air bubbles to dissipate

A critical point is the draining / flushing process. It is important to remove as much of the residual 'old' fluid as possible, in order to gain maximum benefit from the retrofilling and not to compromise the properties of the new liquid.

Alternative fluids are K Class Liquids, having Fire Points above 300^{0}C. If the 'old' fluid is mineral oil then a high percentage of residual mineral oil may result in lowering of the Flash / Fire Points of the ‘new’ fluid. Information relating to the amount of residual mineral oil which can be tolerated before the properties of the new replacement fluid become affected can be obtained from the individual fluid manufacturers.

Filling of the transformer must be done in accordance with the ester fluid supplier’s recommendations. It is especially important to define the transformer stand time (time before the energization of the unit) as the alternative fluids are generally more viscous then mineral oil and typically require longer stand times in order for the fluid to permeate the solid insulation and for any bubbles to leave the fluid.

Oil sampling should be performed prior to transformer energization and again at regular intervals in accordance to the ester fluid supplier’s recommendations. A further safety measure often recommended is the energization at no load for a specified period of time prior to connecting the load.

9 Use of alternative fluids with solid insulation systems

9.1 Transformer life considerations

A transformer’s life expectancy is based on a number of factors, the most important of which is the quality of its insulation system over time. It is therefore important to understand the factors which influence the choice of solid insulation systems and also the choice of fluids that can be used with them.

9.2 Cellulose insulation

Cellulose based paper and pressboard is still the most common solid insulation material used in transformers. Cellulose is a polymer structure made up of many glucose units arranged in chains:

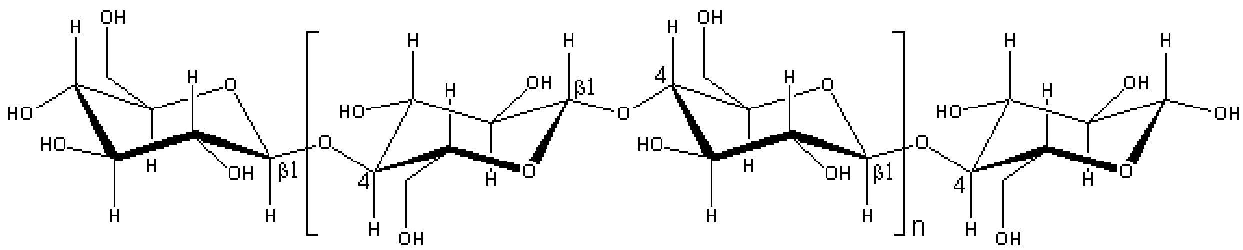


Figure 9.1 - The structure of β cellulose

The average number of glucose units in the polymeric chains, called the ‘degree of polymerisation’ or DP, dictates how mechanically strong the paper is: the longer the chains, the stronger the paper. A key indicator of the potential working lifetime of a transformer is the condition of the paper insulation. In a new transformer, the DP of the cellulose insulation is typically between 1000 and 1200.

As a transformer ages, the paper (cellulose) begins to degrade and de-polymerise, forming chains of shorter length (lower DP)[116, 117.]

As this happens this process forms by-products including water and acids.

The accumulation of acids and water in the cellulose accelerates the aging process leading to a downward spiral of paper decay. The overall effect of this is that the paper becomes progressively weaker. When the average DP reaches 200, the paper insulation is said to have reached the end of its working life.

Another critical factor for all organic materials used in transformer insulation systems is the temperature. It is known that temperature can be an accelerating factor in conventional degradation processes like hydrolysis, oxidation or can have a major impact on physical properties like dielectric strengths. Temperature has also the ability to be the main factor degradation process like pyrolysis.

Typically and historically cellulose insulation has been used in combination with mineral oil, and this remains the most common solid/liquid insulation combination. However this combination can have some operational disadvantages:

- Mineral oil is sensitive to moisture ingress
- Cellulose cannot be used under high temperature conditions
- Wet mineral oil and wet cellulose can cause faults

These setbacks have prompted end users to explore other solid/liquid systems of insulation in order to be able to extend transformer life and to run at higher temperatures. The use of ester fluids has also been catalysed by the drive to find more environmentally acceptable materials.

9.3 Cellulose–alternative fluids systems

9.3.1 Cellulose-Silicone fluid insulation systems

Silicone fluid has been widely used in combination with cellulose insulation in distribution transformers for some years[118,119].

Several studies have been carried out to understand the influence of water, temperature and oxygen on this insulating system. One study [120] suggests that the behavior with water is similar to that of the mineral oil – cellulose system. Advantages over the mineral oil–cellulose system are mainly concerned with the fire safety.

9.3.2 Cellulose-Synthetic ester fluid insulation systems

The combination of synthetic ester and cellulose has been used for over 30 years. This combination is widely used in distribution transformers[121, 122, 123, 124, 125, 126] and increasingly used in power transformers[127].

Advantages over the mineral oil–cellulose system include a higher level of fire safety, more environmentally friendly, and a far greater tolerance to moisture.

9.3.3 Cellulose – Natural ester fluid insulation systems

In recent years the use of natural esters with cellulose has been mainly focused on distribution transformers[128, 129, 130, 131, 132, 133,]

More recently there have been some applications in power transformers[134, 135,136,137].

Advantages over the mineral oil–cellulose system include a higher level of fire safety, more environmentally friendly, and a far greater tolerance to moisture.

One disadvantage of natural esters is their tendency to be more oxygen sensitive than other fluids, leading to their use usually being recommended in lower temperature applications and in sealed systems.

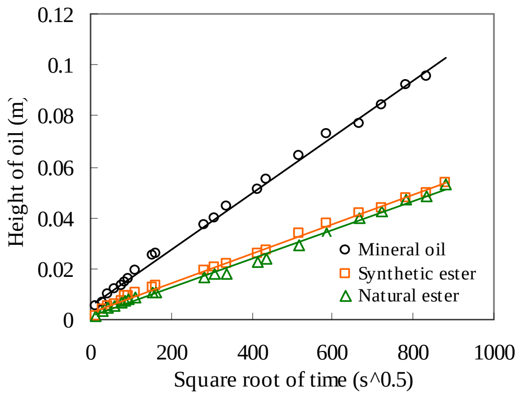
9.4 Cellulose longevity

There is also now a growing body of evidence to suggest that cellulose paper and pressboard can have a longer working life when immersed in esters, as opposed to mineral oil[138,139,140 141].

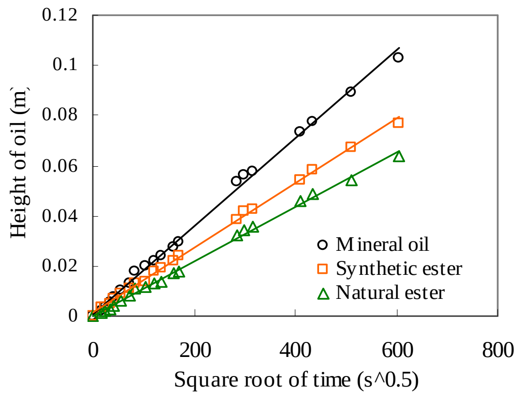
This is partly due to the ability of ester fluids to retain more water in the fluid bulk as a result of their higher polarity[142], and there is some evidence that free acids liberated by hydrolysis may chemically react with the cellulose forming a stronger material[143].

9.5 Cellulose Impregnation by alternative fluids

Studies carried out by the University of Manchester evaluated the capillary action of fluids with 3mm pressboard. Samples of pressboard were placed with their base in the test fluid, the distance which the fluid travelled up the pressboard was then plotted against time. These experiments were carried out at room temperature and also at elevated temperature of 60°C. The results are shown in the graphs below[144]



Capillary Action 20°C



Capillary Action 60°C

Figure 9.2 – Graphs of Capillary action at 20°C and 60°C

The slope of these graphs was calculated and showed that the rate of fluid impregnation was similar in esters at 60°C when compared to mineral oil at 20°C.

A further test was carried out to check the impregnation rate in laminated pressboard blocks. This found that the rate of impregnation for synthetic and natural esters at 60°C was equivalent to the rate of mineral oil impregnation at 20°C. This confirmed the capillary action findings. The graph of the results is shown below.

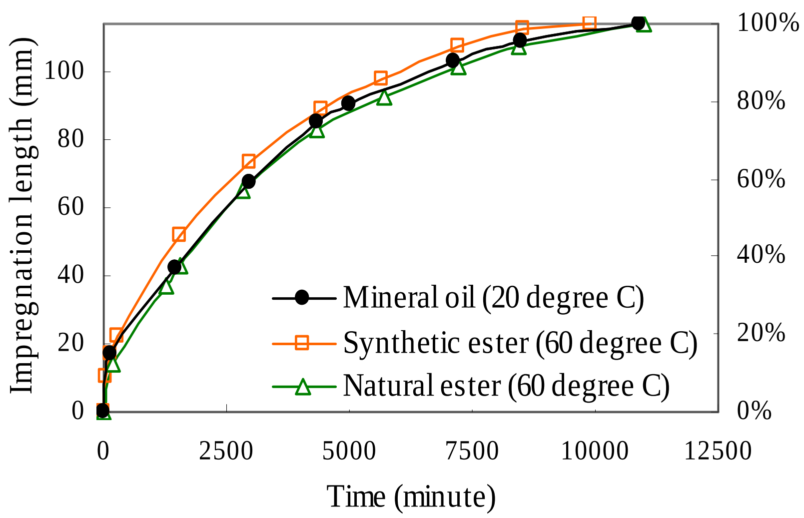
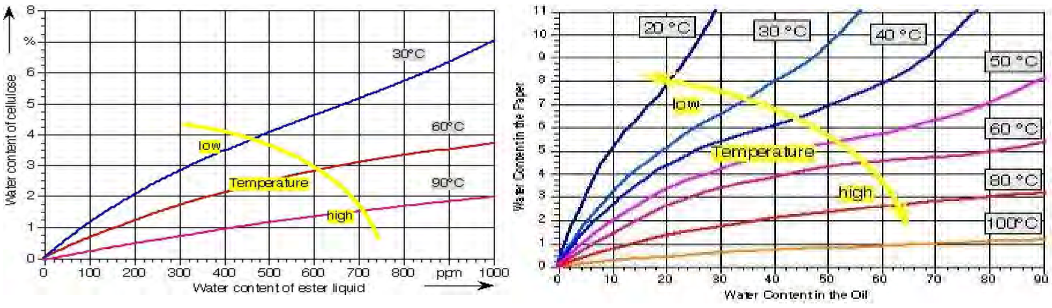


Figure 9.3 – Graph of Impregnation

9.6 Moisture Equilibrium between fluid and cellulose

Moisture equilibrium curves between fluids and paper are shown for both Mineral Oil and Synthetic Ester below[145]



Synthetic ester Mineral Oil

Figure 9.4 – Graphs of Moisture equilibrium in synthetic ester and mineral oil

From these curves it can be seen that for synthetic ester at 60°C, water content in fluid of 200ppm would equate to a water content in the cellulose of 1.1%. At the same temperature, Mineral Oil with a water content of 20ppm would lead to a water content in the cellulose of 2.6%.

It is important to note that the moisture equilibrium curves are most meaningful at higher temperatures, >60°C. At lower temperatures the rate of moisture transfer between the cellulose and fluid is significantly slower and so equilibrium is rarely reached.

9.7 High Temperature Aramid Insulation

The term "Aramid" is derived from a composite of "**Ar**omatic poly**amid**es" and describes a form of synthetic solid insulation commonly used in high temperature applications. These polyamides occur in two main forms: para-linked, and meta linked. Commercial examples, produced by DuPont are Nomex® and Kevlar®

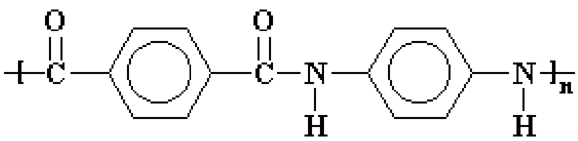


Figure 9.5 - Kevlar - Para linked aramid

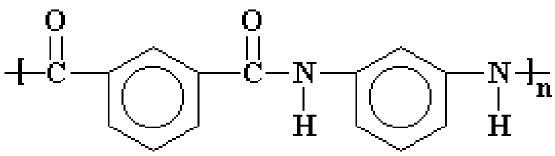


Figure 9.6 - Nomex - Meta linked aramid

It is the meta linked polyaramid which is used as a high temperature insulation of transformers, and for the purpose of simplicity in the brochure it will be referred to as Aramid. Aramid for transformers is available as both a synthetic paper and also pressboard.

Aramid is far more robust that cellulose insulation, and provides high levels of electrical, chemical and mechanical integrity. It is more expensive than cellulose, and is used selectively in high temperature demanding applications, for example in traction transformers. Chemically it is resistant to hydrolysis and oxidation and does not produce the levels of gas and water by-products as does cellulose.

In operational terms, the benefits of using aramid include:

- Stability in high temperatures
- Increased power for a given unit size
- Improved reliability and increased durability
- Low moisture absorption
- Higher resistance against cut and tearing as compared to cellulose
- Higher capacity to outstand emergency overloads
- Higher continuous overload capacity
- Allows for more compact designs

In order to maximise the advantages offered by aramid solid insulation, it is often used with high temperature fluids such as silicone or ester fluids[146]

9.7.1 Aramid – Silicone fluid insulation systems

The combination of silicone fluid with aramid papers for high temperature insulation systems is an obvious improvement over the mineral oil – cellulose system. Prototypes combining silicone fluid and aramid papers were developed as early as 1973[147,148].

Today this system is a commonly used high temperature insulation system around the world.

The longevity of this system has been demonstrated particularly in rail systems where high temperatures within the transformer exist due to overloading. A recent study on the transformers of the first commercial series of the Shinkansen, the Japanese high speed train, has demonstrated the low impact of operating conditions on the life of the insulation system[149].

9.7.2 Aramid – Synthetic ester fluid insulation systems

Increasingly, synthetic ester is being successfully used in combination with aramid insulation in applications such as traction transformers and wind farm generators where high running temperatures are likely and the conditions will be very demanding[150].

This combination of insulation system means that high power transformers can be build smaller[151] and also have the benefit of being environmentally friendly as well as fire safe[152].

9.8 Hybrid insulation systems

A hybrid transformer design is such that the colder areas of the transformer are insulated with traditional cellulose-based Kraft papers, while aramid paper is applied in the hottest areas e.g. wrapped conductors, axial and radial spacers.

This strategy permits the same sort of advantages as for wholly aramid systems, but obviously not to quite the same extent, as cellulose is still present in the transformer. Fluids suitable for running at high temperatures are commonly used with these systems.

10 The absence of corrosive sulphur in alternative fluids

It is generally accepted that the presence of corrosive sulphur compounds and the problems they cause in transformers is inherently an issue for mineral oil. Cigre and many other groups have been investigating this issue, and there is now a wealth of literature on the subject. The references given here represent only a fraction of the work in print[153, 154,155].

Corrosive sulphur is not an issue for fluids other than mineral oil.

Synthetically made fluids such as synthetic esters and silicone fluids do not contain sulphur as they are manufactured from sulphur free raw materials. Natural esters are produced from the seeds of crops and also do not contain corrosive sulphur. Hence these fluids will not cause corrosive sulphur problems in transformers or other equipment. Any slight trace quantities of sulphur that may be detected by sensitive analytical techniques will be chemically different from the types of sulphur compounds which react with metals.

The manufacturers of alternative fluids should be able to provide evidence that their fluids are non corrosive. Appropriate tests may include analytical methods such as ASTM D1275B or IEC 65353.

11 Conclusions

The natural ester, synthetic ester and silicone transformer fluids which are the basis of this brochure, are now seen by the electrical power supply industry as credible alternatives to mineral oil. These are currently found in active service in many sizes of transformer throughout the world.

Major transformer manufacturers and end users are keen to promote the use of these fluids, especially where the advantages they have over mineral oil, such as fire safety, can be usefully employed as a mineral oil substitute in sensitive areas.

To date, there has been much research in both industry and academia to discover and document the properties and behaviour of these fluids. Out of this work has been the development of various fluid testing methods and standards to help and guide the industry to use the fluids to their best advantage. Recognised international bodies such as Cigre, IEEE and the IEC now have several working groups dedicated to furthering the knowledge and application of these fluids.

It is envisaged that the future will see an increasing growth in the use of these fluids in ever more challenging and higher power applications as the knowledge and experience of their benefits become more commonplace.

12 Suggested further work for Cigre

This work contributing to this technical brochure has highlighted other areas of investigation which were outside of the scope of this work. These topics may be of interest for Cigre to follow up with future working groups:

- The study of other synthetic liquids, including synthetic aromatic hydrocarbons which are already used in capacitive voltage transformers[156]
- The study of the properties and advantages of using mixtures of insulating fluids for the optimisation of chemical and electrical characteristics[157]
- Retrofilling of mineral oil power transformers with alternative fluids
- Analytical evaluation of in-service transformers with alternative fluids

13 APPENDIX

13.1 Questionnaire for the Industry Survey

The following survey was sent out to various fluid users. The questionnaire is listed first, and analyses of the replies received are given in the later tables.

CIGRE A2-35 SURVEY FOR INDUSTRY

QUESTIONNAIRE SENT TO TRANSFORMER MANUFACTURERS, UTILITIES ETC

This questionnaire is concerned with assessing and understanding the experiences of industry with using alternative insulating fluids other than mineral oil in transformers. The fluids which are the focus of this group are:

Esters (Synthetic and Natural)

Silicone Fluid.

The group is **not** concerned with PCB, High Molecular Weight Hydrocarbons or SF_6 gas insulation

Over the past 20 years, as safety and environmental aspects become increasing important, the use of insulating fluids other than mineral oil has become more common, and it is important that we learn more about how these fluids are performing in the field.

The CIGRE working group A2-35 has been set up to gather important data and report on the electrical industry experiences with these fluids. This information will be fed back to the electrical industry by means of a formal CIGRE report which will be published.

Confidentiality

The results of this questionnaire will be 'bundled' and presented as a summary. No individual companies or people will be identified.

On behalf of this CIGRE group I would like to ask the recipients of this survey to provide as much detail as possible so that we are able to maximise our learning about the performance of these fluids.

Name (optional) .... **Organisation**...

Country: .... **Date**...

Type of Organisation (eg Utility, Transformer manufacturer etc)...

1 Please indicate the approximate number of transformers using the following fluids

	New Transformers						Retrofilled transformers				
Transformer type	Mineral oil	Silicone fluid	Synthetic ester	Natural ester	Other		Mineral oil	Silicone fluid	Synthetic ester	Natural ester	Other
Power Transformers											
Distribution transformers											
Traction transformers											
Other											

2a Please indicate the approx. number and type of transformers using silicone fluid in your organisation

	New Transformers				Retrofilled transformers		
Transformer type	Approximate number	Voltage & Power rating	Approximate age range		Approximate number	Voltage & Power rating	Approximate age range
Power Transformers							
Distribution transformers							
Traction transformers							
Other							

2b ***Please indicate the approx. number and type of transformers using synthetic ester <u>fluids</u> in your organisation***

	New Transformers				Retrofilled transformers		
Transformer type	Approximate number	Voltage & Power rating	Approximate age range		Approximate number	Voltage & Power rating	Approximate age range
Power Transformers							
Distribution transformers							
Traction transformers							
Other							

2c ***Please indicate the approx. number and type of transformers using natural ester fluids in your organisation***

	New Transformers				Retrofilled transformers		
Transformer type	Approximate number	Voltage & Power rating	Approximate age range		Approximate number	Voltage & Power rating	Approximate age range
Power Transformers							
Distribution transformers							
Traction transformers							
Other							

3 Please comment on which factors you evaluate and select an alternative fluid (please indicate the fluid

Factor	**Comments**
Design	
Safety & Environmental aspects	
Requirements of a Standard	
Price	
Availability	
Others (eg customer requirement)	

4 Please comment on any design considerations for alternative fluids (please indicate the fluid

Factor	**Comments**
Cooling system	
Electrical design	
Breathing system – free breathing or sealed (e.g. bladder, gas blanket, hermetically sealed)	
Materials compatibility e.g. gaskets, seals, painting, materials etc	
Solid insulation impregnation	
Fluid transport and filling issues	
Other e.g. : Tap changers, bushings, Bucholtz relay, Water sensor	

5 Please comment on your retrofilling considerations for alternative fluids (please indicate the fluid)

Factor	**Comments**
What is your procedure and experience of mixing alternative fluids with mineral oil	
Any design changes for the retrofilling or retrofilled equipment	
Why a specific fluid was chosen	

6 Please comment on what methods your organization uses to track the performance of its in-service units which use alternative fluids (please indicate the fluid)

Factor	**Comments**
Which parameters are measured e.g. DGA, acid value, moisture etc	
Frequency of monitoring	

7 Please comment on your experiences with alternative fluids in service in your organisation (please indicate the fluid)

Factor	**Comments**
Advantages and disadvantages Please give as much detail as possible	
Did you have any problems with oxidation stability or sludge formation	
How do you see the future of alternative fluids in your organisation	

8 Please comment on how your organisation disposes of used fluid (please indicate the fluid

Factor	**Comments**
End of life – how do you get rid of the transformer and fluid at the end of its life	

9 Please use this space for any additional comments that you have concerning alternative fluids

13.2 Results from the Industry Survey

Analysis by country of the replies of our questionnaire - 24 replies in total

Country										
Austria	Austria 1									
Brazil	Brazil 1									
Czech	Czech 1									
Croatia	Croatia 1									
France	France 1	France 2								
Germany	Germany 1									
Hungary	Hungary 1									
Italy	Italy 1									
Japan	Japan 1	Japan 2	Japan 3	Japan 4	Japan 5	Japan 6	Japan 7	Japan 8	Japan 9	Japan 10
Switzerland	Switzerland 1									
UK	UK 1	UK 2								
USA	USA 1	USA 2								

Key to Colour Coding & Abbreviations used in the tables

KEY	Synthetic ester	Natural ester	Silicone oil	Mineral oil	Various Liquids

PT = Power Transformer;

DT = Distribution Transformer;

TT = Traction Transformer

1 Please indicate the approximate number of transformers using the following fluids

Country	Organisation	New transformers						Retrofilled transformers				
		Tr. type	Mineral Oil	Silicone	Syn. ester	Nat. ester	Other	Mineral Oil	Silicone	Syn. ester	Nat. ester	Other
Germany 1	Maint. DT	DT	5286	2	2572	3	459			351		
France 1		PT			x	3						
		DT	x		x	x						
		TT	x	x	x							
France 2	Utility	DT				12						
Japan 1	TR manufac.	PT	1600									
		DT	1800	2	4							
		TT		270								
Japan 2	TR manufac.	PT	1000				5					
		DT	6000	23			8					
		TT	1400	1640								
Japan 3	TR manufac.	PT	1000									
		DT	6200	17								
		Other	1300	40								
Japan 4	TR manufac.	PT	70									
		DT	3800									
		Other	3300									

Country	Organisation	New transformers						Retrofilled transformers				
		Tr. type	Mineral Oil	Silicone	Syn. ester	Nat. ester	Other	Mineral Oil	Silicone	Syn. ester	Nat. ester	Other
Japan 5	Utility	PT	490									
		DT	1976									
		Other	274									
Japan 6	Utility	PT	194				7	12				
		DT	8									
Japan 7	Utility	PT	450									
		DT	2900									
Japan 8	TR manufac.	PT	400									
		DT	2390000					260000				
Japan 9	Utility	PT	989									
		DT	5666									
Japan 10	TR manufac.	PT	5300									
		DT	11000	16								
		TT	500	2900								
Switzerland1	TR manufac.	DT	50									
		TT	600-800	x	x	x						

Country	Organisation	New transformers						Retrofilled transformers				
		Tr. type	Mineral Oil	Silicone	Syn. ester	Nat. ester	Other	Mineral Oil	Silicone	Syn. ester	Nat. ester	Other
Austria 1	TR manufac.	PT		1	2							
		DT	80000	1000	1000	10						
		TT	2000	400	500							
Brazil 1		PT	164			13		26				
		other						11				
Czech 1	Utility-Distribution.	PT	every	no	no	no		every	no	no	no	
		DT	almost all	rarely	rarely	rarely		almost all	rarely	rarely	rarely	
		TT	all	no	no	no		almost all	no	no	no	
Italy 1	Utility-Transmission	PT	800									
		other	150	2								
USA 1	TR manufac.	PT	>350			29		>20			24	
USA 2	TR manufac.	PT	>350	4		35		>20			24	
		DT	11000 3ph; 17000 1ph	100 3ph.		3100 3ph 1950 1ph			2		10	
UK 1	Utility	PT	1400			2						
		DT	70000		10							
		TT	20									
UK 2	TR manufac.	PT	190	9								
		DT	40	2								

Country	Organisation	New transformers						Retrofilled transformers				
		Tr. .type	Mineral Oil	Silicone	Syn. ester	Nat. ester	Other	Mineral Oil	Silicone	Syn. ester	Nat. Ester	Other
Croatia	TR manufac.	PT	~2000									
		DT	~180000	200	120							
		TT	~120		3							
Hungary				5%	10%	1						

2a ***Please indicate the approx. number and type of transformers using alternative fluids in your organisation***

Country	Fluid	New transformers				Retrofilled transformers		
		Tr. type	Approx. Number	Voltage & power	Approx. age	Approx. Number	Voltage & power	Approx. age
Germany 1	Silicone	DT	2	6kV/630kVA	1970.1971			
	Syn. ester	DT	2220	6/10kV; 400-600kVA	1996-2008	351	6/10kV; 400-600kVA	1965-1987
	Nat. ester	DT	4	10kV; 400-630kVA	2004			
France 1	Nat. ester	PT	3	242kV/22MVA				
				132kV/90MVA	New			
				110kV/31,5MVA plan				
France 2	Nat. Ester	DT	10	400 kVA; 20 kV	1 - 2 years			
Japan 1	Silicone	DT	2	66kV/5~9MVA	25~30 y			
		TT	~270	25kV/2~4MVA	~20 y			
	Syn. ester	DT	4	3.3kV/0.2MVA	8 y			
Japan 2	Silicone	DT	23	6.6~ 66kV/1~15MVA	5 y			
		TT	~1640	20, 25kV/1~5MVA	~20 y			
Japan 3	Silicone	DT	17	6.~ 22kV/1~2.2MVA	1991-2002			
		other	40	3 ~3.3kV/0.75~4.3MVA	1986-2003			
Japan 3	Silicone	DT	16	22-66kV/1~6MVA, 3 ph.	0-3 years			
		TT	2900	20-25kV/1-6MVA, 1 ph.	0-30 years			

Country	Fluid	New transformers				Retrofilled transformers		
		Tr. type	Approx. Number	Voltage & power	Approx. age	Approx. Number	Voltage & power	Approx. age
Austria 1	Silicone	DT	1000	10~ 30kV/50-4000kVA	0-25 y			
		TT	400	25kV/ <8MVA	0~15 y			
	Syn. ester	PT	1	238 kV-135 MVA	~4 years			
		DT	1000	10~ 30kV/50-4000kVA	0-15years			
		TT	500	25 kV/ 7,5 MVA	0-15years			
	Nat. ester	PT	2	110kV/40MVA&69kV/50MV A	2 years			
Brazil 1		PT	13	34.5,69,138kV/10-40 MVA	12 new, 1 year			
		other	3	138, 230 kV/ 11-22 MVA	3 new			
Czech 1	Silicone	DT	10	22-35 kV	5years	10	22-35 kV	5years
		Other	15	35 kV	5years	5	35 kV	5years
	Syn. ester	DT	10	22-35kV	5 years	10	22-35kV	5 years
Italy 1	Silicone	Other	2	2 kV - 150 kVA	15 years			
USA 1	Nat. ester	PT	29	18-230 kV HV; 10-212 MVA	New	24	15-161 kV HV;10-200 MVA	New to 40 + years
		DT				5	15 kVHV; 1-5 MVA	Unknown

Country	Fluid	New transformers				Retrofilled transformers		
		Tr. type	Approx. Number	Voltage & power	Approx. age	Approx. Number	Voltage & power	Approx. age
USA 2	Silicone	PT	4	13.2-34.5 kV / 7.5 - 10 MVA	New			
		DT	100	4.16 - 34.5 kV / 500 - 3000 kVA	New	2	4.16 kV / 500 kVA	
	Nat. ester	PT	30	13.2-230 kV / 7.5-45 MVA	New	24	15-161kV;10-200MVA	new
		DT	3100 3ph 1950 1ph	1.26 - 34.5 kV / 50 - 5000 kVA	New	5	15 kV; 1-5MVA	nn
UK 2	Silicone	PT	9	above 5 MVA	up to 40 years			
		DT	2	below 5 MVA	up to 40 years			
Croatia	Silicone	DT	200	<=24 kV; <=2000 kVA	<25 years			
	Syn. ester	DT	120	<=24 kV; <=3150 kVA	<10 years			
		TT	3	25kV; 1500 kVA	< 1 year			
Hungary	Silicone	DT	5%	30/0.4 kV; 20/0.4 kV & 10/0.4 kV				
	Syn. ester	DT	10%	30/0.4 kV; 20/0.4 kV & 10/0.4 kV				
	Nat. ester	DT	1	medium voltage				

3 Please comment on which factors you evaluate and select an alternative fluid (please indicate the fluid)

Country	Factor					
	Design	**Safety & Environmental aspects**	**Requirements of a Standard**	**Price**	**Availability**	**Others**
Germany 1	No factors	We place since 1996 transformers with synthetic ester. We fulfil with it the legal restraint with regard to the fire security and water protective law	No factors	The use of tr. with syn. ester as an insulating liquid is more cost-intensive in the acquisition, about an operation duration space of 40 years seen, however more economical. There are other advantages with regard to standardisation, the environmental problems which can not be valued with the cash.	No factors	No factors
France 1		X				X
France 2	No modification/adaptation should be needed	Readily biodegradable and non-toxic				
Japan 1	Synthetic ester based on rapeseed-advantage of cooling with low-viscosity, insulation characteristics then increasing the design flexibility	Synthetic ester based on rapeseed-Possibility of increasing CO2 by using fossil fuel and there are environmental impacts.			Synthetic ester based on rapeseed-There is an effect of downsizing transf. by the characteristics of low-viscosity, and it is reduced the material of volume for transformers	Silicone fluid - customer requirements.

Country	Factor					
	Design	Safety & Environmental aspects	Requirements of a Standard	Price	Availability	Others
Japan 2	Silicone liquid: (viscosity 20cSt) immersed for DT. Normal silicone liquid for TT. Insulation system: silicone liquid -kraft paper or silicone liquid- aramid paper system.	Yes. To reduce global warning, Japan AE Power System developed "Silicone -Fluid transformers" as an alternative option to SF6 Gas Insulated Transf.	No, there is no restriction on the standard. Included existing IEC 60076 standard series.	Silicone liquid immersed transformers are raised price a little compared with the cost of mineral oil immersed transformers.	It is almost equal to mineral oil immersed transformers.	In the rail road company with chiefly high concern for the environment in the metropolitan area etc., these users demand both the environment disaster prevention and compact.
Japan 3						As per customer Specification. Chemical plan, Substation for traction power (subway
Japan 5 & 7						Only mineral oil
Japan 10						Customer requirement
Austria 1						Customer requirement

Country	Factor					
	Design	Safety & Environmental aspects	Requirements of a Standard	Price	Availability	Others
Brazil 1	Natural ester: Increased dielectric life, prevents moisture build-up in insulation paper, essentially eliminates vapour formations under sudden overload, significant reduction in voltage stress gassing tendency, elimination of sludge and copper coking, reduced insurance costs, reduced clearances to equipment and buildings, permits shorter bus runs, reduced energy losses and materials, reduction in physical space requirements, reduction in aging rate of insulation system, operational life extension, increased overload	Natural ester: reduced fire and environmental liability	none	Natural ester: Price is still double of mineral oil but advantages are greater than; Mineral oil: is used for 230kV and 400 kV equipments	Natural ester means an availability greater than mineral oil	At short time there is an expectation of natural ester price decreases because of Brazil produces a lot of natural esters
Italy 1		Power station of transmission utilities are usually located outside downtown and far from the historical centre, so this aspects are not so relevant as for distribution transformers				
USA 1						Customer requirement

Country	Factor					
	Design	Safety & Environmental aspects	Requirements of a Standard	Price	Availability	Others
USA 2	silicone: we go no higher than 34.5 kV	Silicone & Nat. ester are considered "Less flammable" fluids suitable for indoor installation.	ASTM D6871, IEEE C57.147, NBR 15422 are established for the use of natural esters ASTM D4652, IEEE C57.111	Silicone is the most expensive	Silicone-insulating fluids share the base materials with other products	Customer requirement
	Natural ester: the properties of the fluid must be incorporated into the design	Natural esters are very biodegradable and pose less of environmental hazard.		Natural ester is lower than silicone but twice the price of mineral oil	Natural ester-renewable source of materials, can compete with the food industry and biofuels	
UK1	no	yes	yes	no	yes	yes
UK2	must be able to provide dual function of cooling and insulation within the transformer	must meet all appropriate IS and Company requirements	any alternative fluid must meet and preferably surpass existing requirements for mineral oil	competitively priced in relation to mineral oil	lead time comparable to mineral oil, able to deliver to site on worldwide basis	environmental risk to be minimised
Croatia	In case of TT, smaller active part, less weight	Water protected region, Fire security law	very often			mostly customer requirements

4 Please comment on any design considerations for alternative fluids (please indicate the fluid)

Country	Factors						
	Cooling system	**Electrical Design**	**Breathing system**	**Materials compatibility**	**Solid insulation impregnation**	**Fluid transport & filling**	**Accessories**
Germany 1	Cooling system of transf. with syn. ester must be coined a little bit differently and be planed	No design consideration for natural or synthetic	We placed since 1996 transformers with "free breathing" system in connection with synthetic ester.	No design consideration for natural or synthetic	No comment	It should exist two considerations for to fill. Once for synthetic ester and once for mineral oil.	No design consideration for natural or synthetic
France 1			Sealed system (rubber bag and hermetically sealed)		Longer than with mineral oil		No vegetable oil in tap changers but preferably liquids with higher flash point than conventional mineral oil.
France 2			sealed fulfilled tank (natural esters)				
Japan1	Synthetic ester based on rapeseed-There is an advantage of high cooling performance by-the low viscosity ester and there is a possibility of downsizing of the transformer and/or reducing number of heat exchangers.	Synthetic ester based on rapeseed-it is a high insulation performance, and it also has an effect of permittivity matching related insulation performance, then there is a possibility of downsizing the transformer.	Synthetic ester based on rapeseed-sealed type is better	Synthetic ester based on rapeseed-material selection is necessary	Synthetic ester based on rapeseed-it would be able to compact design depend on high insulation performance, effect of permittivity matching and low-viscosity.	Synthetic ester based on rapeseed-it would be necessary to control water content and humidity, because it has high cellular	Synthetic ester based on rapeseed-it is no experience to equip the OLTC, It may be no problem.

Country	Factors						
	Cooling system	**Electrical Design**	**Breathing system**	**Materials compatibility**	**Solid insulation impregnation**	**Fluid transport & filling**	**Accessories**
Japan 3	It is cooling characteristic near the mineral oil immersed transformer.	It is almost equal to the mineral oil immersed transformer.	Nitrogen gas sealed type	It is necessary to choose the material that compatibility is good for the silicone liquid.	N/A	Especially, none.	It is necessary to choose the material that compatibility is good for the silicone liquid.
Japan 10	Viscosity is higher than mineral oil		Sealed	We change materials depending on thermal design.			
Austria 1	PT-should be added; MPT-cooling adapted; TT- the cooler unit and expansion tank were readjusted; DT- safety margin only for silicone fluid	PT-should be added; MPT- adapted; TT- reduced free oil distances with finer barrier systems to avoid fibre bridges for silicone, but no changes compared to mineral oil; DT- no changes compared to mineral oil	MPT&DT: sealed TT- free breathing (silicone and synthetic ester)	Should be considered, different from those of mineral oil; higher grade of materials necessary.	PT: should be considered; MPT- higher temperature (MIDEL7131 and FR3); DT&TT- no changes compared to mineral oil transformers.	PT: should be considered; MPT: fulfilled or customer requirement; DT&TT: transformers will be delivered fulfilled.	Tap changer and bushing compatibility should be checked

Country	Factors						
	Cooling system	**Electrical Design**	**Breathing system**	**Materials compatibility**	**Solid insulation impregnation**	**Fluid transport & filling**	**Accessories**
Brazil 1	Transformer design for mineral oil and natural ester are the same. Ester has an advantage if the transformer works at higher temperature than mineral oil because its viscosity decreases very fast at higher temperatures and the result is an increase of transformer overload capability	Electrical design is the same for both mineral and natural ester.	The breathing system design is the same for both mineral and natural ester oils: e.g. bladder.	Elektronorte specify teflon gaskets for plain flanges. Lifetime of gaskets is much greater than transformer life (no leakages):	For natural ester, the impregnation requires double of time than for mineral oil.	There is no restriction for natural ester transportation. Natural ester filling process requires cleanness of mineral oil before and after treatment.	Tap changer manufacturers are revising design criteria to accept natural ester and two different types are available on the market.
Czech 1	silicone oil or synthetic ester-sealed	up to 35 kV	sealed				
USA 1	Unchanged for retrofills. May add cooling to meet 65 degree C rise or customer accepts higher temperature rise on mineral oil design	No difference	Require positive pressure nitrogen system or conservator with bladder (true for both natural ester and silicone)	Many tests done to ensure compatibility	Same as with mineral oil	Ensure no contact with oxygen. Flush oil filling equipment with mineral oil after handling natural ester fluid.	Works in LTCs as long as fluid does not gel and contact with oxygen is avoided. Moisture sensors must be recalibrated as natural fluid ester holds more water in solution than mineral oil.

Country	Factors						
	Cooling system	Electrical Design	Breathing system	Materials compatibility	Solid insulation impregnation	Fluid transport & filling	Accessories
USA 2	Unchanged for retrofills. May add cooling to meet 65 degree C rise or customer accepts higher temperature rise on mineral oil design	Silicone: not suitable for HV applications Natural ester: little difference for distribution and small power. M&L power requires more careful design	Require positive pressure nitrogen system or conservator with bladder (true for both natural ester and silicone)	Silicone: requires viton gaskets, very aggressive fluid, abrasive on contacts Natural ester: no compatibility issues, may be better than oil for contact stability and contact life	Need to allow for viscosity differences.	Silicone is no compatible with any other fluids. Causes oil for foam. Ensure no contact with oxygen. Flush oil filling equipment with mineral oil after handling natural ester fluid.	Silicone causes coking on contacts Natural ester: Works in LTCs as long as fluid does not gel and contact with oxygen is avoided. Moisture sensors must be recalibrated as natural fluid ester holds more water in solution than mineral oil.
UK1	Yes	Yes, particularly impulse level	Yes-sealed system with bladder	Yes- testing is required	Yes tests performed	Yes-specialist filling	Yes all these are considered

Country	Factors						
	Cooling system	Electrical Design	Breathing system	Materials compatibility	Solid insulation impregnation	Fluid transport & filling	Accessories
UK2	Performance capabilities of the fluid in relation to natural and forced cooling configurations. Compatibility with thermally enhanced solid insulation.	Electrical and thermal properties are of primary importance-any significant reduction in these parameters in comparison with transformer mineral oil is likely to preclude widespread use.	Product range, company standards and customer requirements generally determine the breathing system; however any new insulating fluid would be assessed for all industry standard breathing system if considered appropriate.	Development work is carried out in-house to determine suitability of each new material in partnership with the appropriate OEMs.	Prior to approval for use in manufacturing, all new insulation materials are subject to a rigorous development program to determine the correct processing requirements, including their behaviour in relation to established materials.	Capability to retrofill and process on site. Compliance with land, sea and air transport.	Where new materials are required to interact with auxiliary equipment, guidance is sought from each OEM. Any alternative fluid must be of comparable performance to transformer mineral oil.
Croatia	with silicone oil differently designed	almost equal to mineral oil	Hermetically sealed execution preferred	To choose material compatible with alternative fluids	similar to mineral oil transformers	DT and TT transformers are delivered filled with oil and ready for putting in service	material to be compatible with alternative fluids

5 *Please comment on your retrofilling considerations for alternative fluids (please indicate the fluid)*

Country	Factors		
	Your procedure and experience of mixing alternative fluids with mineral oil	**Any design changes for the retrofilling or retrofilled equipment**	**Why specific fluid was chosen**
Germany 1	Mineral oil and synthetic ester can be mixed well with each other. No special procedure is necessary moreover.	Because our transformers with an average charge of 44% are pursued, no change is necessary in design	We fulfil with it the legal restraints with regard to fire security and water protection.
Japan 2	None	N/A	N/A
Austria 1		In case of retrofilling it should be guaranteed that the gasket material is compatible and does not show leakages.	
Brazil 1	Elektronorte does not mix oils	There are no design changes for the retrofilling or retrofilled equipment.	Elektronorte is still specifying mineral oil for 230 kV and 500 kV transformers because the manufactures are not ready to produce them with mineral oil.
Czech 1	We tested alternative fluids in our laboratory but we don't use them because the price is too high for our operation.	In the future - control tests and then substitute mineral insulating oil by synthetic organic ester.	
USA 1	We avoid getting natural ester fluids in our mineral oil system so the test parameters of the mineral oil are not affected not a major issue). We keep the mineral oil content of natural ester fluid filled units to less than 7% to maintain the fire point greater than 300 °C.	If xfmr has oil pumps they must be analysed with respect to higher viscosity of natural ester fluid.	Commercial considerations, insurance risk assessments, environmental concerns and customer specifications.

Country	Factors		
	Your procedure and experience of mixing alternative fluids with mineral oil	**Any design changes for the retrofilling or retrofilled equipment**	**Why specific fluid was chosen**
USA 2	Silicone contamination can cause main problems, even small amounts, when mixed in mineral oil.		Silicone: requires a "less flammable" fluid, cold weather application.
	We avoid getting natural ester fluids in our mineral oil system so the test parameters of the mineral oil are not affected (not a major issue). We keep the mineral oil content of natural ester fluid filled units to less than 7% to maintain the fire point greater than 300 °C.	If xfmr has oil pumps they must be analysed with respect to higher viscosity of natural ester fluid.	Natural ester: Commercial considerations, insurance risk assessments, environmental concerns and customer specifications.
UK 1	Not used retrofilling		
UK 2	Mineral oil transformers have been retrofilled with Midel in accordance with OEM guidelines. No experience of retrofilling with any other fluid.	Electrical and mechanical design remains unchanged for Midel but material compatibility guidelines from the fluid OEM are observed.	Any derivation from mineral oil is customer led. The price difference is such that alternative fluids are uncompetitive when in direct competition with mineral oil
Croatia	We don't recommend to our customers		

6 Please comment on what methods your organization uses to track the performance of its in-service units which use alternative fluids (please indicate the fluid)

Country	Factors	
	Which parameters are measured (DGA, acid value, moisture, etc.)	**Frequency of monitoring**
Germany 1	Since 1996 we make in some transformers tests. Besides we pay attention on moisture content and disruptive discharge voltage.	2 times per year
France 2	BDV, DDF, water content, DGA, furanic content, acidity(free fatty acid content	3 months (during experimental period)
Japan 1	Synthetic ester based on rapeseed - same as mineral oil but it shall be controlled water content after opening the tank.	Synthetic ester based on rapeseed - same as mineral oil .
Japan 2	It is almost equal to the mineral oil immersed transformers	It is almos equal to the mineral oil immersed transformers
Japan 7	DGA: (H2, CH2, C2H6, C2H4, C2H2, Total combustible gas);Furfural Analyses,	DGE: once every 2 years(age 5 to 20 years), once every 1 year (other ages)
		Furfural analyses: once every 3 years (age more than 3 years)
	Oil acid value, Withstand voltage, Moisture level, Volume resistivity	Other tests: 1st year, once every 3 years (if DGA is caution level, once every year)
Japan 10	DGA	We generally recommend that the measurement of DGA is carried out once per 3 years
Austria 1	yes	On-line, as well as off-line
Brazil 1	The parameters measured are determined by the standard ASTM D6871	DGA: semestral; Physical-chemical: once a year
Czech 1	Appearance, Density at 20°C, water content, BDV, dielectric dissipation factor-tan δ, resistivity, acidity, neutralization value	110 kV- once each two years: 220-400 kV once a year; DT- each 5 years
Italy 1	DGA, water, tan δ, BDV; and NN	5 years
USA 1	As a manufacturer we don't monitor our customer's transformers. We are participating in development of IEEE Guide for DGA in natural ester fluid.	As a manufacturer we don't monitor our customer's transformers.

Country	Factors	
	Which parameters are measured (DGA, acid value, moisture, etc.)	Frequency of monitoring
USA 2	Some parameters as measured for mineral oil. IEEE has published C57.147 Natural ester guide. Am participating in development of IEEE Guide for DGA in natural ester fluid and new High Temperature Transformer WG..	Same frequency as for oil-filled units.
UK1	DGA, acid and moisture	Annual and on line hydrogen
UK2	Measurements in accordance with IEC 61203 for synthetic organic ester fluids where appropriate. IEEE C57.147 would be used for natural ester fluids in lieu of any IEC document.	6-12 months from initial measurements taken during commissioning.
Croatia	same as for mineral oil	same as for mineral oil

7 Please comment on your experiences with alternative fluids in service in your organisation (please indicate the fluid)

Country	Factors		
	Advantages and disadvantages	**Did you have any problems with oxidation stability and sludge formation**	**How do you see the future of alternative fluids in your organisation**
Germany 1	We have a transformer with approx. 500 ppm water in our test row. (We use the "open system" and this is an isolated case.	No problems	Because we since 1996 purchase only transformers with synthetic fluids, I see a very good future for synthetic ester in our companies. We purchase furthermore transformers with this fluid.
France 2		No	increasing use
Japan 1	Synthetic ester based on rapeseed-same as mineral oil. Advantage: environmental performance. Disadvantage: high sensitivity by water content	Synthetic ester based on rapeseed-no experience any problem with 8 years operation for 4 units	Synthetic ester based on rapeseed-high price of fluid
Japan 2	Advantage: disaster, prevention, environment and compact. Disadvantage: Initial cost impact.	None	In the future, the reduction of the fire fighting equipment will be expected by the silicon liquid immersed transformer in the indoor substation.
Japan 10	No advantages. Disadvantage is that the fluid cost is high and we must have two fluid facilities.	No experience.	TT for Europe will use synthetic fluid.
Austria 1	customer	customer	Increasing
Brazil 1	See item (3), design comments.	No	New fluids will made the difference for transformer and reactor design at the future to extend life, reduce costs, increase its function and be environmentally friendly
Czech 1	we have only laboratory experiences	no	I don't know
Italy 1	High price and possibility of trans-contamination during maintenance	No	actually no, at least for HV transformers

Country	Factors		
	Advantages and disadvantages	Did you have any problems with oxidation stability and sludge formation	How do you see the future of alternative fluids in your organisation
USA 1	We respond to customer specification requirements. Customers use natural ester fluids for fire safety benefits, in environmentally sensitive areas, to reduce aging rate of cellulose insulation, to reduce carbon footprint. Disadvantages include development of temperature rise calculation, different handling and manufacturing procedures, additional testing and evaluations to understand compatibility and performance parameters.	Special procedures are used to minimize contact with oxygen.	We expect that natural ester fluid will be an increasing percentage of our dielectric mix.
USA 2	We respond to customer specification requirements. Customers use natural ester fluids for fire safety benefits, in environmentally sensitive areas, to reduce aging rate of cellulose insulation, to reduce carbon footprint. Disadvantages include development of temperature rise calculation, different handling and manufacturing procedures, additional testing and evaluations to understand compatibility and performance parameters.	Silicone absorbs moisture at a very rapid rate and can easily become saturated.	
		Special procedures are used to minimize contact with oxygen and moisture.	We expect that natural ester fluid will be an increasing percentage of our dielectric mix.
UK1	Disadvantages: we are not equipped with processing plant, storage facilities or pumping equipment for other fluids. Difficulty with working on a transformer filled with natural ester because of oxidation tendency.	No	Not sure at present.
UK2	Fluids in use are Midel 7131, silicone and FR3. Advantages of the fluid accrue to our customers in terms of reduced fire risk or environmental impact. All synthetic fluids are significantly more expansive than the standard oil.	Oxidation can be a problem with FR3, silicone fluid and Midel will absorb moisture if not sealed or a hydrating breather is used.	Any increase in the use of synthetic fluids fill be customer driven and will be affected by their compatibility with ancillary equipment.
Croatia			It is increasing. We have three different oil filling and treatment equipment

8 Please comment on how your organisation disposes of used fluid (please indicate the fluid)

Country	Factors
	End of life - how do you get rid of the transformer and fluid at the end of its life
Germany 1	It is easier to decontaminate a transformer with synthetic ester as with mineral oil. There isn't legal restraints for decontaminating this liquid.
France 2	specific way for oil valorisation (no blending with mineral oil)
Japan 1	Internal activity: same as mineral oil. Fluid: possibility of recycle to bio-fuels etc.
Japan 2	It is almost equal to the mineral oil transformers. However as for silicone liquids, reuses is examined if there is no problem on the quality after it abandons it.
Japan 7	Removed transformers are transported to factories by trailers and disassembled. Reusable materials, such as copper and iron are recycled. Mineral oil is collected and transported to factories by tank trucks. It is refined and recycled.
Japan 10	DT-no experience as all transformers are in operation; TT-transformer users get rid of transformer
Austria 1	separate disposal
Brazil 1	For transformers with mineral oil and natural ester oil, Eletronorte will replace with natural ester.
Czech 1	Regeneration of mineral insulating oil
Italy 1	disposal in accordance with local rules
USA 1	Have not had to get rid of a natural ester fluid filled transformer. Scrap natural ester fluid is handled by same scrap mineral oil dealer.
USA 2	Have not had to get rid of a natural ester fluid filled transformer. Scrap natural ester fluid is handled by same scrap mineral oil dealer.
UK 1	This has not yet arisen.
UK 2	Currently we are not involved in the disposal of redundant equipment. Where this is required this is subcontracted to licensed contractors.
Croatia	separate disposal

9 Please use this space for any additional comments that you have concerning alternative fluids

Country	Comments
USA 1	We are actively promoting the use of natural ester fluid in medium and large power transformers and are working with a provider of this fluid to generate the knowledge necessary for wider application.
USA 2	We are actively promoting the use of natural ester fluid in medium and large power transformers and are working with a provider of this fluid to generate the knowledge necessary for wider application.

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