Unveiling the Science Behind Proactive Mitigation of Bushfire Hazards with Natural Ester Insulating Fluid

As searing hot summers become the norm in many parts of Australia owing to extreme climatic conditions caused by global warming, utility companies and distribution system operators may be bracing themselves for extended periods of high alert over the risk of bushfire outbreaks; and not only is the risk of catastrophic bushfires getting higher but the risk to power grids is also increasing because of the greater stress on these grids coming from rising levels of electricity consumption.

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Despite the emergence of new technologies in cable insulation, line spacing, as well as various types of failure detectors and protection devices for power lines, the use of less flammable insulating fluids continues to be one of the most trusted ways the industry has, of combating the risk of fire from power grids. Originally developed to achieve outstanding fire safety and environmental benefits, natural ester has since become the fastest growing dielectric fluid in the market, and widely deployed to improve the reliability, lifespan and loading capacity of transformers as well.

Based on the critical properties relevant to fire safety, this article explains why the use of natural ester-filled transformers is a holistic solution that goes beyond what a less flammable fluid can offer, and why it provides power grid operators and the wider community of stakeholders with greater peace of mind in mitigating the risk of bushfires.

BUSHFIRES AND THE HAZARDS OF TRANSFORMERS

While it is estimated that only about 1-4% of fires are started by power lines in any given year, a disproportionately high number of major bushfires were found to be caused by power line failures, according to investigations following the major bushfires in Australia (Table 1) [1].

Bushfire	Date	Proportion of major outbreaks caused by power line failures
Western districts and Streatham	12 Feb 1977	9 out of 16
Ash Wednesday	16 Feb 1983	4 out of 8
Black Saturday	7 Feb 2009	5 out of 15

Table 1 *Number of major bushfires caused by power line failures in Victoria*

Electrical transformers are generally very reliable with an overall failure rate of about 0.53% per year. What this means is that one in five transformers would experience a failure during its expected service life of 40 years [2]. With the large number of transformers operating in vast areas prone to bushfires, the risk of a transformer causing a catastrophic bushfire outbreak, by its own failure or by exacerbating a fire started by other sources, is clearly significant and needs to be addressed adequately.

In this context, it is understandable that despite significant technological advancements made in the prevention, detection and mitigation of power grid failure following serious bushfires in recent years, the use of less-flammable dielectric fluids in transformers continues to be one of the most widely deployed options in preventing bushfires. Among the different types of less-flammable fluids, natural ester, in particular, has become the fastest growing in market share due to its outstanding environmental benefits as well as its unique properties in extending the lifespan and thermal class of cellulose paper insulation. As will be discussed later, these properties of natural ester fluid not only help to improve the reliability and resilience of transformers, ultimately they also make it an all-round solution in the proactive mitigation of bushfire risks.

FIRE POINT AND THE MITIGATION OF FIRE RISK

Scientifically, fire is essentially a chemical reaction between a combustible material and oxygen, and in order for this reaction to take place, the combustible material would need to be at its auto ignition point, or alternatively, at its fire point in the presence of a spark or ignition source.

With this simple concept, it is possible to estimate and rank fire risk mitigating properties in terms of the relative combustion threshold of the different types of insulating fluids, based on the 'activation energy' required to bring 5,000 liters of fluid from an average liquid temperature in a transformer (c.a. 90oC) to its fire point (Table 2).

Fluid	Fire point (°C)	Energy needed to bring 5,000l of fluid to fire point from 90°C (MJ)	Combustion threshold index
Mineral oil	160	733	1
Synthetic ester	315	2240	3.1
Natural ester	360	3710	5.1

Table 2 *Fire risk mitigating properties based on the 'activation energy' required to bring the different types of insulating fluids to their fire points*

When looking at the sequence of events taking place during a transformer failure, the much higher fire point (combustion threshold) of natural ester in reducing the risk of transformer fire becomes apparent. As shown in Figure 1, transformer failures typically begin when the insulation, particularly those in a degraded condition, fails to withstand the stress created by natural events such as lightning, switching impulse, overloading, ferro resonance, secondary short circuit and line fault, etc. Even though such failures might generate a breach and arc of very high energy intensity as a result, in most cases only the paper insulation surrounding the arc

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would be destroyed, and a small volume of dielectric fluid broken down and vaporised, generating combustible gases which cause pressure to build up.

If the arc lasts a sustained period of time, the internal pressure will eventually dislodge the bushing or other weak parts of the tank and force volatile gases out through the weakest part of the tank. Following the exposure to air and ignition source, the combustible gases will explode, causing more substantial damage.

It is at this point that the type of insulating fluid would make a difference in the propagation of fire. With a typical mineral oil-based insulating fluid of low fire point, the burning of combustible gases could generate enough heat to ignite the bulk of the fluid in the tank, leading to a self-sustained pool fire. On the other hand, with its extremely high fire point, the combustion threshold of natural ester would be too high to cause an outbreak of pool fire, and any ignition caused by the combustible gases would also be quickly extinguished.

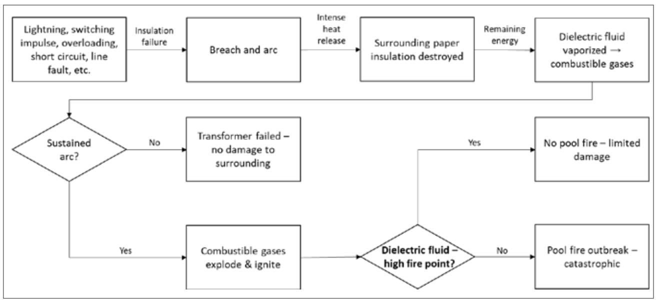

Figure 1 *Sequence of events in transformer failure illustrate the criticality of the dielectric fluid fire point in preventing catastrophic fire breakout*

The criticality of the dielectric fluid fire point in preventing a catastrophic fire outbreak in the event of transformer failure was validated in a series of internal short circuit tests in small transformers conducted by Factory Mutual (FM). During the first test, a typical mineral oil-based insulating fluid was preheated to 128ºC when an internal arc lasting about 8 seconds was generated through a short-circuit fault. The resulting buildup of internal pressure caused the transformer tank's burst disk, which had been calibrated at 20psi, to rupture, and a big pool fire broke out when the spray of vaporised mineral oil from the ruptured disk came into contact with the hot mineral oil in the presence of oxygen in the air, even though there was no external ignition source (Figure 2 top).

When the same test was repeated with a less flammable insulating fluid of over 300°C fire point preheated to 140°C, the increase in internal pressure caused by the sustained arc again ruptured the burst disk. However, when the spray of vaporised fluid from the ruptured valve came into contact with the hot less flammable fluid, it did not cause any pool fire (Figure 2 middle). More significantly, even when an external flame was brought in front of the ruptured disk to ignite the spray of vaporised fluid, the preheated less flammable fluid did not catch fire, and the initial flame was extinguished quickly (Figure 2 bottom).

Based on the above mentioned test and other similar studies, all the relevant industrial standards, including the Factory Mutual Global Property Loss Prevention Datasheet [3] and the UL EOUV and EOVK listings [4], recognise fire point as the most critical property of less flammable insulating fluids in the prevention of pool fires. In 2008, the IEC 61100 standard [5] which classifies less flammable insulating liquids according to fire point and net calorific value was made obsolete. And even though net calorific values are still part of the IEC 61039 [6] classification of insulating fluids, it is no longer relevant to the categorisation of fire prevention properties in the different fire codes and regulations.

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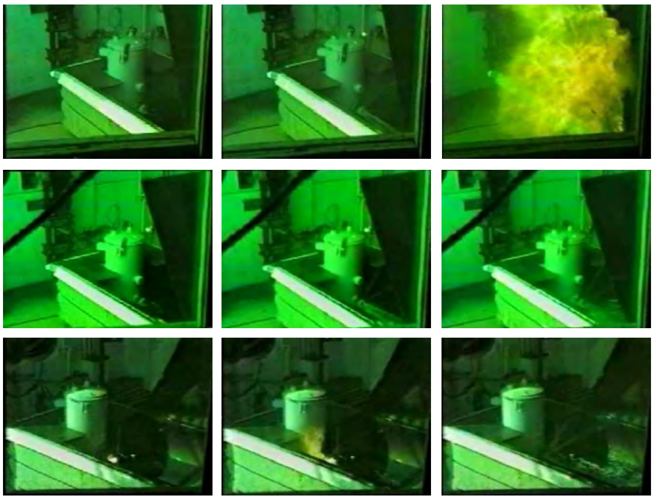

Figure 2 *Factory Mutual internal short circuit tests on mineral oil (top), high fire point less flammable fluid (middle) and high fire point less flammable fluid with external ignition source (bottom)*

COMBATING BUSHFIRES AT ITS ROOT CAUSE - ENHANCING RELIABILITY AND RESILIENCE OF TRANSFORMERS

While the use of less flammable insulating fluids of high fire point is effective in minimising the risk of catastrophic fire outbreaks in the event of transformer failure, the unique properties of natural ester in extending the lifespan and thermal class of cellulose paper insulation enables natural ester to go one step further in mitigating the risk of transformer failure itself.

Unlike mineral oil and other alternative insulating fluids such as silicone oil and synthetic ester, natural ester is capable of absorbing moisture from the cellulose paper insulation and removing it chemically through hydrolysis [7].

This dual drying action, one of the most important properties that makes natural ester the fastest growing insulating fluids in the market, has been validated in a laboratory study where cellulose paper samples previously immersed in mineral oil and then conditioned at saturated humidity were subjected to a further sealed vessel ageing test in mineral oil and natural ester, respectively [7]. During the ageing test, only insulation paper samples in natural ester fluid showed significant reduction in moisture content (Fig. 3). Furthermore, while the moisture content in the natural ester fluid was found to increase initially, it then reduced gradually as the ageing test progressed, reflecting the dual drying actions involving moisture movement from paper to fluid through absorption, followed by moisture removal from the fluid through hydrolysis. The increase in acid number in the natural ester fluid, also shown in Figure 3, provides further proof for the double drying processes, since it reflects the formation of long chain fatty acids as by-products of the hydrolytic reaction of natural ester.

Effective removal of moisture not only prolongs the life expectancy of the cellulose paper insulation by 5-8 times [8-9], it also extends the thermal class of the insulation by 15-20°C as supported by IEC

60076-14 [10], hence enabling the loading capacity of transformers to be increased by some 20-50% [11-13]. Since the ageing of paper insulation, especially those subjected to frequent over-loading, is one of the main causes for transformer failure [2], the use of natural ester insulating fluid clearly provides a proactive way of mitigating the fire risk of power grids at its root cause.

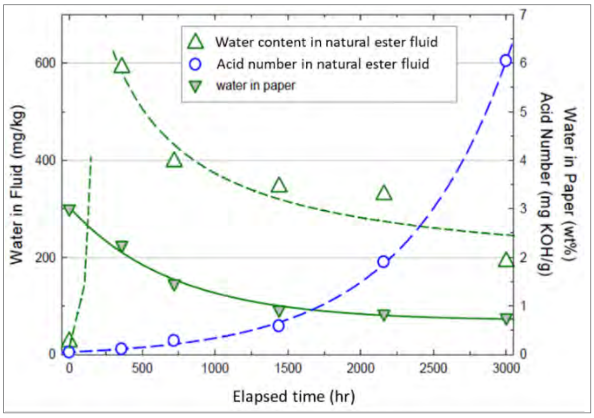

Figure 3 *Results of water content and acid number during the sealed tube ageing test on cellulose paper (pre-aged in mineral oil at 170°C for 400 hours) at 85°C in natural ester*

Even in situations when ageing insulation and overloading might not be of major concern, the use of natural ester could still help in significantly reducing the risk of dielectric breakdown and transformer failure.

While moisture is always seen as the main culprit for the drastic reduction of dielectric capacity in the insulation of transformers in the various factory acceptance tests [14], natural ester is not just capable of drying the cellulose paper as described above, but it is also able to maintain its own dielectric strength much better than mineral oil at a higher moisture content due to its greater affinity with water (Figure 4).

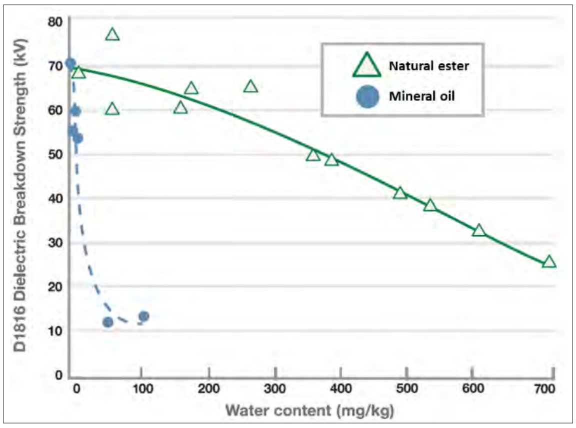

Figure 4 *Dielectric strength of natural ester and mineral oil at different moisture levels*

Besides being better at maintaining the dielectric strength of paper insulation, the dual drying actions of natural ester also help to minimise the likelihood of bubble formation on the paper surface [15], hence further reducing the risk of dielectric breakdown and transformer failure. As illustrated in Figure 5, when the paper insulation is wet with moisture content at around 2.5%, there is a high possibility of bubble formation when the winding temperature reaches 125°C or higher. On the other hand, with dryer paper having a moisture content at around 1%, the tendency for bubble formation remains low as long as the winding temperature is below 170°C.

A HOLISTIC SOLUTION THAT BRING TRUE PEACE OF MIND AGAINST BUSHFIRES

With the highest fire point among the different types of less flammable insulating fluid, natural ester offers the best protection

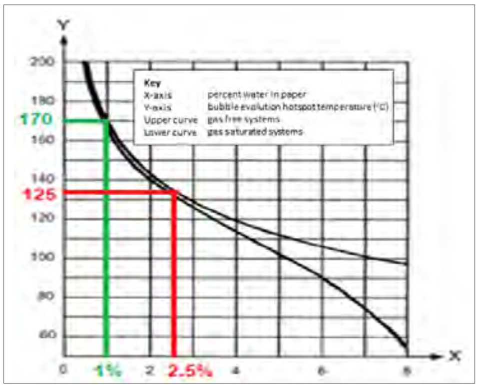

Figure 5 *Temperature threshold for bubble formation on paper insulation surface*

against catastrophic pool fire outbreaks in the event of transformer failure. At the same time, with its unique dual drying properties on cellulose paper, natural ester also allows for proactive prevention of transformer failure by enhancing the reliability and resilience of transformers against the ageing of paper insulation, overloading and dielectric breakdowns due to high moisture levels. As climate changes resulting from global warming continue to raise concerns about the risk of catastrophic bushfires and the overloading of power networks, the use of natural ester-filled transformers is an important consideration for stakeholders looking to a holistic solution that can both combat the consequence and the root cause of bushfires. T&D

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