# The Use of Ester based Transformer Liquids for Reduced Fire Risk and Lower Costs

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Petrochemical, nuclear, mining, utilities and other industrial sites require transformers to deliver power to operate machinery, lighting, equipment, instrumentation and switchgear, or to export generated electricity. Traditionally, mineral oil dielectric liquid has been used because of its electrical and thermal properties; however, it does have some disadvantages.

One key problem with using mineral oil is flammability; typically, transformer mineral oils have a low fire point of around 170°C, which means that the risk of transformer fires is something that cannot be ignored. A variety of events including design defect, voltage surge, natural hazards (e.g. lightning strike), structural damage, in service fault or other deterioration of insulation, sabotage, and maintenance error can lead to transformer fires and explosions. Experience has demonstrated that the consequences are often serious, causing loss of the transformer and potentially adjacent assets, loss of production and, in a worst-case scenario, fatalities.

Not only can a transformer be the cause of a fire event, but also a victim. Transformers can be filled with thousands of litres of liquid, which can significantly add to the already challenging circumstances faced by on site responders or attending fire crew.

To mitigate transformer fire risk, organisations are typically installing fire barriers and suppression equipment, which require significant capital investment and need routine maintenance, therefore adding to asset lifetime costs. As well as the cost, the spacing between transformers, buildings and other equipment needs to be considered because they must be large enough to eliminate the risk of a fire spreading. This can mean longer cable runs and the requirement of larger transformer installation areas.

This presentation gives a comparison of the fire behaviour of mineral oil and ester liquids, through various experiments that have been conducted. Reference is made to how these experiments relate to the application of these liquids in transformers. The recommendations of standards and large insurance companies are discussed, showing that reductions in spacing and fire protection can be gained by specifying a less flammable ester liquid. This has the potential to reduce overall installation costs, despite the ester liquid having a higher cost. In addition, case studies demonstrate how the increased fire safety of ester liquids is being increasingly employed.

Keywords: esters, mineral oil, fire, risk management, transformer, critical infrastructure, reliability, industrial, nuclear

## Introduction

Electrical power is an essential requirement for the operation of any industrial facility. For many decades, transformers have traditionally been filled with mineral oil due to its strong dielectric performance and thermal properties. In industrial settings, transformers are often installed in multiple locations across sites, perhaps close to critical assets, employee occupied locations such as control rooms, environmentally sensitive receptors, or even high-risk locations underground. Worldwide experience has shown that the probability of transformer failures leading to a fire is low. CIGRE 2013 concludes that the probability of a transformer fire is approximately 0.1% per year, however over a 40-year service life the average probability is 4%. Berg, 2015 includes an analysis of data in the OECD FIRE Database showing that of 438 fire events from nuclear power plants, 8% were in oil filled transformers.

With the increasing risk of natural hazard triggered technological ("Natech") accidents as discussed by Krausmann 2016 and Kern 2021, transformers could become the victim of a fire due to being commonly positioned near other assets, at site boundaries and therefore close to adjacent vegetation, or as a result of lightning strikes. As one of the few site assets deliberately connected to the outside world, it is also possible for offsite events to trigger a fault and fire event on site. Of course, onsite events such as that reported in IChemE 1995 may also trigger a transformer fire. Bartley 2003 reports that 3% of the failure insurance claims were due to the transformer being a victim of fire. As transformers typically contain thousands of litres of dielectric liquid, this latent fire load will present an additional challenge for personnel managing any fire event. Transformer fires are sometimes allowed to burn out, and such events are commonly visible offsite, leading to reputational damage. The consequences of these catastrophic failures are not insignificant when potential outcomes include personnel & environmental harm, millions of pounds of damages, extended outage times, logistical challenges of procuring replacements and transporting heavy equipment, and health and safety non-compliance. Therefore, the risk from mineral oil filled transformer fires is far from negligible.

The hierarchy of hazard control is a widely accepted methodology for eliminating or reducing hazards in the workplace. The hierarchy starts with the controls perceived to be most effective and moves down to those considered least effective, as follows:

- Elimination – physically remove the hazard
- Substitution – replace the hazard

- Engineering controls – isolate people from the hazard
- Administrative controls – change the way people work
- Personal protective equipment– protect the worker with PPE

Commonly applied to industrial processes, ancillary equipment such as transformers can be overlooked when applying the hierarchy of control as of themselves, they do not obviously contribute to the bottom line. The inherent risks from mineral oil filled transformers require extensive engineering controls such as fire or blast walls, fire deluge systems, increased separation distances to other assets, and larger bund designs to account for pool fires, influencing the cost of installation projects. In the case of fire deluge systems, these will also require administrative controls including periodic maintenance and testing to ensure that they operate on demand, which further adds to the total cost of ownership.

## Fire Properties and Behaviours

In simple terms, there are two scenarios by which a transformer can become involved in a fire event – as a victim or as the source. When considering a transformer as a victim of a fire event, its contribution to the event will depend on the ignitability of the liquid dielectric. However, if the main tank does not rupture due to being engulfed in flames the likelihood of the liquid becoming involved is reduced. For the development of risk assessments of a transformer as the source of fire due to a fault leading to tank rupture, ignitibility is still important, but the behaviour of the liquid when it is ejected from transformer and away from the ignition source is equally important.

The fire behaviour of a substance is commonly discussed in terms of the flash and fire point. The fire point is defined as the lowest temperature at which vapours of the liquid will ignite and continue to burn, even after the ignition source has been removed. For insulating liquids in transformers, fire properties are classified according to IEC 61039 2008, summarised in Table 1, which describes liquids with a fire point less than or equal to 300°C as O class and those with a fire point greater than 300°C as K class. The liquids are sub-classified according to the low heat value (net calorific value), with a higher number indicating less energy available from combustion to sustain a fire.

**Table 1: Classification of insulating liquids according to IEC 61039**

| Fire Point | | Low Heat Value | |
|---|---|---|---|
| O | ≤300°C | 1 | ≥42MJ/kg |
| K | >300°C | 2 | <42MJ/kg |
| L | No measurable fire point | 3 | <32MJ/kg |

The typical properties and classification of some dielectric liquids are shown in Table 2. Despite the higher fire point of natural esters, this shows the highest fire safety classification (K3) achieved by synthetic esters.

**Table 2: Fire properties and hazard classification of dielectric liquids**

| Dielectric Liquid | Flash Point ISO 2719 | Fire Point ISO 2592 | Low Heat Value | Classification to IEC 61039 |
|---|---|---|---|---|
| Mineral Oil | 150°C | 170°C | 46.0MJ/kg | O1 |
| Natural Ester | 316°C | 360°C | 37.5MJ/kg | K2 |
| Synthetic Ester | 260°C | 316°C | 31.6MJ/kg | K3 |

A typical liquid filled transformer may operate at around 80°C, and so a much greater temperature change is required for K class liquids to reach their fire point. Assuming that there is no heat loss from the transformer, the amount of energy required to raise the liquid temperature to this dangerous state is summarised in Table 3, showing that for the high fire point liquids, the energy input required is about three times higher than that of mineral oil.

**Table 3: Comparison of energy required to reach fire point of dielectric liquids from 80°C**

| Dielectric Liquid | Mass of 1000l | Specific heat capacity | Temperature change | Energy to raise liquid temperature to fire point |
|---|---|---|---|---|
| Mineral Oil | 880kg | 1860J/kg °C | 90°C | 147MJ |
| Natural ester | 920kg | 1848J/kg °C | 280°C | 476MJ |
| Synthetic ester | 970kg | 1880J/kg °C | 236°C | 430MJ |

In the real world the assumption of no heat loss will not hold, so to demonstrate the liquid behaviour in another way, a laboratory experiment was undertaken using an oxy-acetylene torch directed at the surface of a shallow pan of liquid. A thermocouple was used to measure the bulk liquid temperature away from the liquid surface. Figure 1 shows images taken from video footage of the experiment on mineral oil, where it can be seen that after only three minutes the liquid surface has started to flash and after four minutes the oil surface is burning at a bulk liquid temperature below the flash and fire point.

**Figure 1: Images from Mineral Oil Pan Fire Experiment**

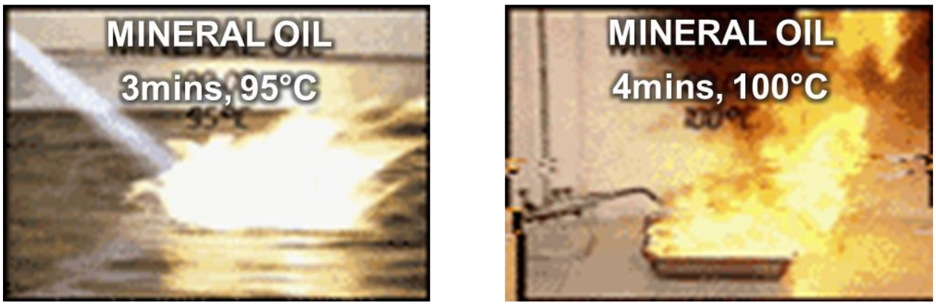
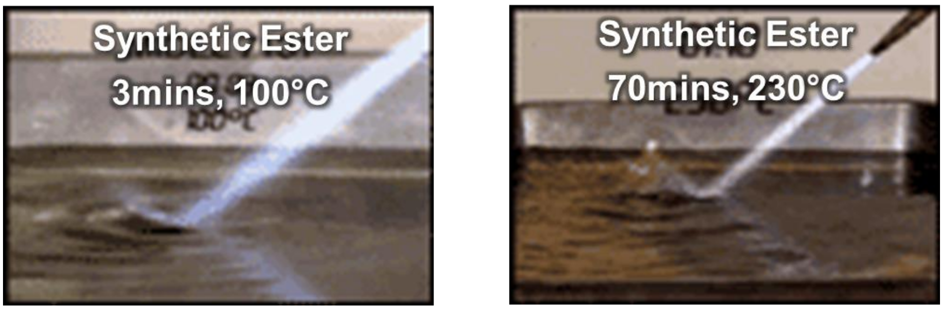


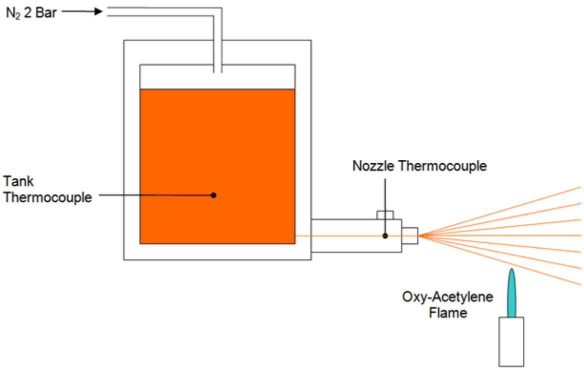

Figure 2 shows the images taken from the synthetic ester experiment, and the contrast is stark in that there is no ignition even after 70 minutes of heat from the torch burning at over 2000°C. This test demonstrates how difficult it is to raise an ester liquid to its fire point.

**Figure 2: Images from Synthetic Ester Pan Fire Experiment**




As with other storage tanks, transformers may develop pin hole leaks at weak points such as welds or flange connections either due to age, exposure to corrosive or abrasive atmospheres, or as the result of an internal fault condition. DIN EN ISO 15029-1 is a standard test conducted on hydraulic liquids to characterise the burning behaviour of a spray under pressure. A version of this experiment was completed using a lower pressure of 2 bar, based on the rupture strength of a typical transformer, to compare the performance of mineral oil against synthetic ester. To replicate an overheating transformer, the liquid was preheated before being placed in the test tank (see Figure 3) and resulted in nozzle temperatures of 112°C for the mineral oil and 120°C for the synthetic ester. Again, an oxy-acetylene flame was used as an ignition source for a fine spray from the nozzle with the time for the spray to self-extinguish recorded.

**Figure 3: Spray Ignition Test Experiment Set Up**



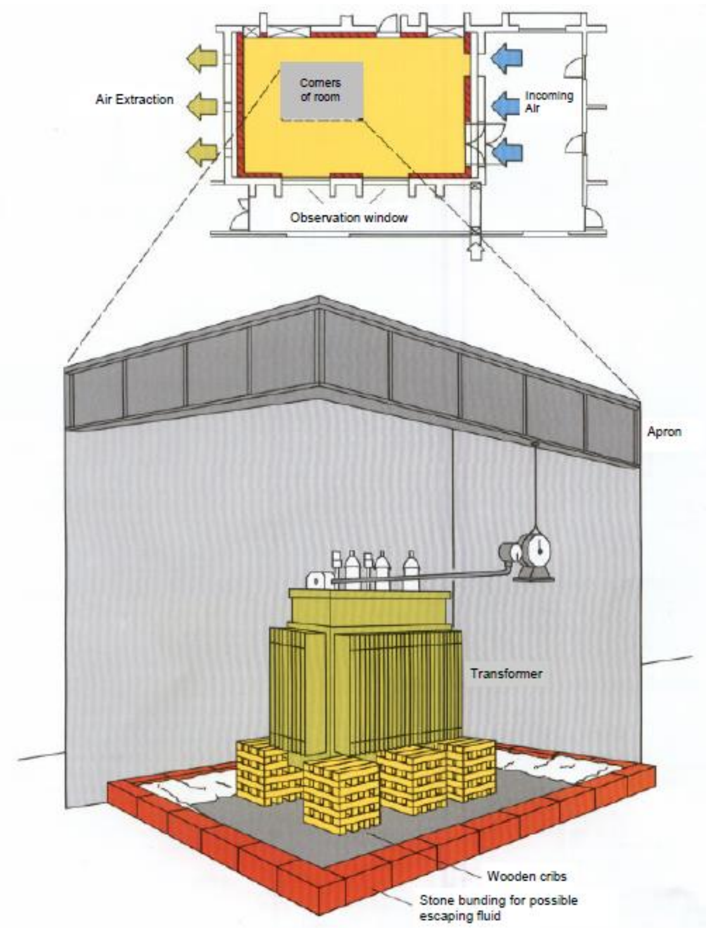

The experiment by Petersmann 2008 was videoed and Figure 4 a & b shows still images from this footage for mineral oil (48 seconds) and synthetic ester (2 seconds) after the torch was removed respectively. In both cases, the mist was ignited by the torch due to the high surface area of the fine droplets allowing rapid heating. However, when the ignition source was removed, the mineral oil continued to burn for up to 49 seconds, which in a practical setting could be sufficient to ignite adjacent materials or an accumulated pool beneath the transformer.

The synthetic ester mist only burned while in contact with the torch (flame temperature >2000°C) and self-extinguished rapidly once the ignition source was removed. The longest burn time recorded was 7 seconds showing that the ester liquid will not burn readily, even as mist, unless a high energy ignition source is present. As transformer protective devices normally act within milliseconds in the event of an electrical fault, thereby removing the ignition source, it is anticipated that an ester will self-extinguish quickly. Even if the internal fault does not trip the transformer operation, it is unlikely that the ester will spread the fire as the liquid cools rapidly when it is not in the flame zone.

**Figure 4: Image from the Spray Ignition Test (a) Mineral Oil & (b) Synthetic Ester**


For technical or economic reasons, transformers are often installed close to the plant for which they provide power. This could be inside or adjacent to a production or storage area, and therefore vulnerable to being engulfed by fire from an onsite event. This often leads to expensive fire walls to isolate the transformer or the dielectric liquid cannot be allowed to escape the transformer for an extended period to accelerate the fire. A sacrificial 630kV transformer containing 365kg of synthetic ester was used by Allianz 1988 to understand how the liquid behaved in such a scenario. To prevent any effects from the flow of supply and discharge air drawn through the test room, and to make both the convective and radiant heat act wholly on the transformer, a "corner" was erected around the transformer (Figure 5), consisting of two walls and a roof with an apron hanging down to approximately 60cm.

**Figure 5: Transformer Victim Experiment Set Up**




The temperatures inside the transformer were measured using 12 thermocouples and the changes recorded automatically. The fire load was provided by 180kg of pre-dried wooden cribs around the transformer tank underneath the radiator fins. Once ignited (Figure 6a) the wood burned for about 70 minutes during which the transformer internal temperatures peaked at 180°C at the bottom and 204°C at the top, well below the ester flash point. Throughout the duration of the fire, the gases escaping from the pressure relieve device couldn't be ignited, nor did the transformer leak at any point. The synthetic ester did not contribute to the fire and no dangerous operating state arose in or on the transformer (Figure 6b). Furthermore, when tested in the transformer manufacturer's factory, it was found that the transformer was still in an electrically working condition.

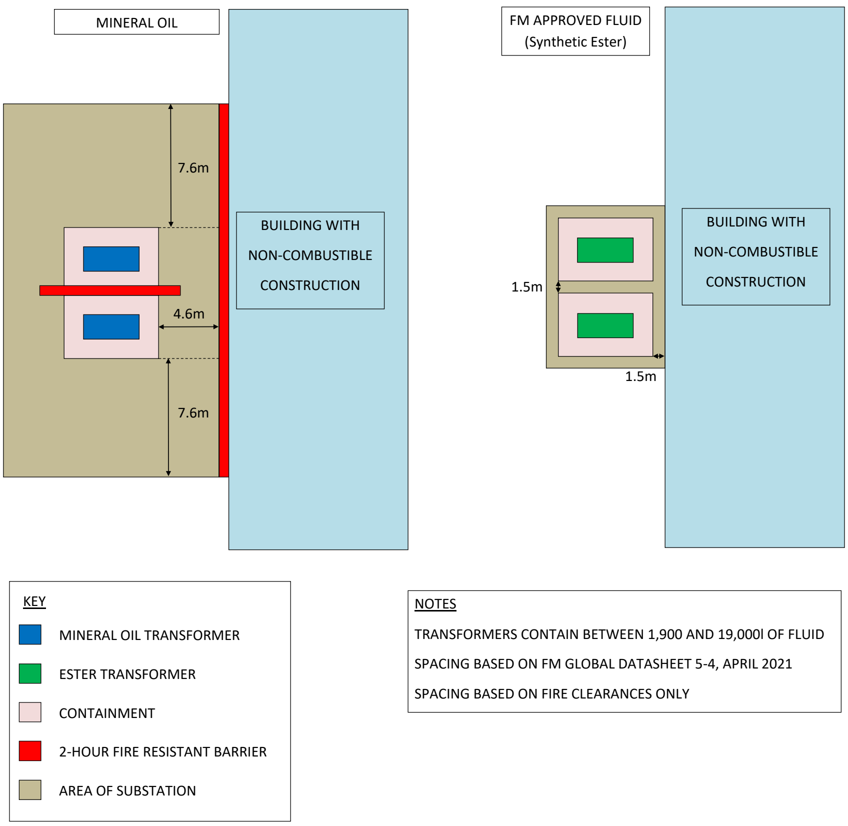
**Figure 6: Transformer Victim Experiment (a) In Progress and (b) After**

## Independent Analysis & Guidance

### Insurance Guidance

Unsurprisingly, insurance companies have taken note of the use of less flammable liquids and the lower risk of using high fire point liquids is reflected in their advice. For example, FM Global's Loss Prevention Datasheet 5-4, 2021 outlines the measures required to ensure that risks are acceptable with different dielectric liquids. This includes a table of clearances between transformers and to adjacent equipment or structures. Using these recommendations Figure 7 provides an example of an installation for transformers containing 2,000 litres of liquid, typical of an industrial application.

**Figure 7: Example Transformer Installation to FM Global Guidelines**




The increased distances around the mineral oil transformers will increase installation costs from fire barriers, fire suppression equipment, and extra cable lengths as well as compromising the placement of any future equipment as part of later site developments. In contrast the use of approved less flammable liquid filled transformers can be placed closer to the building, without the need for fire walls, and if the transformer is also FM approved the clearances for less flammable esters will reduce to 0.9m.

### Installation Standards

The risk reduction from K-class, less flammable liquids is also recognised by many international standards such as IEC 61936-1, NFPA 70 and AS2067. The latter has adopted similar spacing and protection guidance as the FM Global Datasheet, and IEC 61936-1 also allows reduced spacing and protection for both outdoor and indoor transformers when filled with a K-class liquid.

The National Electric Code, NFPA 70, allows similar reductions in spacing and the use indoors of transformers filled with "listed less-flammable liquids" up to 36kV, without the need for expensive transformer vaults. If a mineral oil transformer was specified, then a vault with a three-hour fire rating is mandated.

### SWISSI Risk Assessment

M&I Materials commissioned a study from Swiss Institute for the Promotion of Safety and Security (SWISSI) for a general fire safety case. Buchner 2011 looked at four scenarios for each of four fire safety systems as summarised in Table 4. For each of these combinations, three safety targets were set with regard to operational interruption and the expected damage.

a) the transformer affected is totally destroyed by fire; neighbouring plant sections or transformers should remain thermally intact
b) Fire damage due to an electrical fault of a transformer should be avoided or should be regarded as highly unlikely
c) A fire with a capacity of 10MW in the immediate area should not impair the function of the transformer.

The first two targets consider transformers as the source of a fire, while the third is where the transformer is the victim of a fire. A Buchholz relay protection is a condition of all the safety systems.

**Table 4: SWISSI Equivalence Study Variable Summary**

| | Scenario | Fire Safety System |
|---|---|---|
| 1 | Transformer outdoors with protective screen | Dielectric liquid with Nitrogen extinguishing system |
| 2 | Transformer outdoors without protective screen with little safety clearance | Dielectric liquid with water deluge system |
| 3 | One transformer in a room (fire sector) | Dielectric liquid with spray extinguishing system |
| 4 | Several transformers in a same room (fire sector) | Dielectric liquid without extinguishing system |

Table 5 shows the summary of the findings of the SWISSI report, where the + indicates the safety targets could probably be reached and the – indicates that they probably could not be met. Mineral oil filled transformers fail to meet the safety target in many instances, and even the presence of a fire extinguishing system is insufficient for an oil filled transformer to probably meet the target of fire damage due to an electrical fault being avoided or highly unlikely. The only cases where an ester filled transformer would probably not meet the safety target was for the scenario of a transformer installed outdoors with little safety clearance as a victim of a 10MW fire, which could impair the function of the unit. In such a case, appropriate inherent safety design considerations should be sufficient to ensure that an external fire source in contact with the transformer is not possible.

**Table 5: Summary of SWISSI Findings**

| | No extinguishing system | | | | "Conventional" gas extinguishing systems ($N_2/CO_2$) | | | | "Conventional" water deluge systems | | | | Spray – High-pressure extinguishing system (>75bar) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Scenarios | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| a – Oil | + | - | + | - | + | - | + | - | + | + | + | + | + | + | + | + |
| a – Ester | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| b – Oil | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| b – Ester | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| c – Oil | + | - | + | - | + | - | + | + | + | + | + | + | + | + | + | + |
| c – Ester | + | - | + | + | + | - | + | + | + | + | + | + | + | + | + | + |

The deployment of an inherently safer option in less flammable ester reduces the risk of fire to the point where potentially fallible, add-on engineered safety systems and procedural controls are no longer necessary.

## Case Studies

Synthetic esters were originally developed in the 1970's as a replacement for PCB and an early use was retrofilling an arc furnace transformer. The use of synthetic and natural esters has since been pioneered primarily by grid operators and are now in use up to high voltage transmission ratings, however many industrial companies are profiting from the technical advantages and risk reduction benefits afforded by adopting ester filled transformers.

One case where synthetic ester was chosen with fire safety as a consideration was during the development of a liquified natural gas (LNG) plant in Yamal, northern Russia. More than 20 transformers in various sizes up to 115kV and 125MVA were required to provide power to a remote facility where a fire event could be devastating, an example of which was reported in IChemE, 1995.

Ester filled transformers are known to be more expensive than mineral oil equivalents and this can lead to procurement focussed projects ruling them out, when a more holistic or total cost of ownership model might realise that the increased ester transformer capital is offset through the elimination of fire suppression equipment, reduced civil infrastructure and shortened project timelines as well as lifetime savings, e.g. not needing to maintain fire suppression equipment.

As an example of this holistic thinking, Rio Tinto were constructing a new iron ore mine in Western Australia located approximately 300km inland from the port supplying the project equipment and materials including 39 transformers rated at 33kV. Space on mining sites is often at premium so transformers are often installed adjacent to other assets or buildings, traditionally necessitating expensive fire mitigation equipment and structures. Worley Parsons, the EPC for the project, specified synthetic ester instead of the traditional mineral oil solution, obviating fire walls and simplifying bund design for assets above and below ground. Applying this risk reduction strategy resulted in over AUD3 million savings for the project and is seen as a model for future company developments.

### Retrofilling

It is understood that the risk reduction hierarchy can also be applied to existing assets, and it is possible to retrofill existing mineral oil filled transformers with esters to achieve similar fire safety benefits as for new installations. Indeed, retrofill projects can be driven by insurers concerned about the proximity of mineral oil transformers to critical or vulnerable assets, or by companies seeking to address business continuity challenges, demonstrate social corporate responsibility or manage available capital funds.

In 2017, OQ Chemicals’ Oberhausen plant undertook a review of its internal electrical supply infrastructure including two distribution transformers delivering power to part of the site’s manufacturing operations. As the plant manufactured a range of volatile chemicals, safety was critical, and a fire could be disastrous. The senior leadership team recognised the value of using ester in the transformers and sanctioned their retrofill as a way to protect their employees, the environment and reinforce their business continuity strategy.

For similar reasons, Mangalore Chemicals and Fertilizers Limited (MCFL), part of the Adventz group, was facing a challenge with an ageing 3.3kV, 1.6MVA transformer at its factory located north of Mangalore City. The transformer’s solid insulation was being weakened by the humid climate but could only be taken offline for a limited period to minimise production disruption. Although replacement of the asset was a consideration, MCFL chose to avoid the capital expenditure by retrofilling the transformer with synthetic ester which was completed within 24 hours. After the retrofill, an independent engineering company analysed the new dielectric liquid and confirmed a K class fire point.

More recently, Southern Power Systems was consulted on the condition of a 1500kVA transformer serving a wastewater treatment plant at an ethylene plant in Louisiana. Situated in a remote part of the site adjacent to a wooded area, any mineral oil release from the transformer may have had significant consequences. Three options were considered: capital replacement, re-processing the existing mineral oil to return it to an operable condition, and retrofilling with a canola-based natural ester. The recommendation was the ester retrofill that met the customer mandated risk reduction requirements but achieved a 50% saving over the alternative strategies and with significantly less downtime.

## Conclusions

The properties and behaviours of less flammable ester liquids in transformers can enhance fire safety, and their use can clearly address findings from multiple international surveys that mineral oil transformer fires are potentially catastrophic for employees, assets, and business. As both a potential source of a fire event or contributor to one as a victim, it is important for industrial users to adequately consider the hazards posed by transformers and the options available to reduce the severity of the consequences and the likelihood of the hazard occurring in the first place.

Although it is accepted that esters are more expensive than the traditional mineral oil option, adopting esters from initial design can yield significant project cost and total cost of ownership savings. Similarly, retrofilling existing mineral oil filled transformers has been demonstrated to fit well with strategies for companies seeking to address continuity challenges, demonstrate corporate social responsibility or achieve significant risk reduction.

Ester transformer fluids are proven in thousands of high-risk industrial environments where a zero-compromise approach is necessary, such as oil & gas platforms, refineries, factories, sawmills, distilleries, nuclear facilities, and mines. If prevention is better than cure, the further adoption of ester transformer liquids will benefit industrial users.

## References

Allianz Fire Protection Service, 1988, Fire Test on a Transformer filled with MIDEL® 7131

Berg, HP. and Fritze, N., 2015, Reliability and vulnerability of transformers for electricity transmission and distribution, Journal of Polish Safety and Reliability Association Summer Safety and Reliability Seminars, Volume 6, Number 3

Bartley, WH., 2003, Analysis of Transformer Failures, Proceedings 36th Annual Conference of the International Association of Engineering Insurers, Stockholm

Büchner, M., Schefer, A., 2011, Equivalence study for transformer fire protection using “ester-based” insulating liquid, SWISSI

Conseil International des Grands Réseaux Electriques (CIGRE), 2013, Technical Brochure 537, Guide for Transformer Fire Safety Practices

FM Global, July 2021, Loss Prevention Data Sheets 5-4, Transformers

IChemE, December 1995, Explosion of substation due to inadequately tightened pump seal, The Loss Prevention Bulletin 126

International Electrotechnical Commission (IEC), 2008, International Standard 61039, Classification of insulating liquids

Kern, H., 2021, February 2021, Wildfires — An emerging hazard for industrial installations in Europe?, IChemE, The Loss Prevention Bulletin 277, 25-28

Krausmann, E., August 2016, Natural hazard triggered technological (Natech) accidents – an overlooked type of risk?, IChemE, The Loss Prevention Bulletin 250, 11-14

DIN EN ISO 15029-1, 2002 Edition, October 2002 - Petroleum and related products - Determination of spray ignition characteristics of fire-resistant fluids - Part 1: Spray flame persistance; Hollow-cone nozzle method 1999

Petersmann, 2008, Bericht über die brandtechnische Untersuchung einer Isolierflüssigkeit: Bestimmung der Zündeigenschaften von Sprühstrahlen in Anlehnung an DIN EN ISO 15029-1