Use of Alternative Insulation Liquids

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ABSTRACT

The predominant liquid used for electrical insulation and cooling in transformers is mineral oil. However, it has some limitations, specifically in terms of fire safety and environmental impact. In answer to this, the use of ester-based alternative liquids has been increasing and today they are not just used in special-application transformers (such as traction or windpower units), but are being specified into mainstream distribution and larger power units.

This paper provides a brief history of insulation liquids and covers the different types of fluids available. It will also include detailed information on the various properties of these liquids, including fire behaviour, environmental impact and moisture interaction. Reference will be made to how these properties impact the design, installation and operation of modern transformer systems.

INTRODUCTION

The term “alternative liquids” is commonly used in the power industry to refer to any dielectric fluids which are not mineral oil. There are a number of factors that influence why a user would want to select a liquid that is not mineral oil based, but the predominant reason since the early days of transformers has been for fire protection. Even back in the 1930s alternative fluids such as PCBs were therefore used whenever a there was an unacceptable fire risk and the use of these fluids continued well into the 1970s, until it was recognized that they were posing their own risks in terms of toxicity and environmental impact. At this time replacement fluids were needed in order to maintain fire safety, while removing PCBs from the networks.

Unlike silicone and high molecular weight oils synthetic organic esters could be formulated that were fire safe, but also readily biodegradable and this was particularly attractive for the replacement of environmentally harmful PCBs. This advantage lead to this fluid gradually becoming the predominant choice in Europe, as utilities and other users recognized the benefits of having a product which was less environmentally harmful if it were spilled.

Impact on the environment became more and more important as time went on and the 1990s saw a second wave of dielectric liquid development, as companies started to look for renewably sourced raw materials which could be used. There was a resurgence of interest in natural esters, liquids derived directly from seed oils. Despite the poor oxidation stability of these liquids they offered some real advantages in cost, availability and most importantly sustainability. Several organizations set to developing dielectric fluids from seed oils which could perform well enough to be used long term in transformer systems, and by choosing the right base oils and additive packages we today have a number of natural ester products on the market.

Following on from this the beginning of the 21st century has seen a number of other dielectric fluids developed and put on the market. Not only high fire point solutions, but also direct mineral oil replacements such as GTL-based products and hydrocarbon liquids derived from plant sources. These two fluids are seldom seen as true “alternative liquids”, but are rather combined with mineral oil due to their properties and ability to conform to mineral oil standards.

For the purposes of this paper we will focus on the main high fire point solutions of silicone, synthetic organic ester and natural ester. These three fluids presently dominate the alternative liquids sector and the two ester liquids are currently the only alternatives to be utilized in large power transformers.

FIRE SAFETY

One key consideration when installing new equipment is safety and in the case of transformers especially fire safety, since these units can contain large quantities of potentially flammable fluid. In the past mineral oil has been the fluid of choice for transformers, due to its good dielectric and cooling properties. Unfortunately in terms of the fire safety of transformers, mineral oil is problematic, as it has a relatively low fire point. This has lead to transformer fires being a regular occurrence.

Alternative fluids, including esters, can be used to substantially reduce the fire risk posed by the transformer. Esters have a much higher fire point than mineral oil and this in turn means that they are far less likely to ignite. Under IEC rules there are classifications for dielectric liquids according to fire point and net calorific value. Fluids with a fire point in excess of 300°C are named K-class. Table 1 shows the different classes for mineral oil and the two groups of ester-based fluids.

Table 1
Classification of fluids to IEC 61039[1]

Fluid type	Flash Point (ISO 2719)	Fire Point (ISO 2592)	IEC 61039 Class
Mineral oil	150°C	170°C	O1
Synthetic organic ester	260°C	316°C	K3
Natural ester	316°C	360°C	K2
Silicone Liquid	260	>350	K3

These K-class fluids are also known as less flammable fluids in the insurance industry and the use of these can bring very significant savings in installation costs, especially for larger transformers, with a bigger volume of fluid.

The increased fire safety of esters can also lead to significant reductions in installation costs when taking into consideration the reduced spacing to buildings and between transformers. This in turn can lead to shorter LV cable runs, reducing losses and due to the ability to locate other equipment closer to the transformer, will also reduce MV cable runs from switchgear. In terms of the civil construction costs the use of an ester fluid may remove the need for costly fire barriers.

One well known guidance document for transformer installations is FM Global datasheet 5-4[2], this goes into a lot of detail with regards to fire safety and is also referenced in standards such as IEC 61936.[3]

For outdoor installations a big difference can be made between mineral oil and FM approved less flammable fluids, which include a range of ester-based liquids. To be classified as FM Approved a product must have a fire point in excess of 300°C, i.e. is K-class, and the manufacturer must have regular audits to ensure that a high standard of quality is maintained. A summary of the spacing differences for less flammable fluids and mineral oil is given in Table 2, in this case the building would have a non-combustible construction.

Table 2
FM Global spacing guidelines with no fire barriers

Fluid Volume (l)	Spacing to buildings (m)	
	Mineral Oil	FM Approved
0 to 1,900	1.5	1.5
1,900 to 19,000	7.6	1.5
19,000 to 38,000	15.2	1.5
>38,000	15.2	7.6

If the minimum spacing distances cannot be met then fire barriers need to be installed between the transformer and other equipment, and between the transformer and buildings.

An example of how the use of less flammable esters can significantly reduce installation costs is shown in Fig. 1, this would apply for transformers with fluid volumes between 19,000 and 38,000 litres. This sort of volume would be typical of a medium power transformer in a substation.

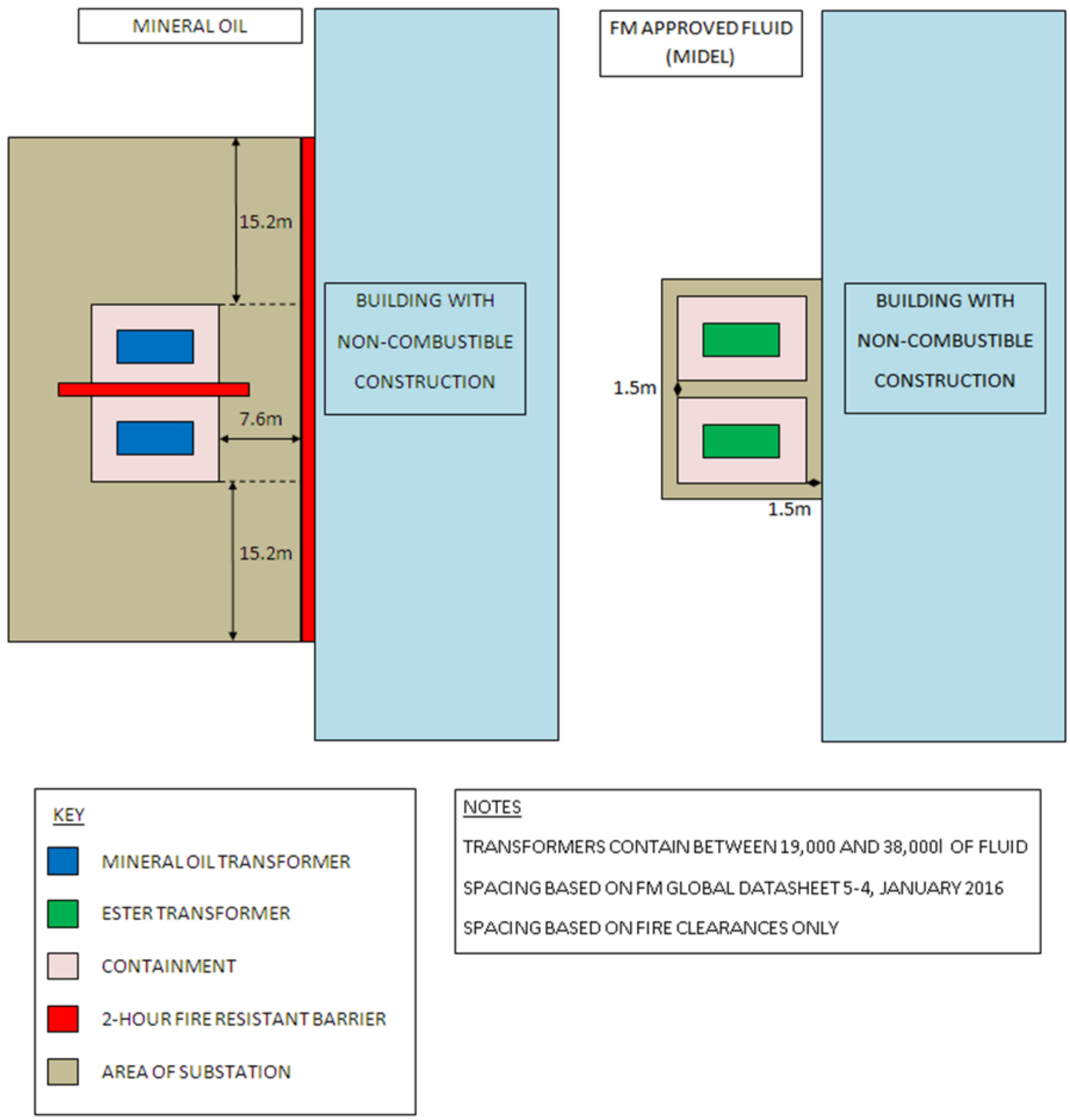

Figure 1
FM Global spacing example

It can be seen that by just using a less flammable fluid spacing can be significantly reduced and 2-hour fire barriers can be eliminated. This in itself will reduce the capital cost of the installation. The ongoing advantage of positioning the transformers much closer to the building is that low voltage cable runs will be shorter, reducing energy costs associated with losses for the lifetime of the installation.

ENVIRONMENTAL PROTECTION

In addition to fire safety, environmental considerations present an important safety issue and should be factored in when choosing a transformer fluid. Any leakage or spillage of fluid can have a direct and sometimes devastating impact on the local environment.

Accidental or negligent misuse of these materials can also lead to legal consequences. Users should ensure related protocols are followed and that state and government legislation is understood before project installations commence.

With transformers, the main component that can damage the environment is the fluid contained in the tank. Mineral oil has traditionally been used, but the risks of use have proven high, especially in environmentally sensitive projects such as wind farms. Should the oil spill after an accident or a fire, extensive damage can result, including the pollution of drinking water or damage to the sea in offshore installations. Clean-up costs are also steep and containment is often required even for transformers with relatively small volumes of mineral oil.

When deciding on a transformer fluid, it's important to consider how long the material persists before it's degraded. The main internationally recognized biodegradation test is the Organisation for Economic Co-operation and Development (OECD) 301.[4] It takes the test substance, mixes it with an activated sludge (usually from a wastewater plant), and then monitors how long it takes for the substance to biodegrade.

For a substance to be readily biodegradable under the OECD guideline, it must reach 60% degradation within 10 days of reaching 10%. This "10 day window" criterion makes this test regime extremely stringent, and it is expected that any material that achieves "readily biodegradable" status will rapidly degrade if released into the environment. It's worth noting that some materials may be termed inherently biodegradable, but this is not equivalent to "readily biodegradable" because these fluids can still degrade slowly.

The graph in Fig. 2 shows the OECD 301 results for common transformer fluids. The chart indicates that ester-based fluids easily meet the readily biodegradable criteria. The fact ester fluids degrade rapidly in the environment, however, doesn't mean they will degrade quickly in the transformer. The processes that lead to biodegradation are very different to those that lead to fluid ageing in operation.

Biodegradation requires the presence of microbes that break fluids down and a suitable environment for them to reside. Usually this means the presence of water and appropriate temperatures. In a transformer system, the environment is far too hot and dry to sustain microbes and they would die off rather quickly, so the fluid could not biodegrade under normal operation.

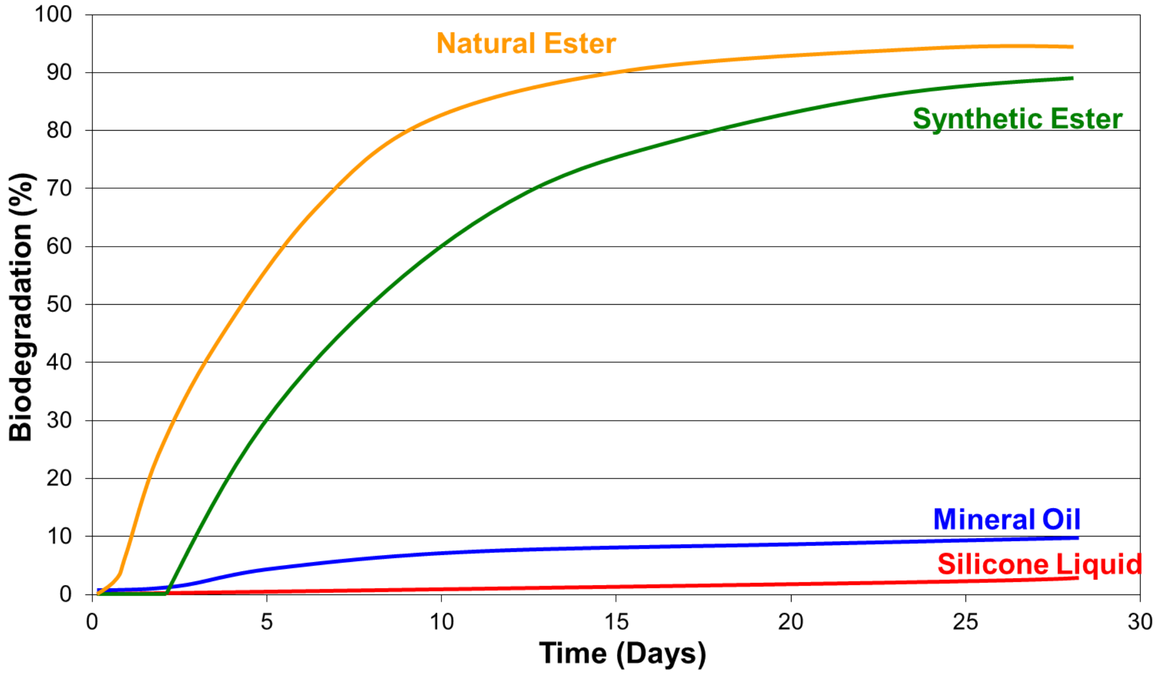

Figure 2
Comparison of OECD 301 biodegradation

MOISTURE INTERACTION

It is well known that mineral oil is susceptible to moisture ingress, which lowers the dielectric strength and leads to a rapid deterioration of the cellulose fibres used as solid insulation. In humid climates it is quite often the case that transformers must be regularly dried, placing an unwanted burden on network operators and giving an unreliable service to consumers.

On the other hand ester fluids interact with moisture in a different way to mineral oil, potentially reducing the amount of maintenance needed. When considering transformers water can come from two places, either the atmosphere or from the degradation of the cellulose paper used as solid insulation. In breathing transformers the moisture present in the oil will mainly come from the air, while in sealed units the paper ageing produces the majority of the water.

The ester functional group is what makes ester fluids different in moisture behaviour to mineral oils. Fig. 3 shows how the ester interacts with water molecules, forming a weak bond, known as a hydrogen bond. This can be thought of as being like a magnetic attraction, where the water is bound to the ester.

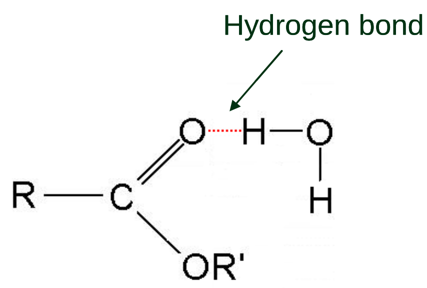

Figure 3
Ester interaction with water

This interaction with water leads to a much higher moisture saturation limit for esters, when compared to mineral oils or other high fire point fluids such as silicone liquid. The other important factor is the amount of ester functional groups in the fluid. Synthetic ester based on pentaerythritol has four ester groups in each molecule, while a natural ester has three ester groups. This means that the synthetic ester has a higher moisture saturation limit than the natural ester, as shown in Fig. 4.

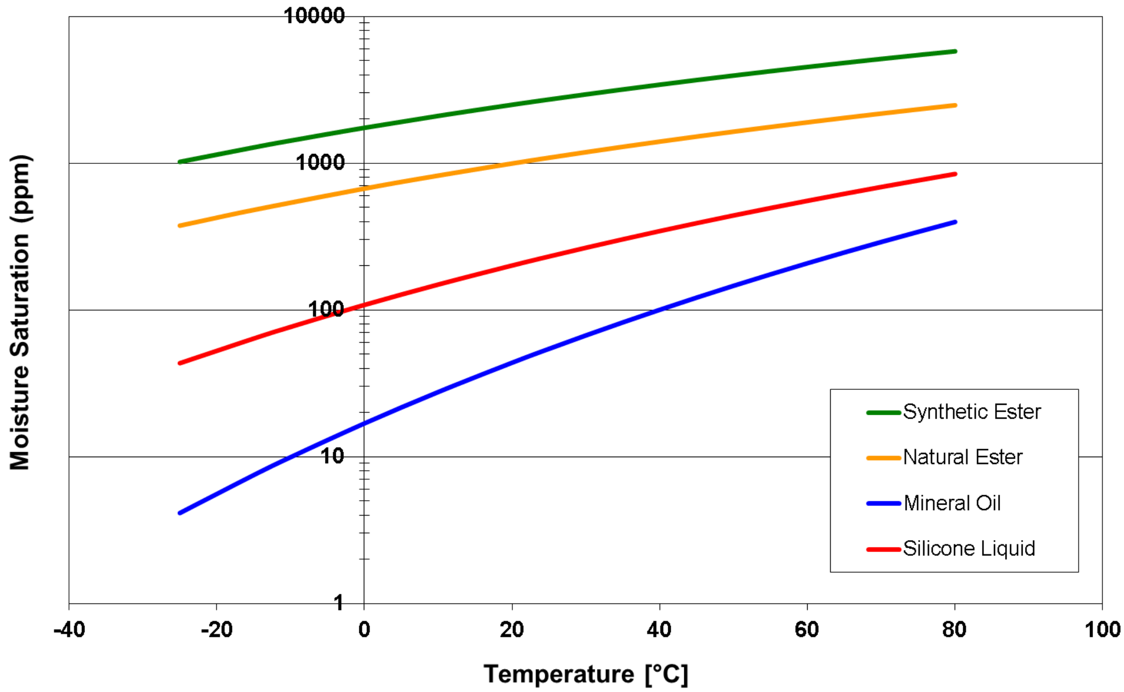

Figure 4
Moisture saturation limit vs. temperature

A higher moisture saturation limit leads to more tolerance to water. This in turn means that the breakdown voltage of synthetic and natural ester will be maintained with much higher water content than mineral oil, as can be seen in Fig. 5.

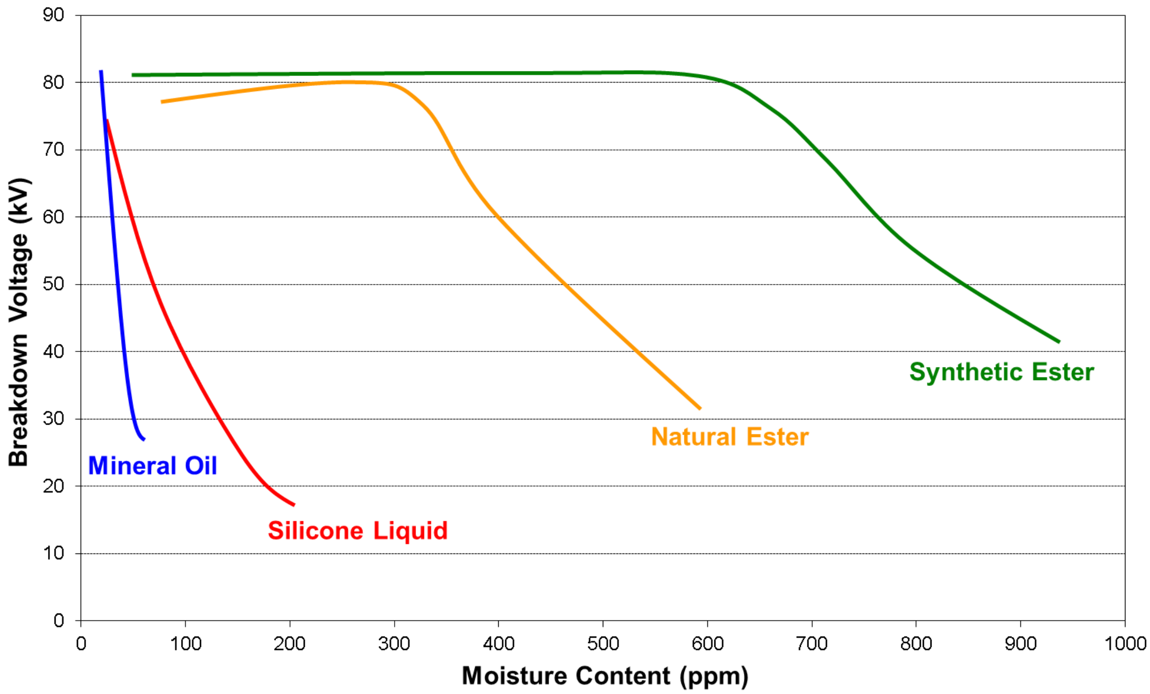

Figure 5
Breakdown Voltage vs. Water Content at 20°C

Another advantage of the ester interaction with water is enhanced paper lifetime. Laboratory studies have shown that ester-based liquids have the potential to provide a much longer life to cellulose, by absorbing and consuming water. This in turn keeps the paper drier and slows the breakdown of the molecular structure. Standards such as IEC 60076-14[5] and IEEE C57.154[6] provide more detail on the advantages to be gained from this increase in life and users have the option to either run assets for longer, or to run at higher temperatures for the same life. This can allow better flexibility for temporary overload, or more compact transformer designs in constrained areas.

OXIDATION STABILITY

There are a range of oxidation stability tests for different dielectric liquids, some of which are designed specifically for a range of liquids. The ASTM D2112[7] test is quick and straightforward method for assessing the relative oxidation stability of different liquids, although it does not necessarily reflect the performance in a transformer system. In this test the fluid is placed in a sealed vessel, pressurized with oxygen and the vessel is then heated to 120°C. The time taken for the oxygen pressure to reduce is recorded and it is this induction time that gives an indication of the relative oxidation stability of different liquids. A comparison of typical results for various types of liquids is shown in Fig. 6. It can be seen from this that silicone and synthetic ester have a high level of oxidation stability, while natural esters exhibit less resistance.

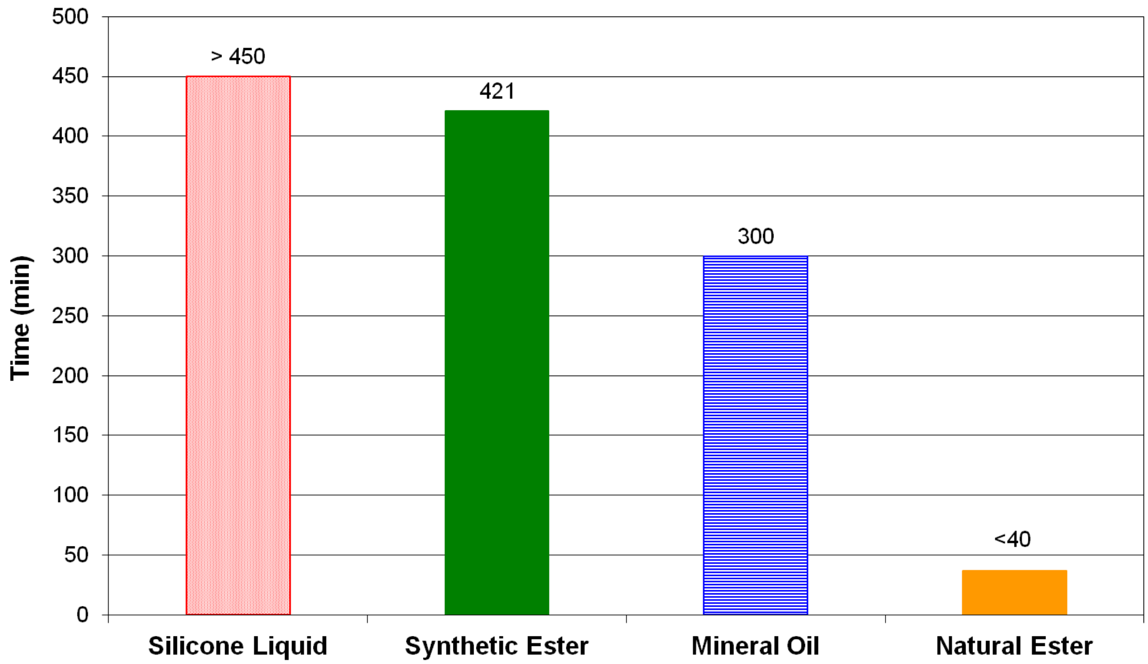

Figure 6
Comparison of oxidation stability results to ASTM D2112 [8]

Due to the lower oxidation resistance of natural esters these liquids are recommended only for sealed systems, where the ingress of oxygen is prevented in some way. This can include the use of a bladder in the conservator of power transformers. Unlike other liquids oxidation in natural esters is characterised by an increase in viscosity, due to polymerisation of the ester molecules. In a transformer system experience has shown that it will take many years for this process to occur, even in the case where the seal is compromised. However more care should be taken with thin films of natural esters as the very large surface area to volume ratio means that oxidation is particularly rapid. This means that practices such as hot air drying of coils impregnated with natural ester are not recommended and time limits should be placed on maintenance activities that expose active parts coated in natural ester to the air.

DIELECTRIC BEHAVIOUR AND TESTING

The electrical behaviour of mineral oil is reasonably well understood, after decades of research and experience in building transformers. In addition modern computer-based design tools allow manufacturers to tighten margins in the pursuit of more compact transformers, which in turn use less raw materials. The behaviour of alternative liquids is less well known and experience has shown that some design adjustments may be necessary for fluids such as esters to be applied to the higher voltage levels used in transmission. In particular researchers have discovered that under impulse conditions ester liquids may offer a lower level of dielectric strength and this has to be accounted for.

Such is the demand for ester transformers at higher voltages that university research into alternative fluids has been conducted in many different research centres around the world. One example of a large scale collaborative project was the 8 year joint research project between National Grid, Alstom Grid, M&I Materials and a number of UK utilities which studied the fundamental behaviour of ester fluids in comparison to mineral oil. The aim of this project was to define what was necessary to use esters at 400kV. This research project incorporated five PhD theses on the subject of ester behaviour under electrical conditions and included both synthetic and natural esters. The outcome of this project was a vast amount of information on the electrical, thermal and ageing behaviour of esters.

Various other institutions have published work on ester fluids, in Europe the other notable independent researchers are Stuttgart University and the Schering Institute at Hannover University. Much of their work mirrored that carried out at the University of Manchester and discovered very similar results. Various other large transformer manufacturers have also carried out their own extensive research work into the use of esters, including Siemens and ABB.

In order to effectively use esters in large power transformers designers first needed to understand their fundamental behaviour, in comparison to the better understood characteristics of mineral oil.

The first factor which affects the design of ester transformers is the difference in permittivity between esters and mineral oil. This brings advantages within winding structures as the permittivity of ester is closer to that of paper, giving a more homogeneous electrical field distribution. Stress in the fluid is also lower with esters, for a given structure, with higher stress in the solid insulation. Since the impregnated solid is a stronger dielectric than the fluid alone this is also beneficial. On the other hand the difference in permittivity also means that peak stress in certain structures can be higher with esters, so small adjustments may be needed to reduce this stress to acceptable levels.

In terms of thermal behaviour the higher viscosity of ester fluids mean that cooling channels may need to be widened, in order to maintain the same operating temperature rises. This in turn impacts electrical design to a degree. Although esters will give a higher temperature rise than mineral oil for a particular design a large amount of laboratory work has also shown that insulating paper ages more slowly in esters than it does in mineral oil. Since the lifetime of the insulating paper is often the life limiting factor for a transformer this is critical. In designing transformers well established temperature limits are applied for mineral oil and cellulose combinations. As mentioned previously the evidence published in IEC 60076-14 and IEEE C57.154 over the last two years indicates that higher temperatures can be accepted with esters, without loss of life. This can work to offset the difference and perhaps even allow the design of more compact power transformers if the full benefits of esters indicated in the standards are used.

Impulse Behaviour

One of the key differences coming out the laboratory research is the behaviour of ester fluids under impulse conditions, where a somewhat lower dielectric strength than mineral oil has been observed. An example of this comes from testing carried out by the University of Manchester using the 1-shot per step (IEC method) and 3-shot per step (ASTM method), with the results shown in Fig. 7.

Larger differences have been found in experiments using very divergent fields, with electrode setups such as needle to plane and needle to sphere. These were designed to produce focussed electrical fields, in order to exaggerate the effects and observe fundamental behaviours. In these experiments ester fluids were shown to have similar discharge inception voltages to mineral oil, meaning insulation structures would be similar, but propagation of streamers appears to happen more readily in esters. For design this indicated that adjustments needed to be made with long oil gaps and divergent fields in esters.

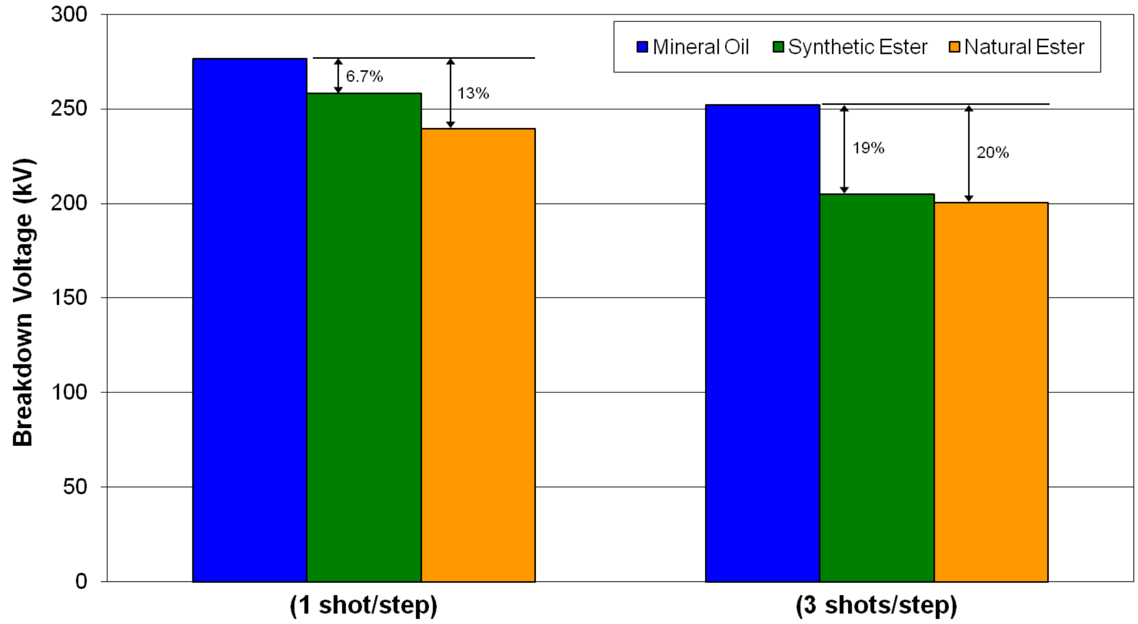

Figure 7
Impulse Breakdown Comparison [9]

Observations such as faster discharge propagation in divergent fields give a clue to how esters will behave in real transformers, but does not give the full picture. In addition to the fundamental research a large amount of testing has been conducted on more realistic insulation structures, to feed into design calculations. This testing and experience gained by transformer OEMs with ester suggest that the differences between mineral oil and ester can be accommodated with some adjustments in design. These changes do add some cost to the transformers, when compared to standard mineral oil units, but this is still far outweighed by the potential cost saving benefits.

Full Scale 400kV Test Rig

As a further development of the university based research National Grid undertook a project in the UK, in collaboration with Alstom UK and M&I Materials Ltd, to test a full scale 400kV coil immersed in synthetic ester. This work was funded by the Network Innovation Allowance (NIA), which provides funding from the UK regulator OFGEM for projects that have the potential to deliver customer benefits. At the point when the project commenced National Grid specifications permitted the use of synthetic esters in transformers at up to 66kV and they had been using the fluid in earthing transformers, to remove the need for fire barriers between the smaller units and the main transformers. The intention of the test project was to prove whether the use of synthetic ester could be extended to higher voltages.

The test rig designed by Alstom consisted of a half stack of a complete centre entry winding of an autotransformer and was designed for 400kV insulation test levels of 630kV AC and 1425 kVp Basic Lightning Impulse (BIL). The winding was of an inter-shielded disc type construction with the top end of the winding designed to withstand application of 132kV system BIL (650kVp) and bottom end designed for application of 400kV system BIL (1425kVp). The design of the winding and a photo of the rig being presented for final test are in Fig. 8.

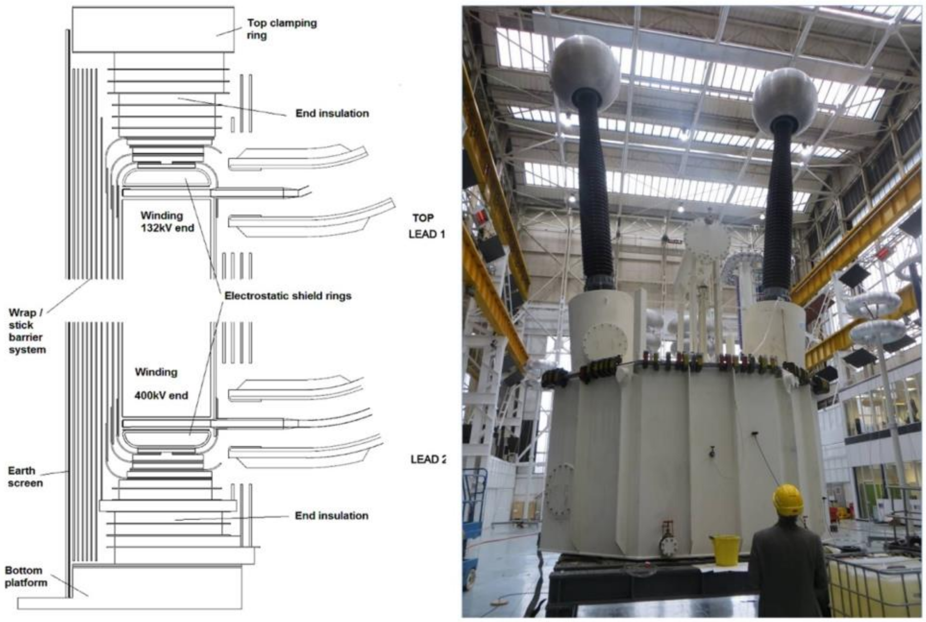

Figure 8
Test Rig Design and Physical Appearance

The outcome from the testing, conducted in the presence of National Grid confirmed the expectations from the university research and Alstom Grid obtained empirical design information, which allows them to adjust their design calculations accordingly.

APPLICATIONS OF ALTERNATIVE LIQUIDS

Since the 1970s the use of alternative liquids has grown substantially, from niche products for special applications to the present time when the mainstream use of ester liquids is now taking hold. Taking the example of synthetic esters it is possible to see how the use of alternatives has grown. The timeline in Fig. 9 shows key project milestones along the path from the early PCB retrofilling days, right up to the present 400kV substation transformer projects.

The environmental benefits of using ester have played a large part in this, with utilities such as Vattenfall Berlin using esters in environmentally sensitive locations. There has also been a large uptake of natural ester-based liquid in the USA, especially in small pole-mounted transformers with the aim of reducing fire risk and the potential impact of a spillage onto soil.

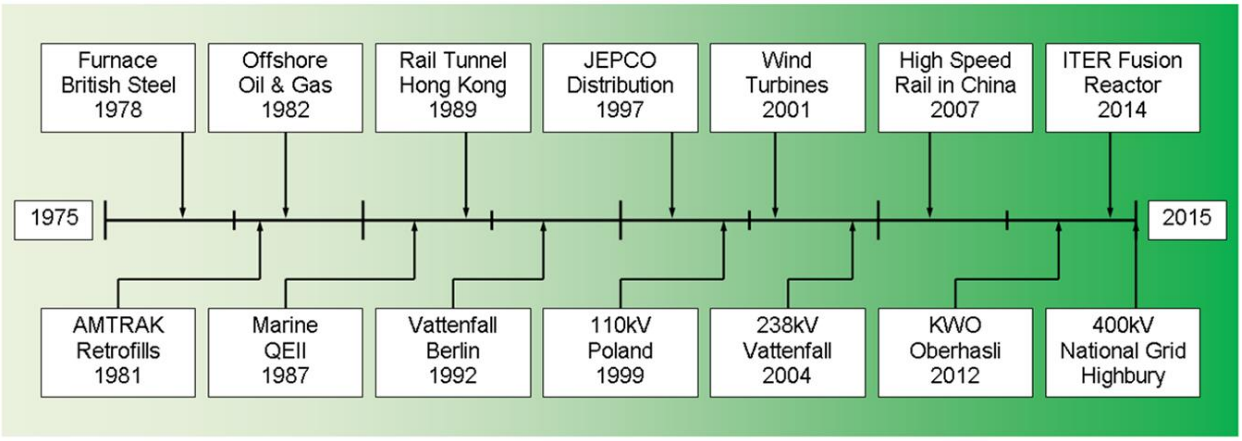

Figure 9
Timeline for synthetic ester liquid

Around the time that synthetic esters were being applied to 110kV power transformers natural esters came onto the market. These fluids had undergone a long development process, to evaluate their performance and this culminated in them being used in both distribution and power transformers. Over the next 15 years an almost parallel path of development in higher voltages for natural and synthetic esters occurred. Table 3 shows a short list of key projects along this development pathway.

Table 3
Power Transformer Projects with Ester-Based Fluids[10]

SYNTHETIC ESTER			NATURAL ESTER		
High Voltage	**Rating**	**Year**	**High Voltage**	**Rating**	**Year**
110kV	25MVA	1999	115kV	15MVA	2004
151kV	110MVA	2002	161kV	200MVA	2004 (retrofill)
238kV	135MVA	2004	230kV	8MVA	2005 (retrofill)
220kV	100MVA	2010	161kV	25MVA	2006
154kV	200MVA	2011	110kV	40MVA	2008
400kV	240MVA	2016	138kV	40MVA	2009
433kV	120MVA	2016	420kV	300MVA	2014

POWER TRANSFORMER CASE STUDIES

Case Study 1: National Grid UK

It is clear from the past history and laboratory work that ester fluids behave in a different way to mineral oil at higher voltage levels; however, the challenges are not insurmountable. The benefits that esters can bring in fire protection and increased transformer life can financially outweigh the extra cost of using an ester.

This is illustrated by the fact that there are a number of large transformer projects under development globally, using both synthetic and natural esters. One key project for synthetic ester which directly followed the NIA funded research is being carried out by National Grid in the UK. Following the many years of research and development, as well as the full scale test rig made by Alstom Grid, the decision was made to install three 400kV synthetic ester transformers in a critical substation located in Highbury, in the centre of London. This substation is part of the London Tunnels project which is aiming to provide long term security of electrical supply to the UK capital.

One of the hurdles to conducting any project on this scale in a dense urban area is obtaining planning consent, which requires many adjustments to the design in order to meet the needs of local residents and the immediate community. The plan for the London site in Fig. 10 shows the main transformer and switchgear building, along with a range of residential buildings surrounding the site. [11]

Figure 10
Plans for National Grid Highbury Development

Case Study 2: Letsi Hydropower Station Sweden

Swedish power company Vattenfall has used synthetic ester power transformers since 2002, when it installed a unit rated at 151kV and 110MVA. Since then the company has steadily increased its fleet of synthetic ester generator units, moving up to 238kV in 2004. Following the positive experience with these transformers, Vattenfall decided to utilize synthetic ester for a major refit project at the Letsi hydro power station. This hydropower plant has been in operation for over 40 years and the underground mineral oil transformers were ready for replacement.

Due to current safety standards it was deemed unacceptable to have new underground mineral oil transformers, specifically for fire safety reasons. After careful consideration the decision was taken to install synthetic ester transformers, in order to significantly increase fire safety. There will be four 433kV 120MVA single phase units installed during 2016 [12]

CONCLUSION

There are a range of alternative dielectric liquids on the market and the list of different fluids is growing all the time. Traditionally these liquids were mainly specified when enhanced fire safety is needed, or a transformer is installed in an environmentally sensitive area, but increasingly users are recognizing the benefits of using alternative liquids for more mainstream projects.

The most commonly use liquids currently on the market are ester-based and these particular products have a suite of advantages including high fire points, ready biodegradability and enhanced moisture tolerance. It has also been found that these fluids can enhanced paper lifetime in laboratory testing, which brings added advantages.

In the future it is likely that alternative liquids will find more uses and the latest installations of 400kV+ ester filled transformers show that the limits once imposed on high fire point limits are being pushed back all the time.

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BIOGRAPHY

Mark Lashbrook received a BEng(Hons) degree in electrical and electronic engineering from Loughborough University in 1995. Following graduation he has worked in a number of engineering roles within the semiconductor, manufacturing and power industries. Mark joined M&I Materials Ltd as a Development Engineer in 2007 and he is currently employed with the company as a Senior Applications Engineer for the MIDEL range of Dielectric Fluids. Mark is a member of the IET.