



**TRANSFORMER  
TECHNOLOGY<sup>MAG</sup>**

# Transformer Oils & Fluids

**Development of Transformer Fluids  
Over the Last Century**

Interview with **Patrick P. Ryan**  
Executive Director at **IEEE PES**

Interview with **Jason Dennison**  
Senior Manager Laboratory and Diagnostic Services at **SDMyers**

**Ergon's Ed Casserly**  
offers insights on  
**Mineral Insulating Liquids**  
In this issue of Transformer Technology

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| Insulating Oils

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Executive Director  
at IEEE PES



## 20 History of Fluids

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Dielectric mineral insulating liquids have changed dramatically over the decades due to advances in refining technologies. How do the refining processes used to manufacture these liquids, and the specifications in the standards, relate to performance? Find out in this article.



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**Univolt™ Transformer Oil****ExxonMobil**

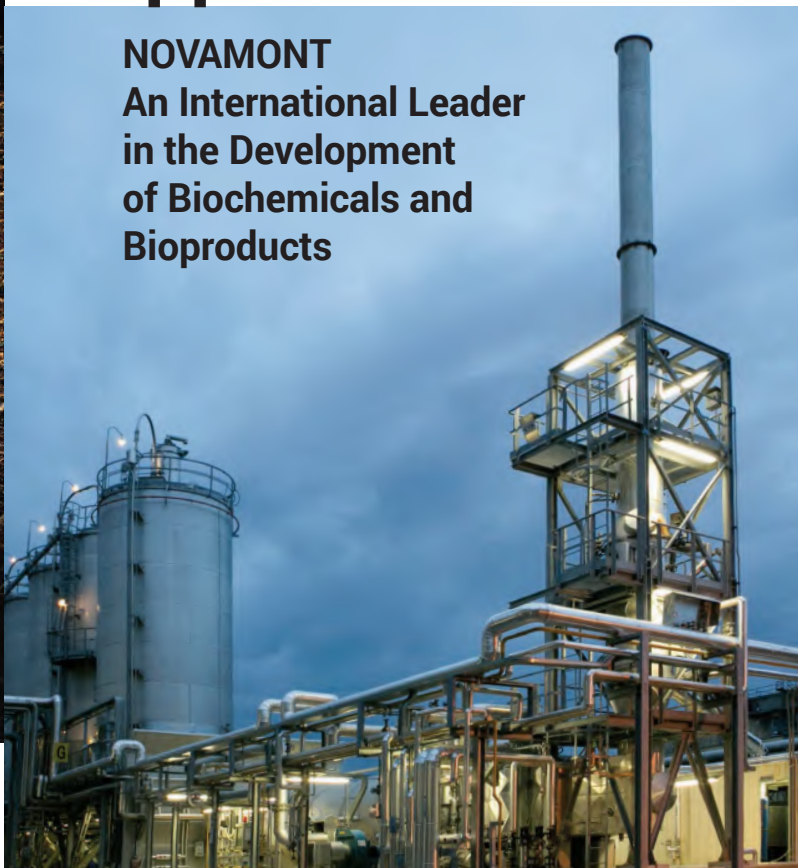
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**NOVAMONT  
An International Leader  
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**Natural Esters**

Either mitigating the fire risk of a pole mounted transformer in a busy downtown area or minimizing the environmental impacts due to an accidental spill in a protected forest area, natural ester immersed transformer reliability has been proven by extensive real-life success cases. How has the evolution of natural esters transformed the industry? Find out in this article by Alan Sbravati and Kevin Rapp.



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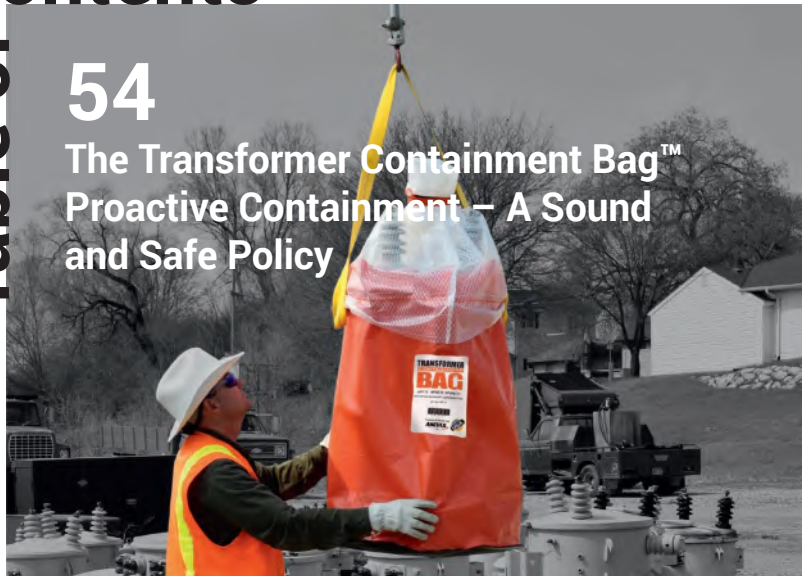
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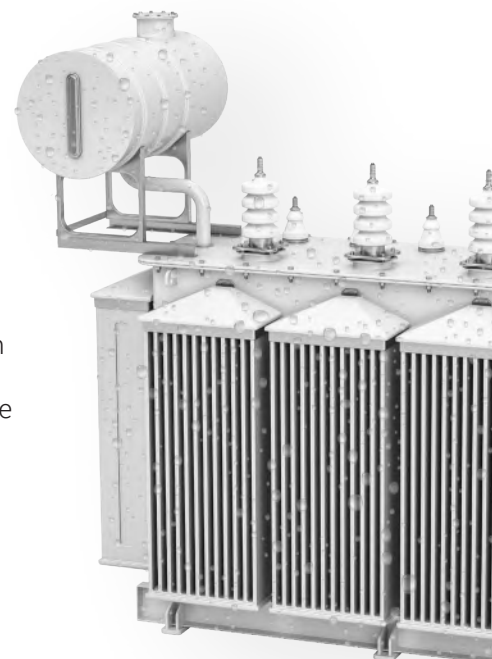
**Corrosive Sulfur**

One of the problems impacting transformer operation is corrosive sulfur and its compounds, which cause premature wear and corrosion and can make the transformer oil unusable. Frank May outlines ways to protect the transformer from corrosion and eliminate the influence of sulfur and its compounds on the transformer.

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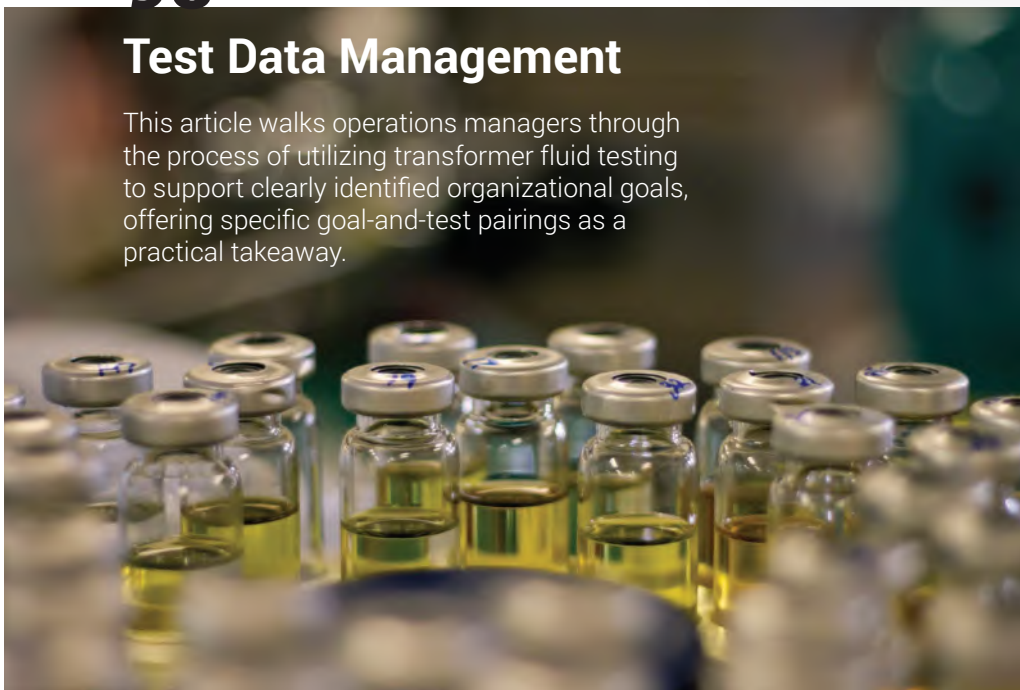
**Best Practices**

Today's energy utility industry is experiencing high pressure to reduce operating and maintenance expenditures. As more limited maintenance strategies are adopted, it is critical to mitigate the risks of unplanned and premature equipment failures. Many utilities achieve this by making capital investments in online condition monitoring equipment and online filtration of insulating oil. This article will focus on continuous online filtration strategies for transformer assets.

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This article walks operations managers through the process of utilizing transformer fluid testing to support clearly identified organizational goals, offering specific goal-and-test pairings as a practical takeaway.



# Impressum

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## Dear Readers and Members of TT Community,

For those of us immersed in transformer technology, this issue will be a keeper, and one you pass around to your colleagues; at least we hope so. This issue speaks for itself. We cover oils, natural esters, synthetic esters, moisture in transformers and how to remediate it, laboratory diagnostics and analysis and even data management and decision making. I greatly appreciate the contributions of our authors and their commitment to creating a knowledge-based, collaborative community.

On a personal note, on January 1, 2020, I added the role of President of the Electric Power Reliability Alliance (EPRA) to my already busy life. Leaving SDMyers is bittersweet in that through my time there, I learned so much and have become friends with some of the industries' finest men and women professionals. SDMyers was founded 55 years ago by Stan Myers and is a faith-based company that follows biblical principles as they attempt to positively impact not only their employees, but their industry and their community. Thank you to everyone at SDMyers who made the last decade of my professional life tremendously fulfilling.

For the future, I urge you to join me at myepra.com and become part of a movement; a movement that will leave a lasting legacy of excellence in industrial and commercial markets. In future issues, I'll share more about that movement, but for now, I want to share something much more important and very personal to me.

In 1986 the group Genesis released a song called "Land of Confusion" and one of the lyrics reads: *"Our generation will put it right; we're not just making promises we know we'll never keep."* But we did - make those promises that we have not kept.

Is my generation, the boomers, leaving things better for the generations to come or did we get so caught up in doing the work and in creating satisfied and secure retirements that we forgot to do what was necessary to leave things better?



I am on a mission. Through this magazine, the Transformer Technology website and through EPRA, I want to rally my generation to share their knowledge and experience with the next generation; to create reliable electric systems, including reliable transformers that industry and society can trust. I want to leave things better than I found them. I believe most of my friends and colleagues will want to join me as well.



We have already begun to move to a more expansive platform, with the launch of the Transformer Technology Community. One of the main new features is the [Body of Knowledge](#), a keyword searchable library of the best information on transformer design, installation, operation, testing, maintenance, monitoring and ultimately life-cycle management. In short, [we want to help the next generation by capturing the legacy knowledge of the current generation.](#)

By bringing technology issues to our members of the community on a more frequent basis, rather than through a quarterly magazine, we will post articles of interest as we receive them and discuss important upcoming events. We had hoped that this issue would also be the preview issue for the IEEE PES T&D Conference and Expo in April in Chicago, but alas, Covid-19 reared its ugly head and for the good of everyone involved, that event has been postponed. And for those of you who appreciate the written word, like me, we will compile a quarterly publication with a mix of articles, interviews and news.

**I challenge our readers to join me in this effort. Write an article, put on a webinar, do an interview or become one of our Technical Advisory Board members.**

There are so many easy ways to make a difference and to pass on your knowledge and experience. Technical knowledge is one important piece, but personal and practical experiences are what the next generation needs to know about. Let us be your voice to the future. Become part of our legacy.

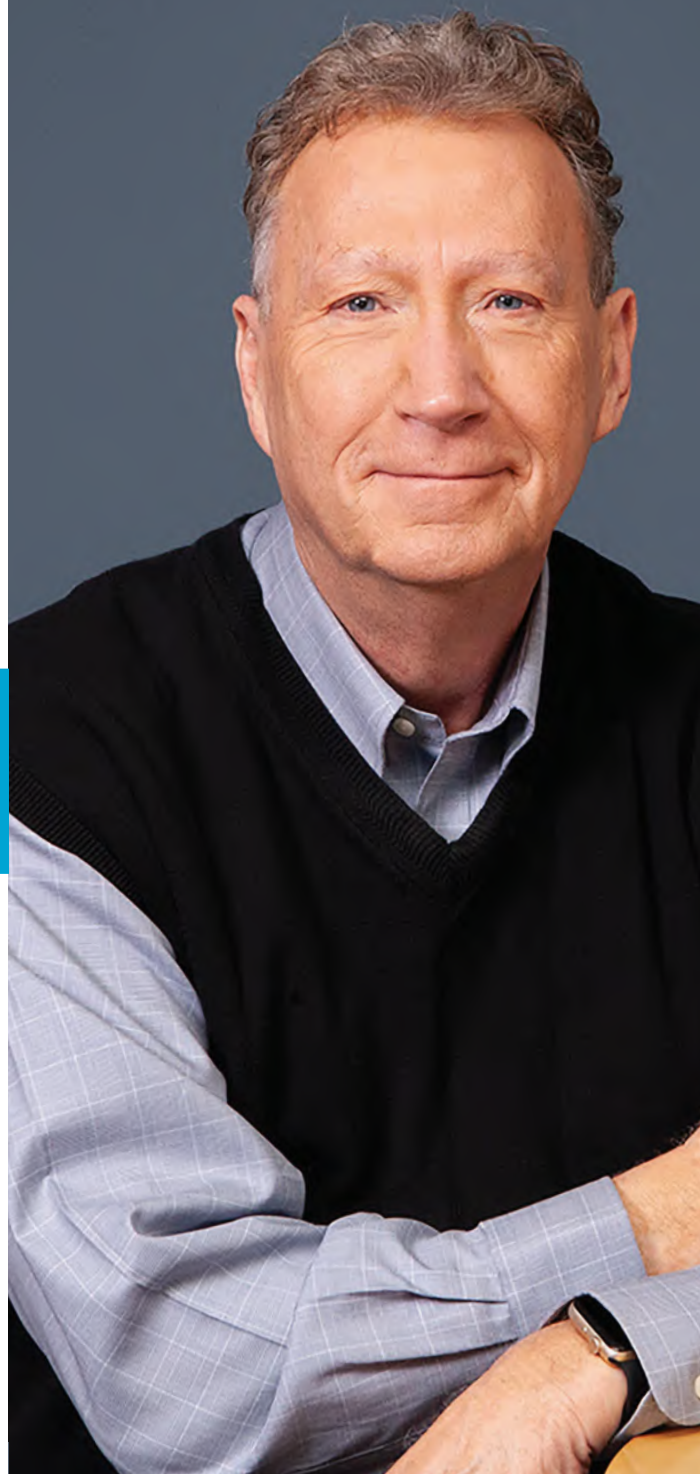
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It is time to lead.  
It is time for a change.



Alan M Ross  
CRL, CMRP  
Editor in Chief  
Transformer Technology

Alan M Ross



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community.

EVENTS  
WATCH



# Events Watch



**CWIEME Berlin**  
**June 30 - July 2, 2020**  
**BERLIN, GERMANY**



**Coiltech**  
**Deutschland 2020**  
**July 8 - 9, 2020**  
**ULM, GERMANY**



**HANNOVER**  
**MESSE 2020**  
**July 13 - 17, 2020**  
**HANNOVER, GERMANY**



**Cigre 2020**  
**Technical Exhibition**  
**August 24 - 28, 2020**  
**PARIS, FRANCE**



**Coiltech 2020**  
**September 23 - 24, 2020**  
**PORDENONE, ITALY**



**CWIEME Americas**  
**September 29 - 30, 2020**  
**CHICAGO, ILLINOIS**



**IEEE PES T&D**  
**Conference and**  
**Exhibition 2020**  
**October 12 - 15, 2020**  
**CHICAGO, ILLINOIS**

# Pat Ryan

**Executive Director**  
at IEEE PES

Interview with **Pat Ryan**



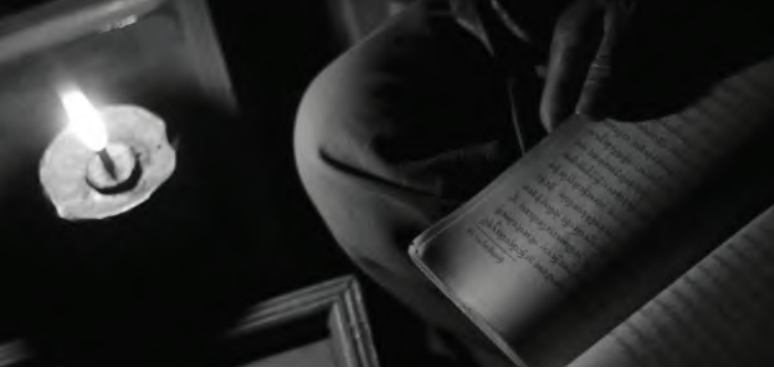


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## Announcing the IEEE Smart Village Initiative

Pat Ryan, Executive Director at IEEE Power Energy Society, is talking about IEEE Smart Village, an initiative with the goal to help bring electricity to all.

**Did you know that 938,400,000 people in the world live in energy deprived environments? Our Editor in Chief Alan Ross met up with Pat Ryan, Executive Director at IEEE PES, to discuss a new initiative within IEEE Power Energy Society that is empowering change – the Smart Village Initiative.**



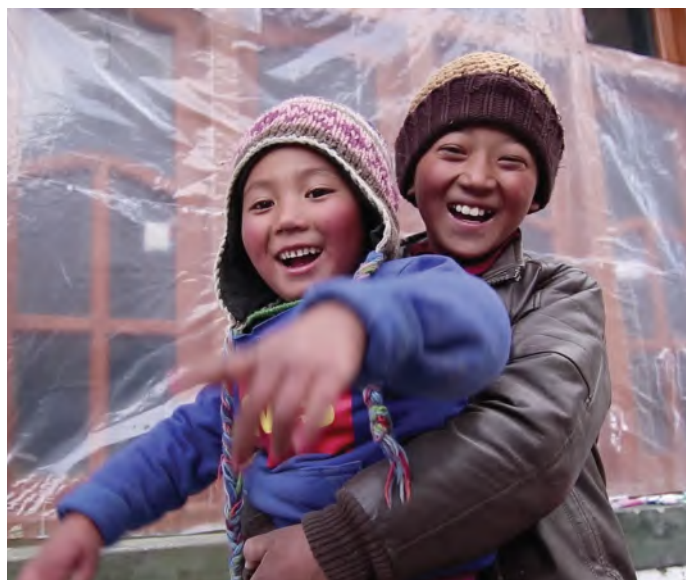
**Alan Ross:** Our very special guest in this edition is Pat Ryan, Executive Director at IEEE Power Energy Society. In this interview, we will talk about a very important thing and something near and dear to Pat's heart, and that is **the Smart Village Initiative within IEEE Power Energy Society.**

Welcome Pat. I know this is an initiative that is near and dear to your heart. Would you tell us a little bit about Smart Village?

**Pat Ryan:** Yes, this is very close to my heart. Smart Village is an IEEE program that is basically humanitarian and has the goal to address three points. The main point is to **bring electricity to those who have none around the world.** And the focus is mostly on off-grid – you could even say way off grid. These sites are not even close to being connected.

If you look at a village in Haiti or Africa or India, these are some of the prime areas that we are working in. We look to bring electricity to them. It is typically a renewable energy, PV – a photo-voltaic solar system that we are bringing there. But there are three important components that go with that. Normally, we test the village, testing its interest in having a mini grid, but also for **sustainability** – will they be able to pay some small amount to keep an entrepreneur going who would establish and maintain this mini grid?





Then, of course, finding an entrepreneur who is interested in having a micro utility is a critical part for sustainability. Without that **business model and an entrepreneur**, you can put in a system that will no longer work in six months unless you bring in expatriates to maintain it. So, sustainability is critical.

And the third part of that, as we bring the electrification and the entrepreneur mode, is to **empower and provide education**. As part of the micro utility system, we may help with the education in the community - by powering up a school for example, and helping bring in computers and internet and curriculum; whatever the need might be to help, we support that village, again, from a sustainability standpoint.





It's a very cool program. National Geographic highlighted one of our programs in the Himalayas for a monastery.

If you look up their archives, you can see a video of a project where they are carrying things in by donkeys through the passes; young monks with TV panels on their backs, carrying them into position and wiring up, and the amazing celebration of that village to have that resource when it was all done. This included an education system with standalone hard drives, with massive amounts of education material on them for the local school there. Because it is so incredibly remote, these resources were extremely valuable to them.

**Smart Village is an IEEE-wide program.** We partnered and are partnering with people around the world to make this happen. It is a huge volunteer effort where volunteers run it all - from every aspect of technical support to program or entrepreneur support, to education support. So, **if you are interested in supporting an awesome humanitarian program, there is a spot available no matter what you're interested in.**





**PR** Yes, I think they are both the same thing. We are working with the World Bank right now to implement some education programs. We are in discussions, but we are not locked in yet. The part we are focused on is to have an extension there - educating people on how to operate, how to design. Using that same experience from the Smart Village Program and scaling that educationally for about 2,200 projects that they are proposing around the world for these off-grid situations. If you just look up [IEEE Smart Village](#), it will pop up immediately. This is a great opportunity for people to really make an impact. And very quickly it will touch your heart, because this is very empowering for those villages.

**AR** Pat, people will find this initiative because I think you have hit a nerve. I mentioned it to a number of people in my circle of influence and they were all excited about it. This idea is life changing. In my own volunteer world, we drill wells in places where water is life, and making it sustainable is also an issue we deal with. There needs to be somebody on the ground making sure that access to this fresh water does not become a political or stumbling block.

**AR** So, to all of my brothers and sisters within IEEE Power Energy Society, and to all of them in the Reliability Society, let's get behind this one. I think this will be a defining program for IEEE, so that we take the best of what we have, the technology that we have, and we collaborate.

Thank you for leading this effort Pat. I knew it was a passion of yours.

The idea that the first world and the developing world can have an impact on a Smart Village is incredible. You called it a mini-grid - meaning it is for a location versus a micro-grid, which might be for a city.



# Development of Transformer Fluids Over the Last Century

by **Corné Dames**

+++++

The transformer is the most important part of the power system. Therefore, the insulating fluid is an integral and important part of the whole system as well. Since power equipment cannot operate without energy losses, which lead to rises in temperature, it is essential to dissipate the generated heat. One of the significant purposes of the dielectric fluid is just that – reducing the heat within the transformer. These insulating fluids prevent short circuits, protect the transformer from adverse chemical reactions in the unit, and act as a cooling agent by actively removing heat by means of flow through the unit and the cooling fins. We will look at the development of transformer fluids over the last century and how they evolved to meet the needs of industry more efficiently.

## History of transformer fluids

Mineral oil has been the fluid of choice for power transformers for more than 100 years. The first operational power transformer was built in 1884. In 1890, the first three-phase transformer was built and in the same year the first oil-cooled, oil-insulated transformer was constructed – demonstrating the value of transformer insulating fluids for over a century.

Petroleum based oils have been used as liquid dielectrics since before 1887. These low viscosity **paraffinic petroleum oils** provide superior insulation when impregnated into

paper or other solid dielectrics, and they also provide excellent heat transfer for the removal of heat generated due to electric losses. However, the paraffinic crudes contain large quantities of wax and therefore have a high pour point which renders them unacceptable for use in electrical apparatus exposed to low temperatures. Namely, in sub-zero climates a large amount of insoluble sludge is formed, which reduces the heat transfer capacity due to lower viscosity.

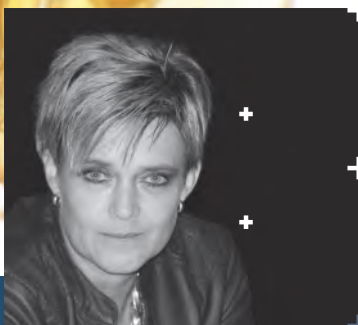
Later the paraffinic variant was replaced with **naphthenic oil**, which remained in liquid form at very low temperatures, but had a higher flammability than the paraffinic oils, posing a new problem. The oxidation products of naphthenic oils are higher in quantity, but these products are soluble in the oil and therefore do not create any adverse problems. The aromatic compounds of naphthenic oils remain in liquid form even up to -40°C.

Modern petroleum refining has changed quite extensively over the last 30 to 40 years. Improved technology, specifically catalytic hydro-processing, has brought many benefits and efficiencies. Refined oils are extremely complex

blends and may consist of more than 3,000 different hydrocarbons, principally paraffinic (40-60%), naphthenic (30-50%), and aromatic (5-20%). Aromatic hydrocarbons come under many different names, e.g. polynuclear aromatics, polycyclic aromatics and polyaromatic hydrocarbons (five to fifty years in the development of insulating liquids). The aromatic content determines the water solubility of different oils. Polyaromatic hydrocarbons may present a health concern, with recent studies suggesting that naphthenic oils with more than 2% polyaromatic hydrocarbon content are potentially carcinogenic.

Naphthenic oils are manufactured by typical solvent refining processes with hydroprocessing or hydrotreating, or mild hydrofinishing. These processes tend to leave residual substances in the oil, including sulfur compounds and aromatic nitrogen. When a process of hydrocracking or hydroisomerization is used during the refining process, almost all contaminants are removed, including sulfur. Sulfur content in oils has degradation consequences in transformers, with high failure probability. The failure due to corrosive sulfur content has been studied, and extensive data mining results have been published in *Engineering Failure Analysis*, Vol. 92.

**Isoparaffinic oils** have better heat transfer capabilities than naphthenic oils. In 1930 Polychlorinated Biphenyls (PCBs) or Askarels were produced to overcome the high flammability problem in naphthenic oils. PCBs had a very low flammability, low acid formation and better oxidation stability than naphthenic oils, making them a perfect solution to the naphthenic oil problem. The PCB oil is a synthetic liquid, a chlorinated aromatic hydrocarbon used in high risk areas where a fire could cause loss of life or extreme disaster. The use of this insulating fluid continued up to the 1970s when it was determined that they were not environmentally acceptable, and they were found to be a carcinogenic substance. The use of PCBs has since been banned due to their effect on the environment and organisms.



Corné Dames is the Managing Director of Independent Transformer Consultants, always striving to keep on top of new developments and research. She has expertise as Laboratory Manager in the analysis of transformer oils and as diagnostician identifying problem areas in transformers, as well as profiling of transformers according to available results thus empowering the customer to take preventative steps in maintenance. Corné has vast practical and theoretical knowledge on reliability maintenance programs. Coming from a strong chemical background she has insight in all the chemical processes that is part of the transformer system coupled with technical insight helps customers optimize their reliability maintenance and electrical asset lifetime.

**Transformer insulating fluids prevent short circuits, protect the unit from adverse chemical reactions, and act as a cooling agent by actively removing heat by means of flow through the unit and the cooling fins.**



### Mineral oil as transformer insulating liquid

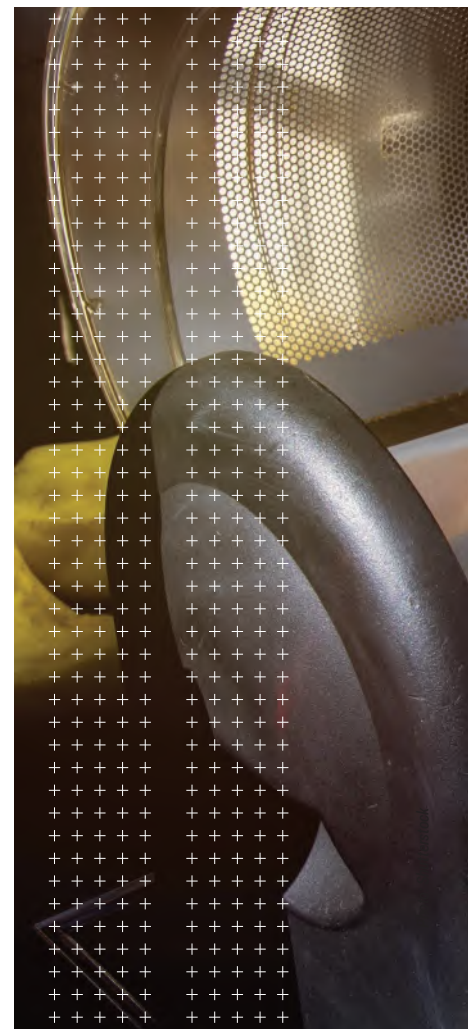
The chemical structure of mineral oils is extremely complex, including both hydrocarbons and non-hydrocarbons. The hydrocarbon chains constitute the main part of mineral oil, containing only carbon and hydrogen in the chain. The aromatic (ring) structure increases stability of the oil, but if too many aromatic rings are present, it will decrease the dielectric property of the oil by increasing its solvency for the solid particles immersed in the oil.

The sulfur compound concentration is dependent on the source of the crude oil. In high concentrations it will cause corrosion of the copper plate and wire that are in direct contact with the oil in the transformer. Similarly, with the presence of nitrogen compounds the stability of the oil will be reduced.

The dielectric fluid should ideally have a high impulse strength, high electric strength, high volume resistivity, high thermal conductivity, high specific heat, high flash point, low viscosity, low volatility, and low dielectric dissipation factor. It must also have a high resistance to chemical deterioration, be non-flammable, inexpensive and easily obtainable.

**The dielectric fluid should ideally have a high impulse strength, high electric strength, high volume resistivity, high thermal conductivity, high specific heat, high flash point, low viscosity, low volatility, and low dielectric dissipation factor. It must also have a high resistance to chemical deterioration, be non-flammable, inexpensive and easily obtainable.**

*The transformer industry had to find alternatives to PCBs thus exploring new fluids that would meet all the required criteria needed to ensure safe and sustainable operation of the transformers.*





### Alternatives to mineral oil: Synthetic and natural ester fluids

Various oils and fluids have been tested to use as an alternative to mineral oil.

Silicone fluids (polydimethylsiloxane or PDMS), for example, have excellent insulating properties, higher fire point than mineral oil, they are less flammable and have excellent anti-oxidative properties and thermal stability due to higher bonding energy (more energy-heat is required to have them bond with other molecules). This oil serves as a replacement for PCBs. Silicone oils are ideally used with Aramid paper, but not Kraft paper [1].

HTH – High temperature hydrocarbons (high molecular weight hydrocarbons) were used as the second alternative to PCB oils.

Several of these fluids were available. Transformers filled with synthetic liquids such as silicone, ester, perchloroethylene, etc. are used for special applications. However, the high cost and availability of these liquids has limited their use [2].

Members of the chlorofluorocarbon family (freons) were used commercially. These fluids are non-flammable, have very good electrical insulation characteristics, but are very expensive. The boiling point is quite low and thus they evaporate at normal transformer operating temperatures. Due to this factor, new electrical equipment has been designed that uses a two-phase cooling system which is very effective in heat removal [3].

### The search for new, biodegradable and environmentally friendly solutions started in the mid-1990s.

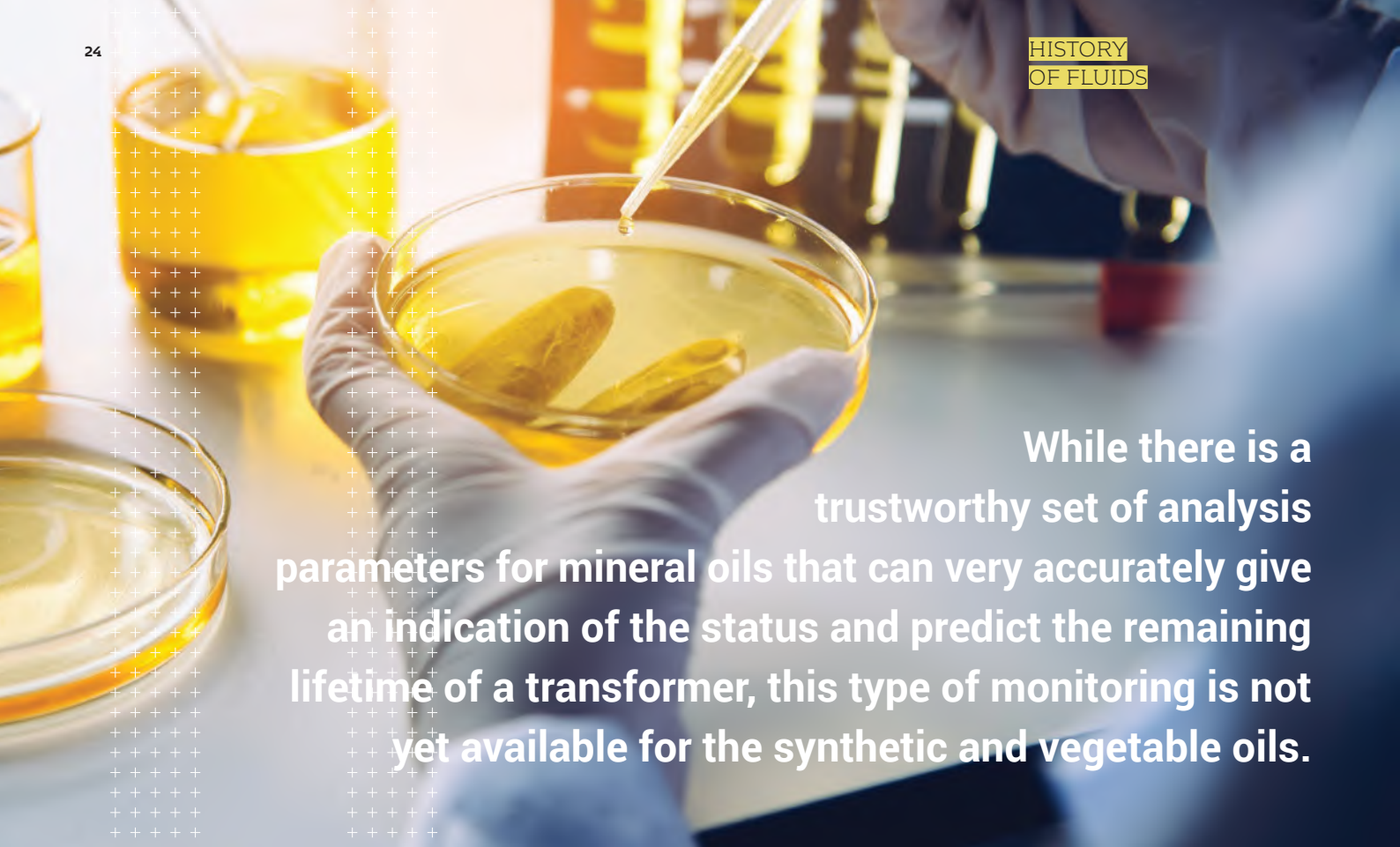


C2C14 – Tetrachloroethylene is a non-flammable fluid that was introduced in 1980 under the tradename “WECOSOL” [4]. Good electrical properties and low viscosity of this fluid provides excellent heat transfer. It can be mixed with mineral oil or used unmixed, which will provide non-flammability and improved lubrication properties at a lower cost.

Isopropyl biphenyl is a hydrocarbon composed of propylated biphenyl isomers used in capacitors as dielectric fluid. It was introduced under the tradename “WEMCOL” as a replacement for PCBs in 1978. It is flammable but has excellent properties for capacitor use.

The crude oil selection is the most important step in the manufacturing of mineral oils. The degree of refining and the kind of processes and treatments may greatly change the characteristics of the final product. The end-product should have a structure with the perfect balance of naphthenes, paraffins and aromatic rings. There is no failsafe way to produce the perfect mineral oil. Regardless of the method the oil should have high electrical performance, gas absorbing properties, chemical stability and oxidation resistance. Aromatic hydrocarbons, sulfur and nitrogen content are extremely important factors when buying mineral oil.

Mineral oil is poorly biodegradable and therefore poses a threat to the environment which forced industry to look at alternatives.



While there is a trustworthy set of analysis parameters for mineral oils that can very accurately give an indication of the status and predict the remaining lifetime of a transformer, this type of monitoring is not yet available for the synthetic and vegetable oils.

In the mid-1990s the industry seriously started considering biodegradable, readily available sources as a successful replacement of mineral oil. Vegetable oil was regarded as the most viable option considering it is readily available, a good insulator and fully biodegradable. However, a major concern with vegetable oils was long term stability, which is vitally important, as vegetable oils contain components that degrade in a relatively short time. The degree of unsaturation is an indication of thermal instability, becoming more unstable as the degree of unsaturation progresses from mono- to tri-unsaturation. These oils have high oxidation instability.

The presence of copper in transformers enhances oxidation. So, powerful oxidation inhibitors are required to ensure stability in the vegetable oil structure. The purity of the oil is also very important as the presence of ionic impurities can act as conductors. The first commercially available vegetable oil was BIOTEMP®, patented by ABB in September 1999. The base fluid consists of high oleic oil sunflower or amended canola oil, with the oleic content over 80%. Another oil was registered in March 2000 by Cooper Industries; it was Envirotemp™ FR3™.

Vegetable oils are hygroscopic, absorbing water in vast quantities at room temperature, up to about 1,200 ppm. The moisture value should be decreased to 100 ppm. Antioxidants are added to stabilize the oil. Commonly used antioxidants are DBPC (2,6-di-tert-butyl-paracresol). A special antioxidant package is used in BIOTEMP® consisting of complex amine and phenols. The FR3 fluid does not pass the ASTM oxidation test because of its lower mono-unsaturated content, which should be over 80% for long term transformer use [5].

Synthetic esters are a broad class of synthesized compounds from organic acids and alcohols. They do not generate dioxins or other toxic products in the presence of fire, and they have good biodegradability. During biodegrading they will only form carbon dioxide and water. These liquids have been developed to resist oxidation and they can absorb considerably more moisture than mineral oils before insulation performance deteriorates. Esters can also be used to retro-fill units previously filled with mineral oil, since up to 3% of mineral concentration in ester fluids does not affect the electrical or dielectric properties of the insulating system. Several types of esters are used in electro-technology, e.g. tetra-esters and phosphoric esters.

### Silicon fluids

These fluids are chemically known as polydimethylsiloxanes or PDMS. They were introduced in the 1970s as substitutes for PCB oils and have proven to be very popular. Their use has been restricted to those units that pose risk to personnel and/or property. They are environmentally friendly, flame retardant, age well, and they strongly resist oxidation and sludge formation. However, their higher viscosity leads to problems with efficient cooling of the units, so their use requires de-rating of up to 10% for safe operation and to avoid overheating. Also, they have very bad biodegradability.

### Vegetable oils

Vegetable oils are readily available natural products, and therefore should be considered as ideal raw material for fully biodegradable insulating liquids. There have been ongoing trials since the 1900s to use these liquids as dielectrics. However, their poor dissipation factor and oxidation stability, higher pour point, relative permittivity and viscosity have been their main disadvantages as dielectric. Since the 1990s they have been in the spotlight again due to environmental concerns about mineral oils,

especially in the coastal regions. The development of chemical additive packages reduces the pour point and enhances oxidation stability, but sometimes these packages also contain an antimicrobial copper deactivator.

### Nano liquids

Liquids that contain added nanosized particles have better thermal and dielectric properties, thus extending transformer lifetime and increasing loading/cooling capacity. The most common nano-additives include metals and metal oxides. Mineral oil infused with TiO<sub>2</sub> particles enhances dielectric properties. It has also been suggested that the addition of magnetic nanoparticles may increase the dielectric strength of transformer oil. However, although the dielectric strength of magnetic nano liquids may be up to 13% higher, their increased loss factor may cause thermal problems under operational conditions. Recently, nano liquids containing a new type of semi-conductive nanoparticle was found to improve insulating and anti-aging properties of mineral oil but have little effect on other electrical parameters e.g. conductivity/resistivity and dissipation factor.

### Cryogenic liquids and liquefied gas

The feasibility of substituting CF<sub>4</sub> gas for SF<sub>6</sub> gas as an insulant for bushings of high-temperature-superconductivity materials was recently explored. Mixtures such as liquid oxygen/nitrogen may exhibit better cooling performance than liquid nitrogen, although highly chemically reactive oxygen may have serious risks associated when used in units with partial discharge or arcing. Superconductors cooled by cryogenic liquid have considerable industrial and research potential because they facilitate high current densities without Joule heating. However, there is still much research needed in this area.

### Performance analysis of different insulating fluids

What follows is an overview of an overall performance analysis of different insulating fluids [6], and while it may seem that the analysis slightly favors vegetable and synthetic ester fluids, it is still a bit risky to throw everything overboard and fill all your transformers with these new fluids. Mineral oil has been with us for a very long period of time and has a proven track record. There are no adverse long-term effects on the transformer

operation and lifetime. We have established a trustworthy set of analysis parameters for mineral oils that can very accurately give an indication of the status and predict the remaining lifetime of

a unit. This type of monitoring is not available for the synthetic and vegetable oils. We still have to monitor units filled with alternative fluids for a very long period of time before we can safely say there would be no negative long-term implications associated with the use of these fluids, as well as to effectively apply predictive

maintenance models to the units filled with these new types of fluids.

### Fire and flashpoint

Research has shown that vegetable oil has better thermal behavior than mineral oil. In the research, palm and coconut oils were used. High temperature or high molecular weight hydrocarbons (HMWH) are alternatives to PCB liquids. They have higher boiling points and higher molecular weight, and they are classified as paraffinic, consisting mainly of saturated compounds of long, straight-chain structures. They also have higher viscosity which reduces their heat transfer capabilities. They are used in collaboration with Aramid paper insulated transformers and especially in conditions with very high operating temperatures.

### Arc quenching property

Vegetable oil has better arc quenching. Less acetylene and hydrogen was formed under arcing conditions in vegetable oil than in mineral oil, and CO and CO<sub>2</sub> production was higher for vegetable oil than mineral oil.

### Dielectric breakdown strength

Vegetable oil came out as the winner in this category. The effect of moisture on the dielectric behavior in ester fluids is smaller, compared to that of mineral oil. Palm and coconut oils were used in the test.

### Oxidation stability

Vegetable oil has superior oxidation stability compared to mineral oil due to the fact that there is little change in breakdown voltage and acid value over time.

### Test of insulating liquid

Insulating liquids are subjected to thermal, electrical and mechanical stresses during the operating cycle of the transformer. There are also chemical reactions that take place between all the phases and materials in the transformer and these reactions are catalyzed by operating temperature: the higher the temperature, the faster these reactions take place.

**We still have to monitor units filled with alternative fluids for a very long period of time before we can safely say there would be no negative long-term implications associated with the use of these fluids.**



### Dissolved Gas Analysis

DGA is used as a specialized diagnostic test to determine the internal condition of the transformer. This method has been used with great success with the analysis of mineral oil in transformers.

However, the various new types of oils coming on the market are complicating the diagnosis, and the DGA methods used in esters, synthetic esters and other insulating liquids are not yet 100% dependable. There are still a lot of uncertainties in the interpretation at this point in time.

Often a customer is not even sure what type of insulating liquid has been used to fill the transformer and the information about specific concentrations of the insulating liquids in the transformer is not available. Great caution should be taken when interpreting DGA diagnosis in both synthetic and natural fluids as this can cause extreme confusion and unnecessary cost to the client. The methods for interpretation of fault diagnosis, abnormal combustible gas formation limits and dissolving of gases in liquids other than mineral oil are very different from those for regular mineral oil and the laboratory teams should familiarize themselves with the new standards and interpretations.

**The search for a reliable, biodegradable, highly effective, and chemically inactive insulating fluid is still ongoing.**

**Mineral oil has a low cost, availability and excellent performance.**

**However, the growing demand for fire safety, material sustainability, environmental friendliness and extended asset lifetimes have driven the identification and development of alternative liquids for insulation purposes.**

### Conclusions and Perspectives

Various additives are available to prolong the life and efficiency of insulating liquids. Each application – transformers, capacitors, bushings or cables – requires an insulating liquid with specific electrical, chemical, and physical characteristics.

Mineral oils have been used in electrical apparatus for over a century, and they have a long and proven track record. The requirements on quality and stability have become more stringent and improvement in refining technology has advanced. Mineral oil has a low cost, availability and excellent performance. However, the growing demand for fire safety, material sustainability, environmental



friendliness and extended asset lifetimes have driven the identification and development of alternative liquids for insulation purposes.

The search for a reliable, biodegradable, highly effective, and chemically inactive insulating fluid is still ongoing.

The inherent properties of mineral oils have ensured their use as electrical insulant over the last century and will probably ensure their use for decades to come. Unfortunately, the growing demand for petroleum products may lead to a shortage in the mid-21<sup>st</sup> century. Also, given the growing environmental concern, fully

biodegradable oils, improved with additives that are sustainable and biodegradable, will become increasingly important.

Natural and synthetic ester fluids are only limited to use in distribution, traction and mobile transformers as the outcomes of using these liquids over a lengthy period of time might have adverse effects on the power units. Collection of data and track records for in-service equipment and continued fundamental investigations will provide a knowledge data base to ensure the engineer is equipped with the information needed to make informed decisions on selecting the best fitted insulating liquid for the application at hand.



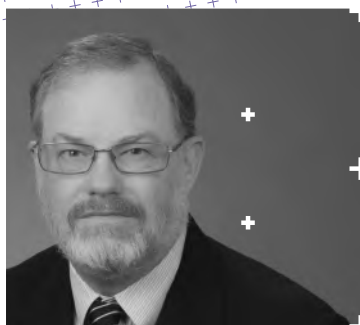
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# Mineral Insulating Liquids – Where They Are From, Where They Are Going

by **Edward Casserly**

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**Ed Casserly** received his B.A. in Chemistry from the University of St. Thomas and his Ph.D. in Organic Chemistry from Rice University, both in Houston, Texas. He began his career as a research chemist with Pennzoil and Penreco, a specialty hydrocarbon producer. Ed has been involved with R&D and technical support for specialty petroleum products for 35 years. He is a co-inventor on seven U.S. patents on synthetic hydrocarbon fluids and has published numerous technical papers. Ed is currently Senior Scientist at Ergon Refining, Inc., in Jackson, Mississippi. He is a member of IEEE, Cigre USNC, IEC TC10/TC14, and ASTM D27 (Vice-Chair).



Dielectric mineral insulating liquids have changed dramatically over the decades due to advances in refining technologies. The original oils were refined at a lower severity compared to today's mineral oils, but they met the basic requirements as understood at the time. Due to higher power requirements, higher loads, and smaller footprints, today's insulating liquids must meet the more stringent requirements in today's standards. The refining processes used to manufacture these liquids, as well as the specifications in the standards and how they relate to performance, will be discussed in this article.

## Introduction

Dielectric mineral insulating liquids have been around since the dawn of transformers. The first U.S. patent which disclosed the use of waxy paraffinic mineral oil, wherein the wax was considered an asset since it absorbed the heat from the core as the wax melted, was granted to Elihu Thomson of the Thomson-Houston Electric Company in 1890 [1]. The first U.S. patent which disclosed the use of naphthenic mineral oil was granted to Harold Maitland of Sun Oil in 1926 [2].

Insulating liquids from paraffinic mineral oils could only be used in tropical climates since the residual wax resulted in high pour points. The isoparaffinic insulation liquids [3] with acceptably low pour points were available after the development of new catalysis technologies which were commercialized in the 1980s and 1990s. More recently, gas-to-liquid (GTL) insulating liquids [4, 5], which are highly isoparaffinic, have been produced from natural gas.

WHILE THERE IS NO MAGIC LIST OF PROPERTIES OR VALUES THAT DEFINE AN INSULATING LIQUID THAT WILL ULTIMATELY PERFORM FOR 30 YEARS OR MORE, MANY DECADES OF EXPERIENCE HAVE SHOWN WHAT HAS WORKED OVER THE YEARS.

Figure 1.  
Timeline of the development of mineral insulating liquids

1890 U.S. patent on  
paraffinic insulating liquid

2004 U.S. patent on  
isoparaffinic insulating liquid

1926 U.S. patent on  
naphthenic mineral liquid

2009 U.S. patent on  
GTL isoparaffinic insulating liquid

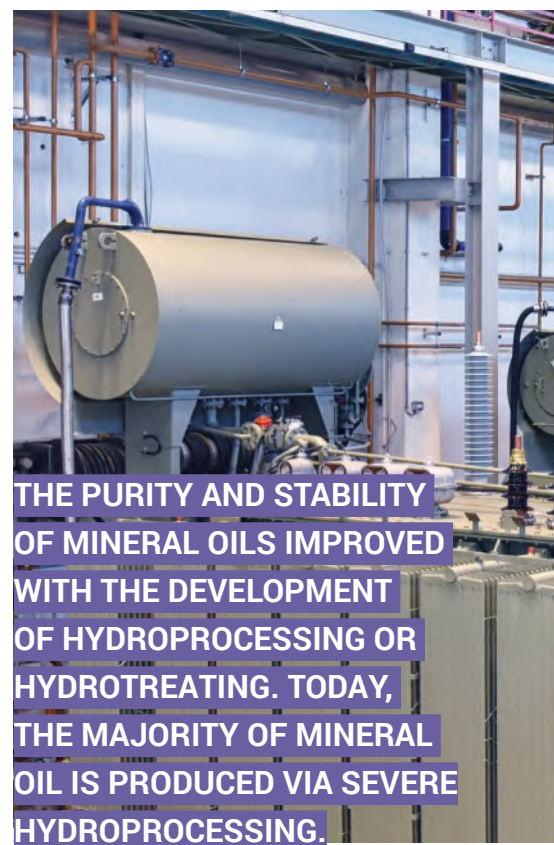
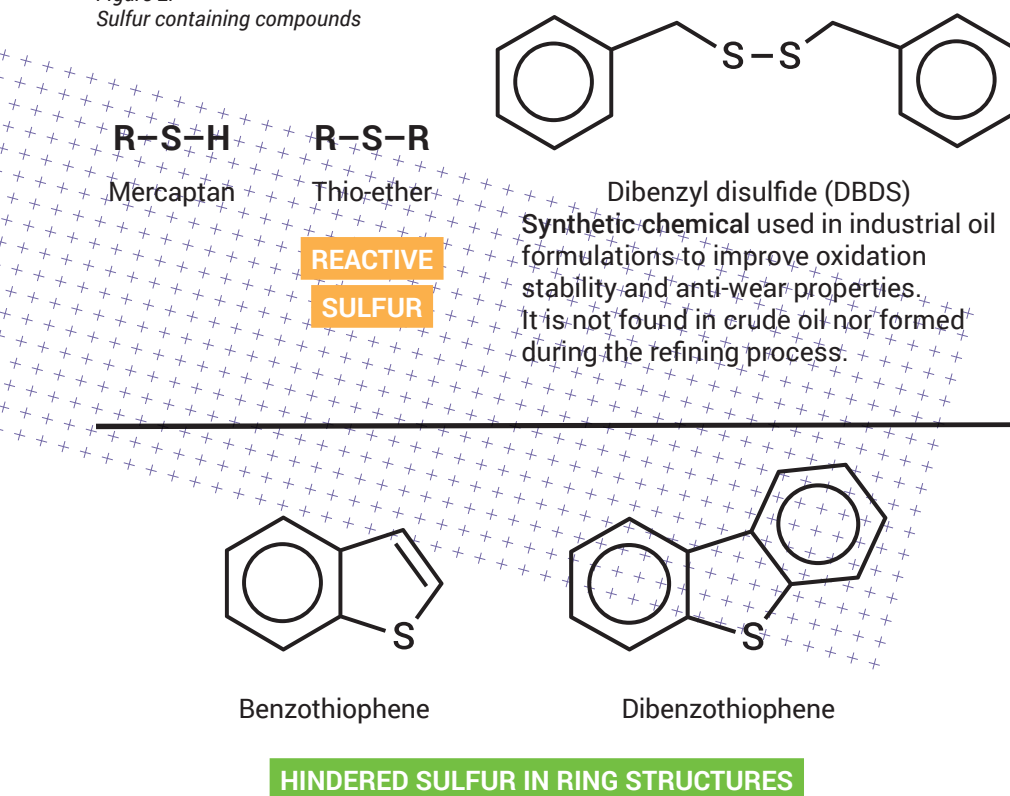


These hydrocarbon liquids have some inherent chemical differences, but all must meet the same international specifications: ASTM D3487 [6] or IEC 60296 [7]. These specifications have been developed and revised over the decades by international committees of chemists and engineers. ASTM D3487 was last revised in 2016, and IEC 60296 is currently under revision with an expected publication date in 2020. The standards list the properties considered relevant to adequately describe the physical, chemical, and electrical properties of the insulating liquid as they relate to the performance in the transformer. While there is no magic list of properties or values that define an insulating liquid that will ultimately perform for 30 years or more, many decades of experience have shown what has worked over the years. The Technical Committee 14 (Power Transformers) of the International Electrotechnical Commission (IEC) has produced a technical report, IEC TR 60076-26 ED1, which describes the requirements of insulating liquids for use in power transformers [8]. This is especially important as new technologies may require the development of new international standards specific to those technologies.

## Refining Technologies

In the early 20<sup>th</sup> century, simple refining techniques such as clay adsorption, acid treatment, and solvent extraction were utilized to remove impurities from the distillates derived from crude oil. These refining techniques physically removed the more polar components and some aromatics to produce mineral oils of adequate purity and stability for that time in history. In addition, solvent dewaxing was utilized to remove the wax in order to lower the pour point. The oxidation stability of these oils was enhanced by the presence of hindered sulfur compounds, which are natural antioxidants. These naturally occurring hindered sulfur compounds remain in the oil after processing and are distinct from the other sulfur compounds which can be corrosive. Corrosive and potentially corrosive sulfur compounds include elemental sulfur, mercaptans (including hydrogen sulfide), sulfides, and disulfides, Figure 2 [9]. Processing had to be balanced to remove the corrosive compounds but leave the non-corrosive sulfur compounds. This facilitated the production of uninhibited transformer oil, i.e., transformer oil without any added synthetic antioxidants.

Figure 2.  
Sulfur containing compounds



The purity and stability of mineral oils improved with the development of hydroprocessing or hydrotreating. In this technology, the oil is treated at elevated temperatures in the presence of high-pressure hydrogen and an active metal catalyst. This effectively removes polar compounds and saturates aromatic compounds to saturated hydrocarbons called naphthenes. This was first used to process fuels to remove the olefins, in order to make the fuel more stable and less likely to form gum. It was applied to mineral oils in the 1960s and 1970s. When this process is taken to the extreme, the end product is 100% saturated hydrocarbons which can be certified for use in food and pharmaceuticals. Since food and pharmaceuticals are low-volume specialty applications, most mineral oils are produced to conform to industrial applications. Today, the majority of mineral oil is produced via severe hydroprocessing. One consequence of hydroprocessing is the removal of all or nearly all the sulfur compounds in the oil, including the hindered sulfur compounds which are natural inhibitors. The removal of most, if not all, the sulfur makes it easier to produce an inhibited oil but more challenging to produce an uninhibited oil.



**THE FUNCTIONAL PROPERTIES OF MINERAL INSULATING LIQUIDS ARE DEFINED BY TWO SIMILAR, BUT NOT EXACTLY THE SAME, INDUSTRY STANDARDS: ASTM D3487 AND IEC 60292. THEREFORE, IT IS IMPORTANT TO SPECIFY WHICH STANDARD IS BEING USED AND WHICH TEST METHODS ARE USED IN THE CHARACTERIZATION.**

Naphthenic mineral oils are produced via the distillation and hydroprocessing of naphthenic crudes which are wax-free, i.e., devoid of normal paraffins and specifically chosen to have inherently low natural pour points. Naphthenic refineries typically do not have refining processes to remove residual wax contamination since they have been selectively chosen.

Isoparaffinic mineral oils are produced from paraffinic crudes via distillation and a series of hydroprocessing techniques called hydrocracking, hydroisomerization, and hydrofinishing. The hydrocracking process opens up aromatic rings so that the sulfur and nitrogen can be effectively removed. Hydroisomerization will isomerize the normal paraffins to isoparaffins, and the hydrofinishing will saturate remaining aromatics and any olefins generated in the other processes. While it sounds complicated, it is highly efficient and has relatively high yields since the aromatics are converted to naphthenes and the normal paraffins are converted to isoparaffins. Earlier refining techniques physically removed the aromatics and normal paraffins; they did not convert them to usable products.

The GTL mineral oils start with methane, i.e., natural gas. Through the Fischer-Tropsch process, methane is converted first to carbon monoxide and hydrogen, which is then converted to normal paraffins or wax. The wax is then converted to isoparaffins via hydrocracking, hydroisomerization, and hydrofinishing. The GTL is different from the other isoparaffinic mineral oils in that it is nearly all isoparaffinic with minimal amounts of cycloparaffins or aromatics.

### **Functional Properties of Dielectric Mineral Insulating Liquids**

The functional properties of mineral insulating liquids are defined by industry standards: ASTM D3487 and IEC 60292. The specifications in the two standards are similar, and the test methods used to characterize the oils are also similar, but they are not exactly the same. Therefore, it is important to specify which standard is being used and which test methods are used in the characterization.

As noted, there are two main types of mineral insulating liquids: naphthenic and isoparaffinic, Figure 3 [10]. While the names imply different chemical compositions, the differences are more of kind rather than type [11].

Naphthenic mineral oils contain cycloparaffins, isoparaffins, and aromatics. Isoparaffinic mineral oils contain the same chemical structures but in different ratios. None of the oils contain straight chain normal paraffins or wax since that leads to high pour points. It is these differences in the chemical composition which determine some of the physical properties. Carbon-type analysis, as defined in ASTM D2140 [12] or Brandes IR [13], can be used to differentiate naphthenic and isoparaffinic mineral oils. Per the ASTM method, the percentage of aromatic carbons ( $\%C_A$ ), the percentage of naphthenic carbons ( $\%C_N$ ), and the percentage of paraffinic carbons ( $\%C_P$ ) are determined from the physical properties of the oil, i.e., the viscosity, density, relative density, and refractive index. In the Brandes IR method, the percentages are determined by the intensities of the infrared absorptions at about  $1,600\text{ cm}^{-1}$  and  $720\text{ cm}^{-1}$ . A naphthenic mineral insulating liquid is generally defined as one where the  $\%C_N$  is greater than 40 and the  $\%C_P$  is less than 50. An isoparaffinic mineral insulating liquid is generally defined as one where the  $\%C_P$  is greater than 50. This further illustrates that the different mineral oils share many of the same chemical structures.

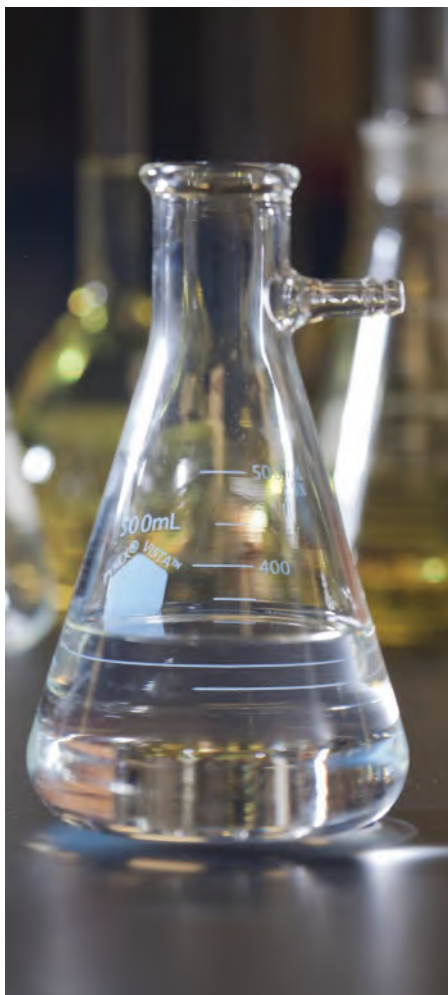
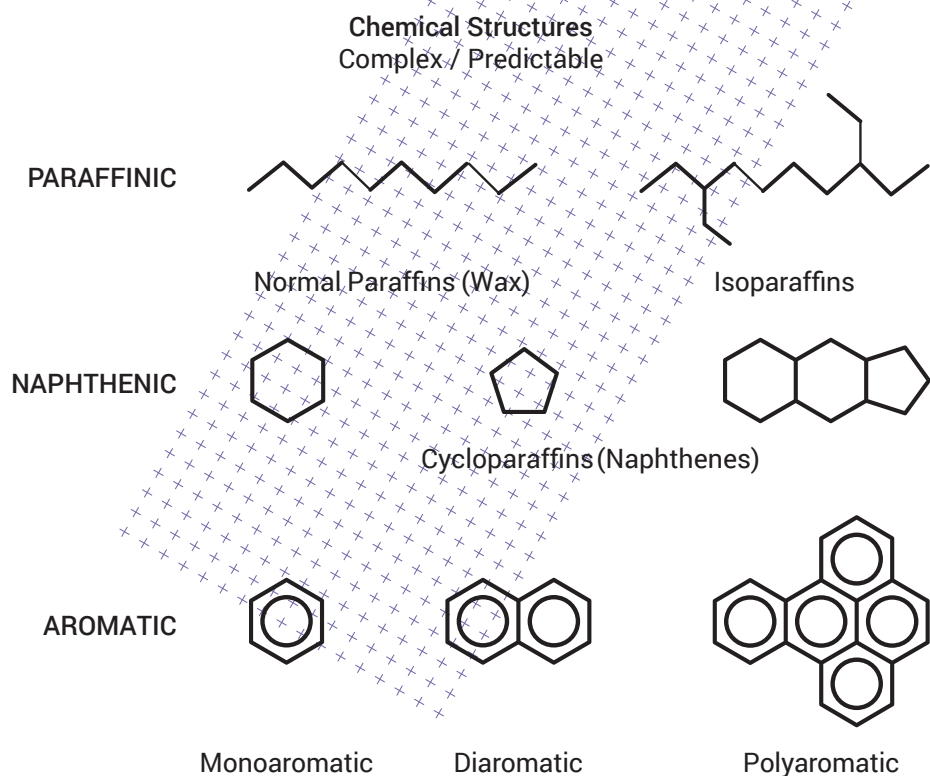


Figure 3.  
Basic chemical structures found  
in mineral insulating liquids



The viscosity of the oil is determined mostly by the distillation range, but the chemical composition has some influence. Isoparaffins have a lower viscosity than the corresponding cycloparaffins of the same distillation range. This is especially evident at very low temperatures. The same is true of density and relative density, where isoparaffins have a lower density than the corresponding cycloparaffins.

The flash point of the oil is determined by the distillation range, specifically the beginning of the distillation range.

The pour point of mineral oils is determined mostly by the ratio of the chemical structures, but the distillation range has some influence. Since the isoparaffins are derived from paraffinic crude, it is imperative that all the normal paraffins be converted to isoparaffins. For this reason, naphthenic mineral insulating liquids generally have lower pour points than isoparaffinic insulating liquids. Even residual amounts of normal paraffins can raise the pour point.

**TWO MAIN TYPES OF MINERAL INSULATING LIQUIDS ARE NAPHTHENIC AND ISOPARAFFINIC, WHICH CONTAIN THE SAME CHEMICAL STRUCTURES BUT IN DIFFERENT RATIOS. IT IS THESE DIFFERENCES IN THE CHEMICAL COMPOSITION THAT DETERMINE SOME OF THE PHYSICAL PROPERTIES.**

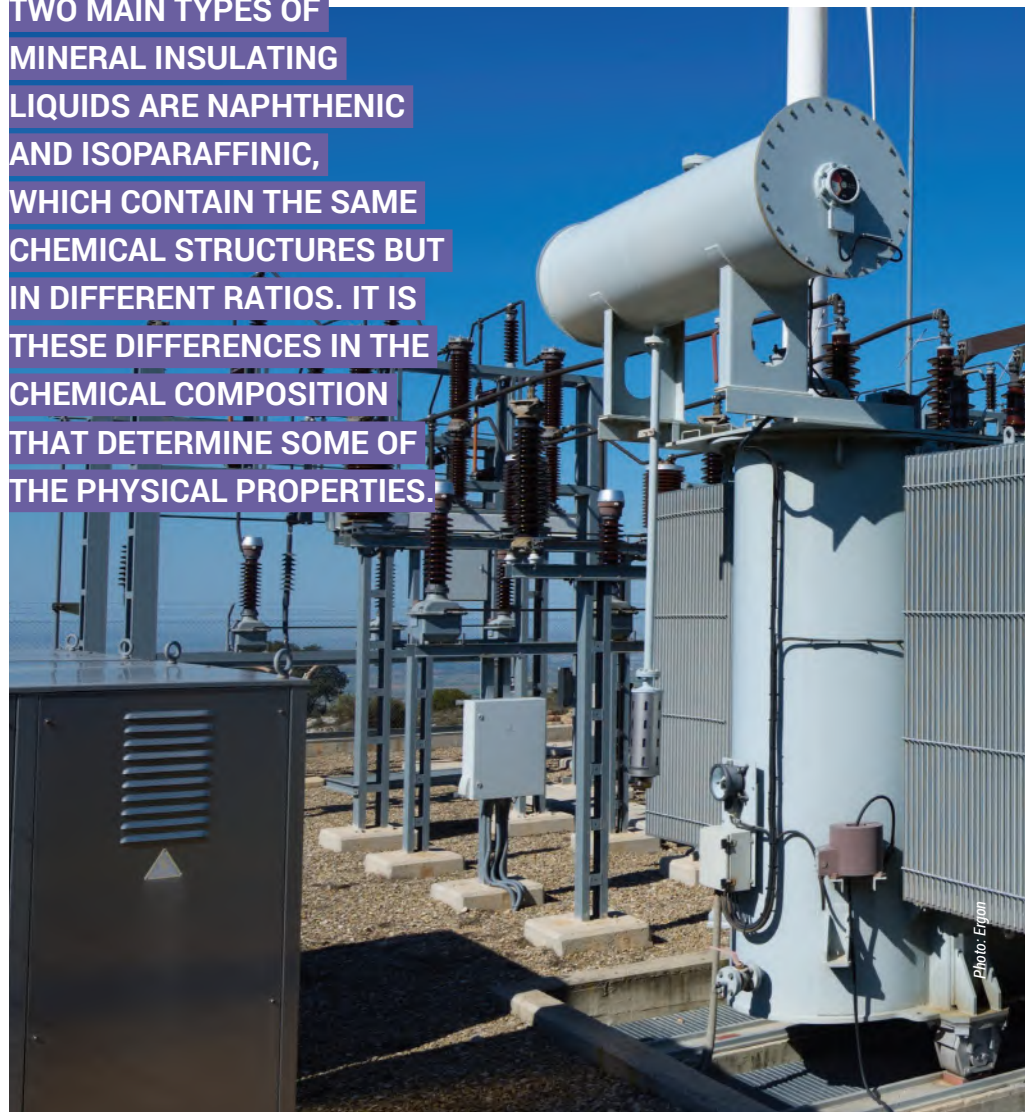
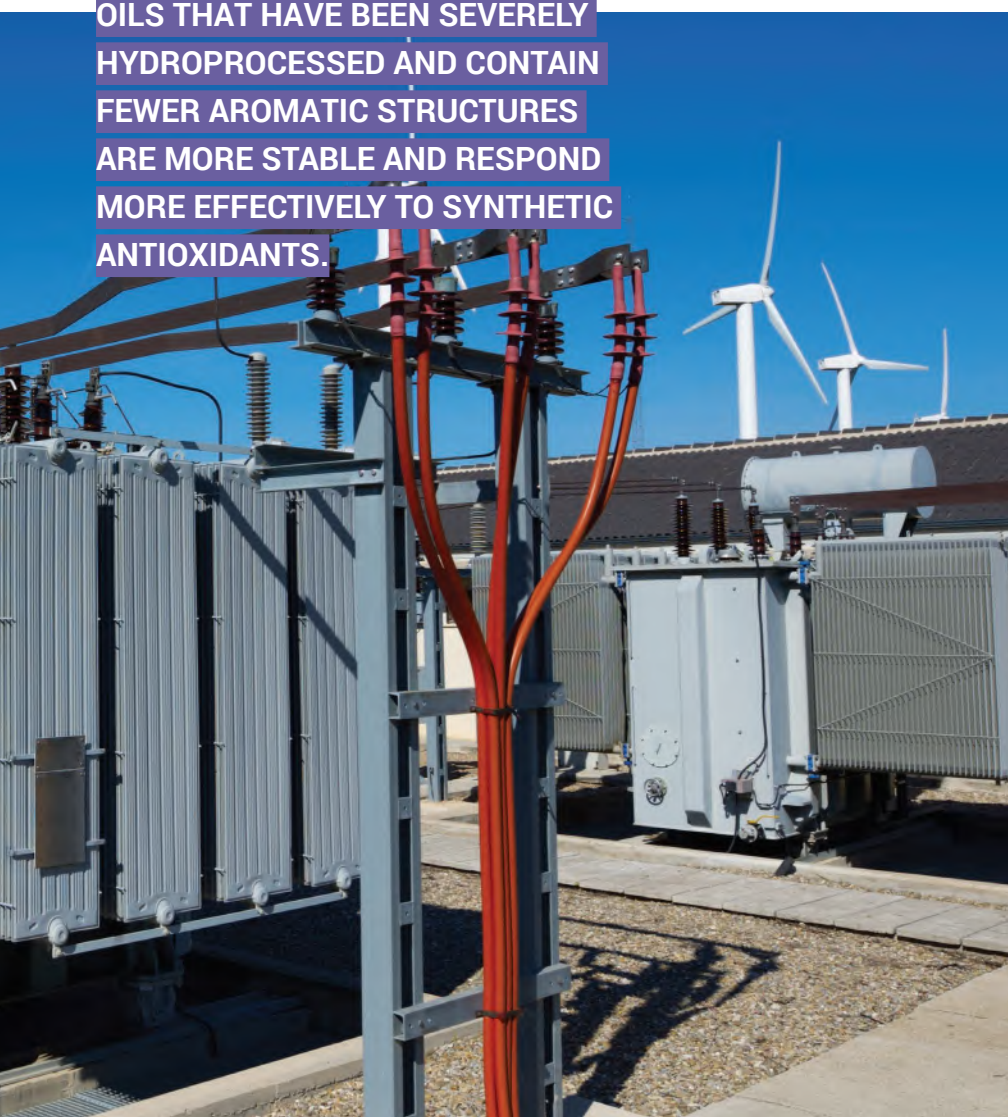


Table 1.  
Comparative properties of mineral insulating liquids

|                                      | Naphthenic | Isoparaffinic | GTL    |
|--------------------------------------|------------|---------------|--------|
| Viscosity, mm <sup>2</sup> /s, 100°C | 2.4        | 2.2           | 2.6    |
| Viscosity, mm <sup>2</sup> /s, 40°C  | 9.8        | 7.8           | 9.4    |
| Viscosity, mm <sup>2</sup> /s, 0°C   | 66.7       | 36.2          | 46.3   |
| Density, kg/m <sup>3</sup> , 20°C    | 0.8826     | 0.8299        | 0.8049 |
| Relative Density, 15.6/15.6°C        | 0.8863     | 0.8335        | 0.8085 |
| Aniline Point, °C                    | 75         | 98            | 112    |
| Refractive Index, 20°C               | 1.4830     | 1.4571        | 1.4502 |
| Flash Point, COC, °C                 | 154        | 174           | 190    |
| Color, ASTM                          | 0.1        | 0.1           | 0.1    |
| Pour Point, °C                       | -56        | -40           | -41    |
| Water Content, mg/kg                 | 16         | 17            | 14     |
| Interfacial Tension, mN/m            | 42         | 40            | 51     |
| Viscosity-Gravity Constant           | 0.857      | 0.801         | 0.768  |
| Gassing Tendency, µL/min             | +12        | +25           | +54    |

**OILS THAT HAVE BEEN SEVERELY HYDROPROCESSED AND CONTAIN FEWER AROMATIC STRUCTURES ARE MORE STABLE AND RESPOND MORE EFFECTIVELY TO SYNTHETIC ANTIOXIDANTS.**



## THE DIELECTRIC PROPERTIES ARE GENERALLY DETERMINED BY THE LEVEL OF MOISTURE, SOLUBLE POLAR CONTAMINANTS, OR SOLID CONTAMINANTS.

The solvency of mineral oils is determined mostly by the ratio of the chemical structures, but the distillation range has some influence. Aromatic structures have the highest solvency, then cycloparaffins, then isoparaffins, and then normal paraffins. Since naphthenic minerals have higher concentrations of aromatics and cycloparaffins than the isoparaffinic mineral oils, they have a higher solvency, i.e., lower aniline points. These differences, while not extreme, could lead to differences in compatibility with materials of construction, such as gaskets and seals. It is important to be cognizant of these differences, especially when retrofilling.

The oxidation stability of the bulk oil is determined by the oxidation stability of the individual chemical structures. With respect to the chemical structures found in petroleum mineral oils, the oxidation stability is generally in the following order: isoparaffinic first, then naphthenics, then aromatics, and finally polars. It is the ratio of the chemical structures which determine the overall stability of the oil. It is known that oils that have been severely hydroprocessed and contain fewer aromatic structures are more stable and respond more effectively to synthetic antioxidants [14, 15]. Phenolic antioxidants, such as 2,6-di-tertiary-butyl-para-cresol (DBPC), which has the common name of butylated hydroxytoluene (BHT), and 2,6-di-tertiary-butylphenol (DBP), have historically been used in transformer oil. While other antioxidants could theoretically be used, there are no current standard methods for the analysis of other antioxidants in transformer oil [16]. The standards for mineral insulating liquids require that all additives and the concentrations of antioxidants and passivators be disclosed.

The presence of aromatics is important for gassing tendency. Certain aromatics are known to lower the gassing tendency, and these can be added to the insulating liquid. Examples of some aromatics are described in IEC 60296. Isoparaffins, without added aromatics, have high gassing tendency values, some higher than the +30 specified in ASTM D3487, and there is no general requirement in IEC 60296. While this is ultimately a decision made by end-users based on their preference, at this time, the correlation of gassing tendency and equipment performance

is limited. The dielectric properties are generally determined by the level of moisture, soluble polar contaminants, or solid contaminants. As long as the oil is properly dried, filtered to remove particulates, and devoid of polar contaminants, the insulation liquid should have acceptable dielectric properties.

## Conclusion

Dielectric mineral insulating liquids have proven robust and effective for over a century. From early iterations as acid-treated or solvent-extracted

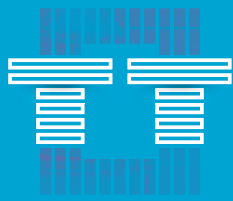
insulating liquids to today's severe hydroprocessing, naphthenic mineral insulating liquids have been the primary insulating liquid for decades. In the past 25 years, isoparaffinic mineral insulating liquids have been available due to new refining hydroprocessing, and, more recently, GTL mineral insulating liquids have been developed. These hydrocarbon liquids all meet the same stringent requirements defined in the international standards and meet the functional requirements for use in today's transformers.

**AS LONG AS THE OIL IS PROPERLY DRIED, FILTERED TO REMOVE PARTICULATES, AND DEVOID OF POLAR CONTAMINANTS, THE INSULATION LIQUID SHOULD HAVE ACCEPTABLE DIELECTRIC PROPERTIES.**

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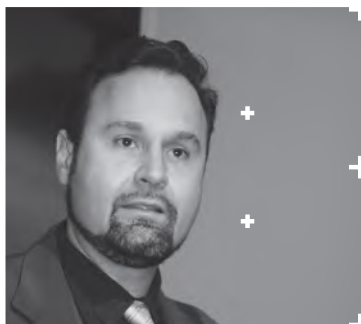
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**Alan Sbravati** started his career working for a transformer manufacturer, mainly developing calculation and design tools for power transformers. After almost 9.5 years in the same company, he was the R&D&E manager for power transformers in Brazil and responsible for two global R&D projects directly related to transformer design and thermal calculation. After three years in a commercial role, he moved back to a more technical position at Cargill. Over the last six years he has been working with the development and application of alternative insulating liquids, especially natural ester fluid (FR3™), holding the position of Global Technical Manager since 2018. Alan chaired the Brazilian Standards Committee from 2012 to 2016, prior to moving to USA. He participates in IEC TC 14 and Cigre working groups. Currently he is a member of IEEE Transformers Committee, and he is active in many subcommittees and task forces.



**Kevin J. Rapp** is the Principal Chemist for Global Dielectric Fluids of Cargill Bioindustrial. With over 40 years in the electrical industry, including 27 years in R&D where he invented Envirotemp™ FR3™ fluid and found that ester liquids enhance the life of cellulose insulation in transformers. Kevin is involved in standards as Technical Advisor/Chairman of USNC of ANSI/IEC TC10, ASTM D27.15 and D27.91 Subcommittees. Kevin was awarded IEC 1906 Award in 2011, US-EPA Presidential Green Chemistry Award in 2013, ASTM Service Award in 2015 and installed as ASTM Fellow with Distinguished Merit Award in May 2018. He holds many patents and has published numerous papers as a member of ACS, AOCS, ASTM, CIGRE, IEC and IEEE.

# Evolution of Natural Ester Transforms Industry Norms

by **Alan Sbravati**  
and **Kevin Rapp**





## Natural Ester Dielectric Liquid Development

Alternative liquids development motivation is strongly linked with the restrictions for polychlorinated biphenyls-based liquids (mostly known as PCBs) during the early 70s. The first alternative liquids the industry started using were hydrocarbons of high molecular weight, currently named as “less flammable hydrocarbons” as per ASTM nomenclature, and silicone based liquid (polydimethylsiloxane). Late in the 70s and early 80s other synthetic liquids started to be considered, with synthetic ester liquids based on pentaerythritol esters being the predominant option.

Finally, in the early 90s, researchers started developing applications based on vegetable oils, which are natural ester liquids or triglycerides. Cooper Power System got the first patent for the development of FR3 fluid in that period. Back in the early days of transformer development, around the 1890s, vegetable oils were considered for liquid immersed transformers. But just over one hundred years later the production process and proper formulation lead to a robust product, able to exceed the life expectancy of the transformer.

Although natural ester liquids were the latest development, its application overtook all the other alternative liquids, being estimated that over 2 million transformers have already been produced using FR3 fluid since the first commercial application in 1997. It is worth mentioning that this first transformer is still in service in a large amusement park in the southeast of the United States, and recent analysis of a sample confirmed that after 22 years of continuous service, most of its properties are still compliant with the requirements for “new unused natural ester liquids”. Acid value and dissipation factor were expected to gradually increase along the years, while still far from the “continuous service” proposed limits.

## Application of Natural Ester Filled Transformers

Transformers immersed in natural ester liquids can be found either in tropical rain forests of South America or in the streets of cold Minneapolis, MN (in the northern part of the United States), Stockholm (Sweden) and the fjords regions in Norway. Either mitigating the fire risk of a pole mounted transformer in a busy downtown area or minimizing the environmental impacts due to an accidental spill in a protected forest area, natural ester immersed transformer reliability has been proven by extensive real-life success cases.

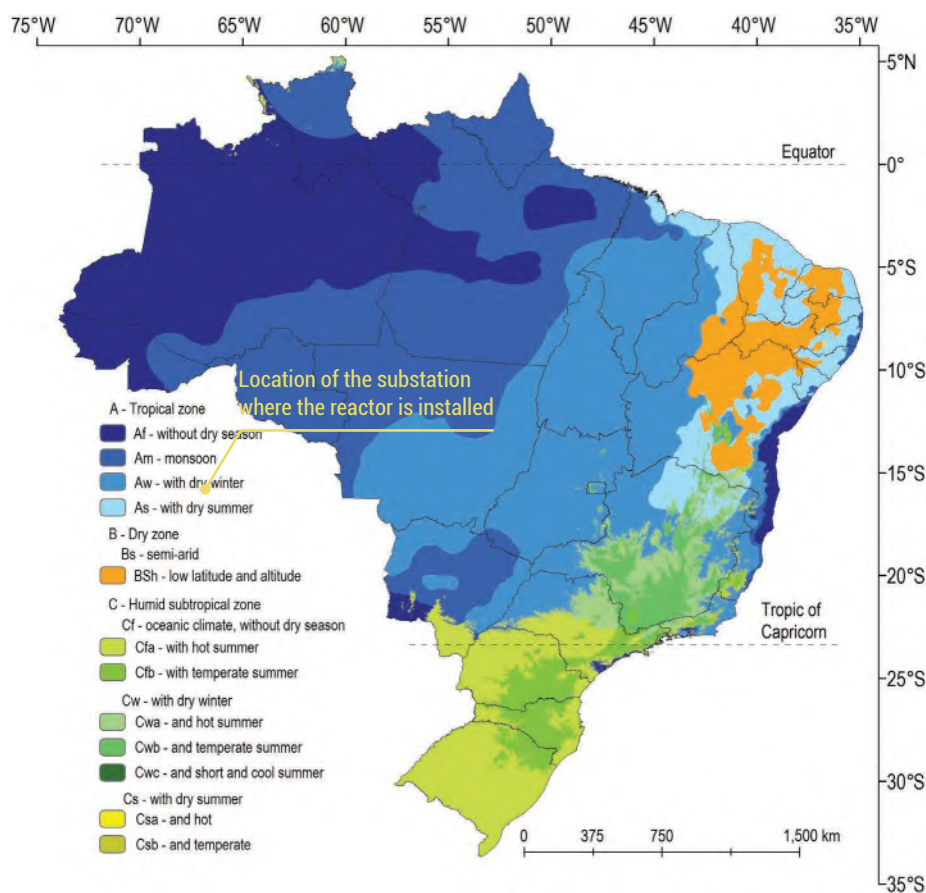
An interesting example of such validations happened a few years ago in South America. A shunt reactor was installed in a remote region, at the border of the Amazon rainforest. Figures 1 and 2 show the substation location and a photo of the reactor. As later identified, the oil conservator rubber bag was not properly installed during the field assembly, keeping the reactor in a free breathing condition.

Due to the network, the reactor was continuously at nominal capacity (loading is defined by the system voltage) while the ambient temperature was rarely under 20°C (68°F) and often close to 40°C (104°F). Also, moisture was mostly

very high (with no dry season), which all configured very harsh operating conditions for a free breathing unit.

After a few months in service, insulating liquid samples indicated increased moisture content. This was continuously monitored and the presence of leak point was raised. Consequently, the moisture value stabilized and acidity started to increase, followed by reduction of dissipation factor. This behavior clearly confirmed the initial suspicion of breach on the sealing system. Oxidation of the fluid was also a point of concern for the end user, but all laboratory analyses showed no reason for concern.

Figure 1. Koppen climate classification [1]



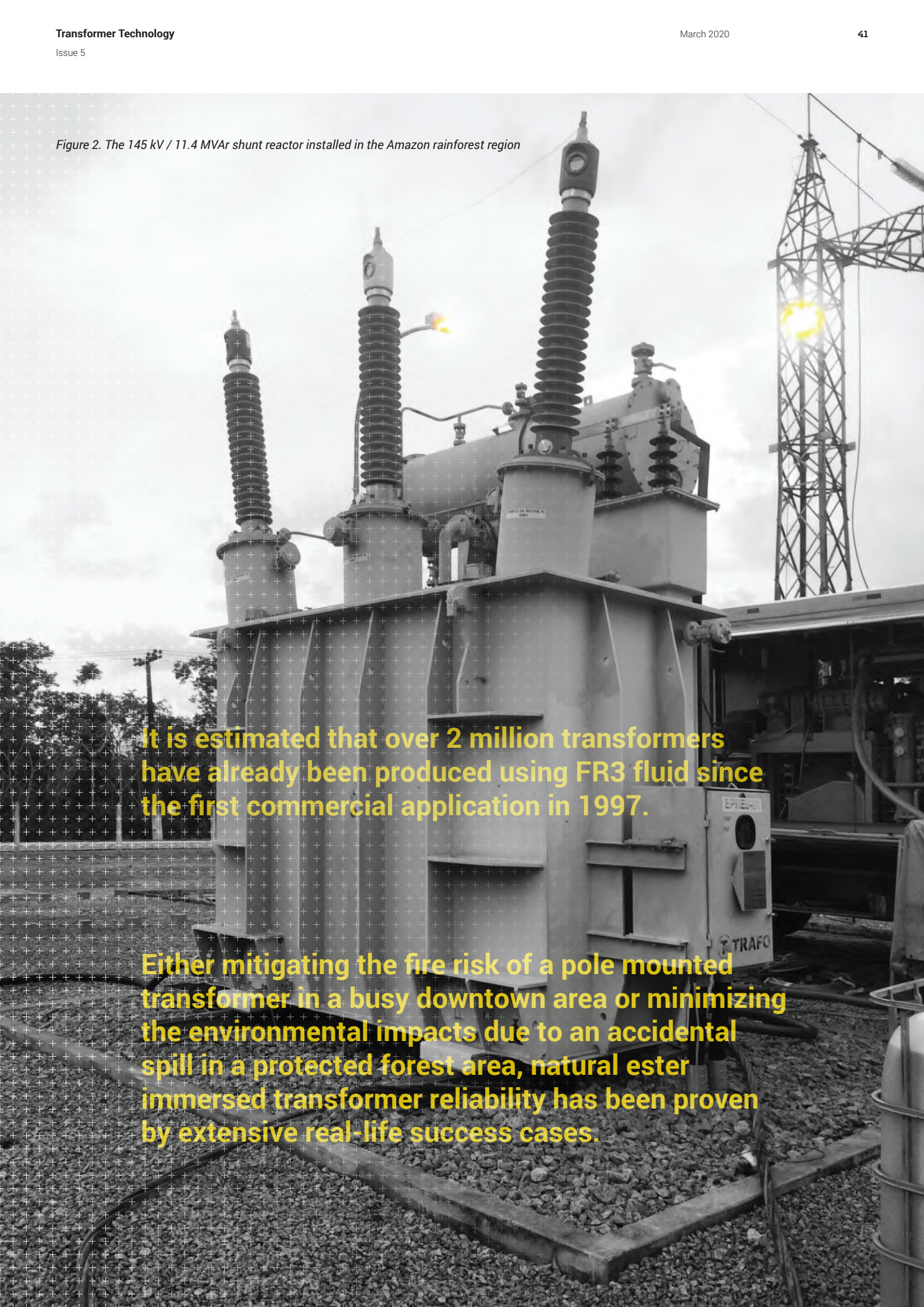
Seven years later, a planned outage was made possible. The natural ester viscosity had increased about 3%, indicating some oxidation was going on. The main real concern for the team was whether they were going to find excessive moisture content in the solid insulation materials, given the climatic conditions. However, the dew point measurements showed that the value was around 0.9%, which was a very good result. So, the overall conclusions were as follows:

- The moisture absorbed from the ambient was consumed by the fluid, without reaching the coils.
- Oxidation is a long-term process, taking several years to affect the fluid.
- Well formulated natural ester liquids are a very robust solution.

## Dielectric Properties

While the early adopters of natural ester immersed transformers were mainly motivated by the fire safety and environmental benefits, the main driver for adoption of natural esters today is their dielectric properties. The "continuous drying" process enabled by the capacity of natural ester to absorb more water and, particularly, by the hydrolysis reaction, is the most relevant advantage of natural esters compared to all other alternative liquids.

Figure 2. The 145 kV / 11.4 MVar shunt reactor installed in the Amazon rainforest region



**It is estimated that over 2 million transformers have already been produced using FR3 fluid since the first commercial application in 1997.**

**Either mitigating the fire risk of a pole mounted transformer in a busy downtown area or minimizing the environmental impacts due to an accidental spill in a protected forest area, natural ester immersed transformer reliability has been proven by extensive real-life success cases.**

Driven by moisture content and/or temperature, the reaction of the water with one of the non-hindered ester groups in the triglyceride results in the consumption of the excess moisture, generating as byproducts long chain-free fatty acids of low reactivity (mild behavior).

Moisture is one of the biggest enemies of electrical equipment. When a transformer manufacturer keeps a large core and coils inside a high-tech vapor phase oven for over a week, their main target is to reach the required dielectric capacity for the lightning impulse and other potentially destructive high voltage tests. In a mineral oil immersed transformer, in the course of the transformer life, moisture content in insulation paper tends to increase in traditional transformers. From the typical 0.5% in a new transformer, values in the range of 2% or 2.5% are not uncommon, yet highly detrimental for the dielectric withstand capacity of the insulation system. Conversely, continuous drying prevents moisture content increase in sealed FR3 fluid immersed transformers.

The continuous drying process is also key for the reduction of paper degradation rate in transformers immersed in natural ester liquids, in comparison to mineral oil and other alternative liquids. Paper degradation generates water as a byproduct, which also has a catalytic effect for further degradation, configuring a self-induced reaction. The presence of natural ester breaks this cycle – the moisture does not remain impregnated in the paper as it gets consumed by the reaction with the natural ester (hydrolysis). As a result, the thermal class of the very same thermally upgraded paper is proposed to be 20 degrees higher when it is immersed in natural ester, compared to the 120 value when immersed in mineral oil. Due to this, a superior resilience to demand fluctuations can be added to the improved long-term reliability and a reduced need for maintenance interventions to dry out the insulation system.



**The capacity of natural ester to absorb more water, which enables the “continuous drying” process and reduces paper degradation rate in transformers, is the most relevant advantage of natural esters compared to all other alternative liquids.**

## Case Examples

The main motivation for utilities recently converting all their new transformer purchases to natural ester immersed transformers is to reduce the frequency and duration of outages, either through the increased dielectric reliability and reduction of maintenance interventions for drying processes or by mitigating the external effects caused by failures, thus speeding up the restoration of the site.

Two utilities that adopted the use of natural ester for their transformers, one an energy distribution utility and the other an energy transmission company, applied two different approaches to explore the superior thermal performance of this liquid.

The starting point for the distribution company was the relevance of life expectancy of their transformers. The demand fluctuations that were associated with climatic conditions (heat waves) where their transformers were installed resulted in high peak demand, possibly exceeding the nameplate capacity of the transformers for short periods. Therefore, they started evaluating the use of natural ester to expand the transformers peak capacity and extend their lifespan.

A sensitivity analysis, where different values of life extension were applied to a percentage of the transformers replaced every year, confirmed that although initially costing a little more, the life extension would result in a positive net present value in comparison to traditional transformers. The quick payback of the additional investment motivated the financial department of the utility to adopt the new solution. Fire safety and environmental benefits came as additional benefits.

In the case of the transmission company, their initial motivation was the lifecycle costs, as the European normative makes them responsible for the final destination of the assets. This was quickly shaded by the possible economic savings they

envisioned by exploring the higher thermal class as an alternative for avoiding increasing the number of transformers in a substation.

Their power transformers were designed for two different capacities. The rated capacity, at conventional temperature rise limits, and an additional "permanent overloading capacity", using the increased temperature rise limits. Although all guaranteed parameters were still at the rated capacity, the nominal life expectation for the insulation material would only be reached at the amplified capacity, what qualified it as a possible continuous loading condition. And they reached a 50% increment of capacity at the higher temperature rise limits.

The practical result was that, for a typical substation having

**The main motivation for utilities opting for natural ester immersed transformers is to reduce the frequency and duration of outages, either through the increased dielectric reliability and fewer maintenance interventions for drying processes or by mitigating the external effects caused by failures.**



## References

- [1] C. A. Alvarez, et al, "Köppen's Climate Classification Map for Brazil", *Meteorologische Zeitschrift*, Vol. 22, No. 6, 711–728, January 2014.

2+1 transformers (one being a spare unit), the effective capacity was equivalent to three times the rated capacity of one transformer. Should an event happen to one of the units, the other two remaining transformers would be able to keep the same loading, using their "permanent overloading capacity" of 1.5x during this period. The cost reductions associated with saving not only one transformer, but all the adjacent area and the associated electrical installations became the major benefit.

In summary, the main motivation for a customer to adopt natural ester as the insulating liquid for their transformers is to have peace of mind. Transformers immersed in natural ester liquids are safer, more sustainable and improve the system reliability and resilience of the asset.

## An international leader in the development of biochemicals and bioproducts



The dominant economic model of the final decades of the 20th century and the first decade of the 21st century was a linear model, inherently **dissipative and degenerative**, in which raw materials, coming mainly from nonrenewable sources, were exploited to create industrial products that at the end of their service life are often thrown away. While this industrial model brought technical and economic achievements, it created an economy based on the continuous depletion of soil and natural resources. Such an increasingly globalized economy, with increasingly short-term objectives, is growing faster and faster and will not be sustainable long term as it aims solely to secure a profit, to the detriment of the quality of life and of natural capital.

It is time to think about the products in a different way. It is necessary to conceive products in a circular economy system where they are designed to represent a solution during their use **and not a problem when their service life comes to an end**. Conversely, they can become a resource, a raw material useful to be introduced again in the value chain, in a circular bioeconomy perspective.

**NOVAMONT has recently developed two dielectric fluids for oil filled transformers, applying a completely new approach in the selection and synthesis of new raw materials, their refining and composition.**

To establish this new system, technical challenges are even harder but a new perspective is possible.

Environmental and social issues are becoming more and more important and will shape the way the industry in every sector will act. Transformer industry is not an exception, with the growing demand for Eco-Design and more efficient, high performance and low impact products.

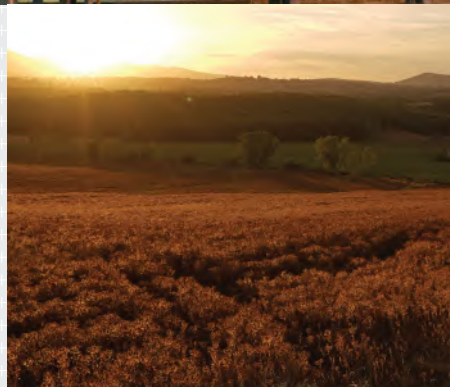
**NOVAMONT** mission is to develop materials and products from renewable sources, by putting together chemistry and agriculture, activating biorefineries that are integrated into the territory and providing application solutions that have a low environmental impact, that guarantee an efficient use of resources throughout their life cycle, with social, economic and environmental advantages for the system.

**NOVAMONT** promotes a **model of bioeconomy** as a factor of **territorial regeneration**, based on three pillars:

- **Reindustrialisation** of no longer competitive sites thanks to **proprietary technologies first in the world** in order to create "**bioeconomy infrastructures**", integrated with the territory and interconnected each other;
- Development of **low impact value chains** through the valorisation of marginal land not in competition with food production, integrated in local areas and connected with the bioeconomy infrastructures;
- Products and value chains are conceived and designed to provide **sustainable solutions** for specific environmental, social and economic problems.



**NOVAMONT mission is to develop materials and products from renewable sources, by putting together chemistry and agriculture, activating biorefineries that are integrated into the territory and providing application solutions that have a low environmental impact and guarantee an efficient use of resources throughout their life cycle, with social, economic and environmental advantages for the system.**

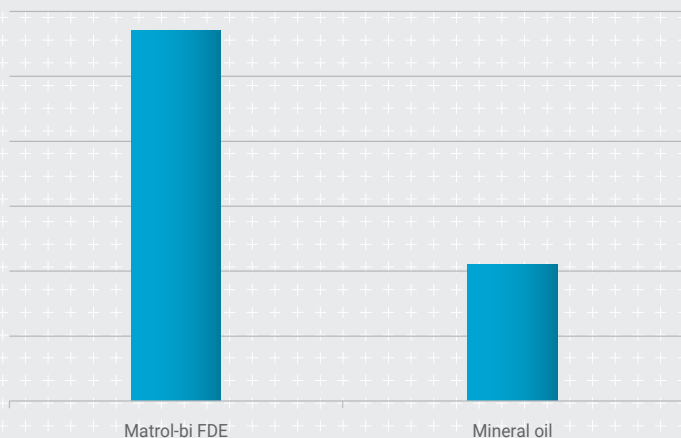


Since the invention of oil immersed transformers, many different attempts have been done to develop valid alternatives to mineral based dielectric fluids. Sometimes such attempts resulted in good technical performances, having on the other side huge environmental, health and safety drawbacks (think about PCBs). Despite their high performances in insulation and cooling, low viscosity mineral oils also have several drawbacks: above all, they are highly flammable, having a fire point often lower than 160°C, and they do not protect the solid insulating part of the transformer – the Kraft paper. Furthermore, they come from a non-renewable source, they are not biodegradable and, may have adverse health effects.

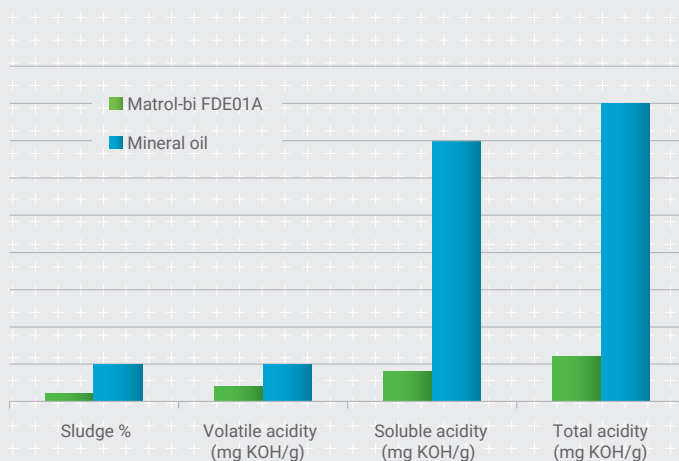
**Novamont is now able to offer two grades of dielectric fluid, Matrol-Bi FDV01A and Matrol-Bi FDE01A. Both grades not only represent a better option from an environmental point of view, but they overcome the performances of mineral oils, assuring many technical advantages.** Matrol-Bi **flash and fire points** are definitely higher than most of the widespread dielectric mineral oils. **Matrol-Bi** fluids are based on natural or synthetic based esters and guarantee a **reduced fire risk and limited damage in case of accidents** with the possibility to increase the safety level of transformers installed in densely populated areas. The reduced risk of fire and accidents can also lead to lower prevention, maintenance and insurance costs. Thanks to their higher polarity (compared to mineral oils), natural and synthetic esters are capable to dissolve higher amounts of water without compromising their dielectric performances. While mineral oils are generally able to absorb up to 60-100 ppm of water, Matrol-Bi FDV and FDE are able to absorb up to 1000 ppm. **They can prolong the life of the insulating Kraft Paper**, absorbing water and slowing paper ageing, and thus prolonging the service life of the transformer.

**NOVAMONT now offers two grades of dielectric fluid: Matrol-Bi FDV01A and Matrol-Bi FDE01A, both of which overcome the performances of mineral oils, assuring many technical advantages.**

RPVOT (min)



Oxidative stability according to IEC 61025-C, 164 h.



Despite the elevated oxidative stability, low temperature fluidity is outstanding.

| Viscosity (cSt)  | 100°C | 40°C | 20°C | 0°C | -20°C |
|------------------|-------|------|------|-----|-------|
| Matrol-Bi FDV01A | 9     | 41.5 | 92.2 | 256 | 982   |

Matrol-Bi FDV01A fulfils and exceeds IEC 62770 standard requirements.

Matrol-Bi FDE01A is a patented synthetic ester fluid which has a low viscosity compared to other commercial synthetic dielectric fluids, very close to the viscosity of mineral oils. This parameter is critical because the lower the viscosity, the greater the capacity of the fluid to impregnate the solid insulation and protect it, to remove and disperse the heat. Thanks to low viscosity and excellent low temperature fluidity, Matrol-Bi FDE01A is particularly suitable for retrofilling of old transformers designed for mineral oils since there is no need to change the design of transformer.

| Viscosity (Cst)  | 100°C | 40°C | 20°C | 0°C | -20°C |
|------------------|-------|------|------|-----|-------|
| Matrol-Bi FDE01A | 4.75  | 21.9 | 48.4 | 143 | 644   |
| Mineral oil      | 3.7   | 15.6 | 37.7 | 129 | 765   |

Despite low viscosity the ester has high flash and fire points (>250°C and >300°C), fulfilling and exceeding all the requirements of IEC61099 standard. Compared to a widely used mineral oil, it has exceptional oxidative stability and a low tendency to form sludge and deposits.

The aim to combine excellent performance with respect for the environment is today possible. High-performances, extended transformer life, high oxidation stability and low gassing tendency, enhanced asset performance and biodegradability are the key attributes of Matrol-Bi.



Both Matrol-Bi synthetic and natural esters are renewable (>85%) and readily biodegradable, reducing long term risk to the environment in case of accidents and spilling. The amount of gasification is low and the specific heat is comparable to that of mineral based dielectric fluids.

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# Managing the Reliability of an Industrial or Commercial Electrical Power System / E 02

by **Chuck Baker**

+++++

## Cast

**Andy** ..... Reliability Manager of Electrical Power System  
(recently hired by Brian, the Plant RVP)

**Brian** ..... Regional Vice President  
(head person for this plant)

**Jill** ..... Director of Operations

**Kevin** ..... Director of Reliability

**Tim** ..... Electrical Engineer  
(who reports to Andy)

**Tina** ..... Maintenance Manager  
(who reports to Brian also)



**Chuck Baker** is the President of PowerPro 360, a company offering power system reliability assessment and reliability maintenance programs for Industrial and commercial organizations. Chuck entered the world of Substation and Power System Maintenance 36 years ago and has spent a majority of that career on the operations side of power and distribution system maintenance and the development of power system maintenance programs.



Hello, I am Andy.

I have been recently hired by Brian, the regional VP of Smith Industries, to be the reliability manager of electrical power systems. This plant had been ranked the lowest in terms of reliability by the corporate group, which is why I was hired. The biggest contributor to this shortfall had been the power system.

It was my directive to bring reliability to the power system, specifically. Due to this being a special project, I was to report to Brian for the first year, which made the lines of responsibility with Kevin—the director of reliability—a little awkward.

I had just walked out of a meeting with Brian, Jill (director of operations), Kevin, and my EE, Tim when I received an email from Kevin asking for a few minutes of my time to do a meeting recap. I was free, and so was he, so I went to see him right away.

I had done reliability program building before, and the biggest challenge I had faced was changing the way people look at traditional maintenance.

It's a different culture. The only way I knew to make it work was to communicate, communicate, communicate.

As I walked into Kevin's office, I figured it was time to practice that communication.

Kevin opened with a question before I sat down.

"Thanks for the update, Andy. Can you let me know a little more about arc flash? The arc flash survey... what is it? And why do we need it? Have we been negligent by not having an update since 2005?"

I saw this as a great opportunity to team with Kevin. Over the course of 45 minutes I walked him through a little of the history and the reality of the situation.

I made these points:

- Arc flashes occur where a flashover of electric current leaves its normal path.
- Temperatures at the arc points can exceed 35,000 degrees – four times the temperature of the sun's surface.
- The sound from an arc flash can reach 140 decibels.
- An arc flash can be caused by dust, moisture, or a tool dropped during inspection.
- When arcs cause equipment to explode, flying metal pieces can travel at a life-threatening 700 mph.
- Anything that produces electric current has the potential to create an arc but can be mitigated through arc flash services.
- Regulations on arc flash standards come from NFPA 70E, which gives instructions on how to comply with OSHA's electrical safety regulations. When an arc flash occurs, it is estimated that should the victim survive, medical costs can run as high as \$1M and the resultant OSHA fines have run as high as \$500k.
- The real problem with arc flash is what it does to a human. For those who survive, recovery can be a torturous medical process.
- It is estimated that the number of arc flash incidents per year run from 2,000 to 3,000. Bottom line—arc flash is a real risk.





As I was explaining this to Kevin, he listened intently and took notes in silence. His next question answered why he was listening and not asking questions.

"Why haven't we been doing this?" he asked. "And what do we need to do to make it happen?"

I asked Kevin if he would be OK if I got the group together and walked everyone through the answer to this question. He agreed, we shook hands, and I headed back to my office to set up the meeting.

I sat down at my desk and opened Outlook. I brought up a new meeting request. I entered the title of "Arc flash studies background" and thought—who to invite? I knew

Tim needed to be there. The EE will play a key role. Obviously, Kevin. I included Jill too, as she owns operations and needed to be aware of the training component, and although Tina reports to Jill, I invited her as well. I looked at everyone's calendars and select a start time of 9:30 the next morning, with the meeting ending by 10:30, and hit launch.

While sitting with a cup of coffee the next morning, I thought through what I should say. I had previously talked to Brian several times about this, but I needed to make sure they really understood this well. I picked up my coffee and binder and headed down the hall to conference room H. Almost everyone was already seated. Jill arrived the same time I did.

I was quite pleased when Kevin opened the meeting by stating how serious the subject was. I was really surprised how accurately he reviewed the key points we talked about the day before. As soon as he finished and turned the meeting over to me, the questions started flying:

**"When did these arc flash concerns and regulations begin?"**

"In 1981 Ralph Lee, a PE and IEEE member, released a whitepaper entitled 'The Other Electrical Hazard: Electric Arc Blast Burns.' It got a lot of attention. In 1995 NFPA 70E got on board by addressing arc flash as a hazard and established arc flash boundaries, introducing the concept of approach limits."

**"You said our last one was in 2005. How often should we be doing this?"**

"The standard for electrical safety in the workplace—NFPA 70E—states in Article 130.5 that an arc flash study needs to be reviewed every five years or whenever there is a significant change in the electrical system. The five-year interval is straight-forward requirement. The other key area that I want us to make a priority is training. Under the NFPA 70E standard, arc flash training not only needs to be completed every three years, but it must also be documented, and employees must be able to demonstrate that they understand how to safely work on electrical equipment."



### **“Are we in trouble since we haven’t done this since 2005?”**

“Smith Industries cares and is doing the right thing. We have made this a priority and we are going to keep it one. The bottom line, in my opinion, is that the goal is to keep employees and contractors safe. We are already proceeding with getting the things we need, and we need to work as a team to make this happen.”

### **“What is required to do an arc flash study”**

I didn’t want to overcomplicate it, so I gave them just the highlights.

“The reason I won’t go into too much detail now is that the arc flash study will generate a large amount of critical data. The study will require specialty software, a project lead by a professional engineer, and everyone’s cooperation. What I think is cool is that not only will we use this data in the arc flash, but this data will also be used to begin to build a reliability centered power maintenance program (RCPMP). That is the fundamental reason Brian created this position. But let me back up and give you the fundamental steps we will be going through.”

For the next hour I walked them through the **key steps required for an arc flash study**:

1. Update the one-line diagrams. This is critical information that is required for accuracy and when identifying all key bus and components in the electrical system.
2. Perform a short circuit study. I explained that with an accurate one-line, a professional engineer will determine the potential short circuit current that can be generated at each key spot throughout the circuit. When the PE knows what could be generated, they will go onto the next step.
3. Perform a protective device study. This looks at the locations we identified as having a potential short circuit. We look at the calculated energy that could be present and then we check on the protective device that would be responsible to limit or stop the short circuit.

I also pointed out that there are two phases to this which could be done simultaneously:

- a. Identify what the protective device ratings and or settings are at today. This is required for the arc flash study.
- b. Recommend what changes should be made in the protection system.

I explained that I was taking both options and would explain why a little later.

From this data, I told them, we would post labels showing the required arc flash protection that is required at each potential area throughout the plant. This would allow employees and contractors to see the potential risk and that they must wear appropriate PPE when in that area servicing equipment.

When I completed the overview, Tina asked me a question I had been expecting all morning.

“Andy, you mentioned a reliability centered power maintenance program earlier, and then you just mentioned that on the protective device study you are going to drill down at the same time and have the PE recommend changes throughout. Are those two related to each other?”

I told her that they were, and that I was going to be sitting down with her and Tim over the next few weeks to plan how we were going to tackle this project. Tina and her team needed to be a part of this. I repeated that the information generated during the arc flash study was priceless and a key ingredient for the Reliability Centered Power Maintenance Program, which I intentionally mentioned again to begin to get them familiar with the concept.

“I am already on board with that,” she replied. “I have implemented RCM in about 70 percent of the production process and have plans for the balance. Knowing that the power system is officially underway is exciting and I am looking forward to teaming with you.”

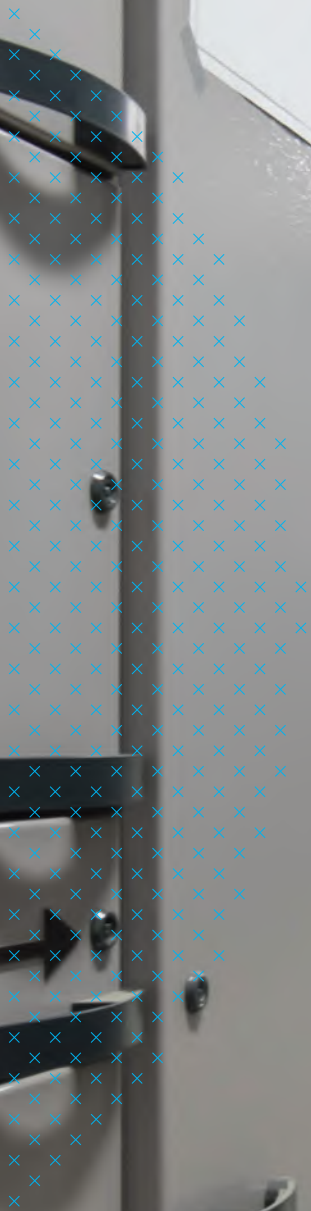
I pointed out that we were about 35 minutes over the scheduled time and

asked if there were any other question or comments before we break up.

The responses I got were wonderful. Kevin jumped in and explained that he and Brian had been working on this program for three months and he was excited that we were finally moving forward in the right direction.

*Arc flash protection*

Jill, the director of operations, said that she was on board and that it sounded like a positive push for decreasing down time. She asked that I keep Tina (the maintenance manager) in the loop every step of the way. Tina, who held a lot of key data on the power system, seconded what Jill said that and reminded me to let her know if I needed anything.



I knew this was going to be a real challenge, and I was reminded of a relevant quote by Niccolò Machiavelli:

**“There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.”**

Tim just sat back with a slight smile on his face. I didn't know him well enough to know what that smile meant.

I felt as if the culture at Smith Industries was one of true teamwork with a common goal of safely and efficiently producing profitable products and leaving the customer wanting more.

My next step would be to sit down with Tina and Tim and walk through the fundamentals of executing this arc flash study. I would explain to them why the data generated through the arc flash study was going to be critical for the RCPMP, and I would give them some detail on the plan itself.

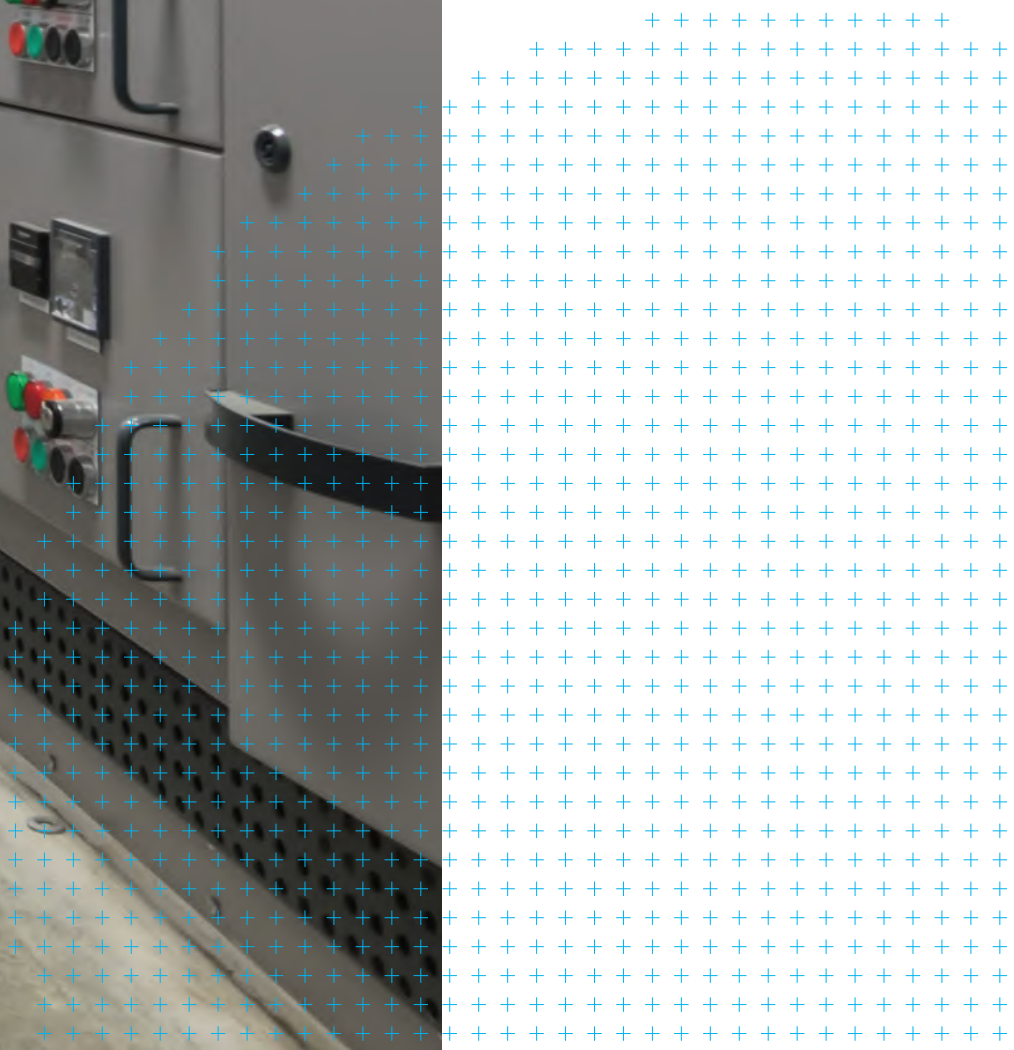
But first, I needed to get back to my desk and complete the “48-hour Brian Arc Flash Report!”



**Authors note:**

**The next update on the Smith Industries saga will be in the June edition of Transformer Technology. But I want to do something a little different. Transformer Technology has allowed me to provide short articles in April and May that will only be available online. I want to use these two opportunities to walk you through what really happened with Brian's strategy to bring Andy on board, and how he worked with Kevin for several months prior to Andy's arrival. The reality with trying to implement a new and deeper program challenges the current culture and if not done properly will never work. I am looking forward to sharing that with you. Check out [www.transformer-technology.com](http://www.transformer-technology.com) to find out more.**

**Chuck Baker**



# Proactive Containment A SOUND AND SAFE POLICY

US PAT. 10,266,307 Other PAT. PEND. CAN. PAT. PEND.

**TRANSFORMER  
CONTAINMENT  
BAG**  
LIFT IT, MOVE IT, STORE IT! ALL IN ONE BAG!



It is important for line crews to stay vigilant when it comes to safety. Utilities continually look for new ways to improve service levels, maintain compliance and become more competitive, and it may be necessary, from time to time, to stop and reassess safety considerations and regulatory compliance. That is especially true when considering the changes in the workforce caused by the loss of legacy knowledge as one generation passes the torch to the next generation.

Of the many jobs line crews perform, transformer changeouts are possibly the least enjoyable. There are numerous safety concerns a line crew must consider when engaging in those projects. Most obvious would be the proscribed procedures for safe handling of live conductors. But of no less importance is the safe operation of the vehicle mounted crane/hoist, the required type and condition of the necessary gear and tools, and the individual responsibilities of each line crew member present during a changeout.

According to the Department of Labor – Occupational Safety and Health Administration (OSHA) the responsibility for lifting any load (in this case a transformer) belongs to the “Designated Personnel” as defined in 29 CFR 1910.180 [1] and rigging the load (again the transformer) belongs to the “Rigger” as defined in ASME B30.5-2018 [2].

**It might seem obvious, but how does the “Rigger” attach the load to be lifted?** Most utility line crews attach or rig the load utilizing a certified sling [3, 4] to the manufacturer’s engineered lifting lugs which are located on the transformer. This allows for the load to be balanced and secure [5] in compliance with OSHA guidelines, the transformer manufacturer’s guidelines, and The Lineman’s and Cableman’s Handbook: “...by using the lifting lugs built into the transformer at time of manufacture” [6].

Circumstances, for example a leaking transformer, can complicate the duties of the “Rigger” and the “Designated Personnel” on the line crew during this process. It raises the question of how the line crew follows their training for safe lifting and minimizes the potential of a spill. This part of the process can be messy and potentially dangerous. Depending on the location and age of the leak, transformer oils can spill when you’re removing the transformer from the mounting brackets, all the way to placing it on the back of the truck and taking it back to the yard. As most line crews already know, **even non-leaking transformers can start to leak once they are jostled during a changeout.**

**The Transformer Containment Bag™ manufactured by Andax Industries, provides for both complete access to the transformer manufacturer’s lifting lugs and complete containment for the transformer, ensuring 100% OSHA Compliance.**





MOVE IT



STORE IT

## The Transformer Containment Bag™ is the recipient of the Product of the Year award for Safety from Plant Engineering and Environmental Protection publications.

### References

- [1] US Department of Labor - Occupational Safety and Health Administration, 2020
- [2] ASME B30.5-2018, 2018
- [3] US Department of Labor - Occupational Safety and Health Administration, 2020
- [4] ASME B30.5-2018, 2018
- [5] US Department of Labor - Occupational Safety and Health Administration, 2020
- [6] Thomas M. Shoemaker, 2017
- [7] Thomas M. Shoemaker, 2017

# ANDAX

613 West Palmer St.  
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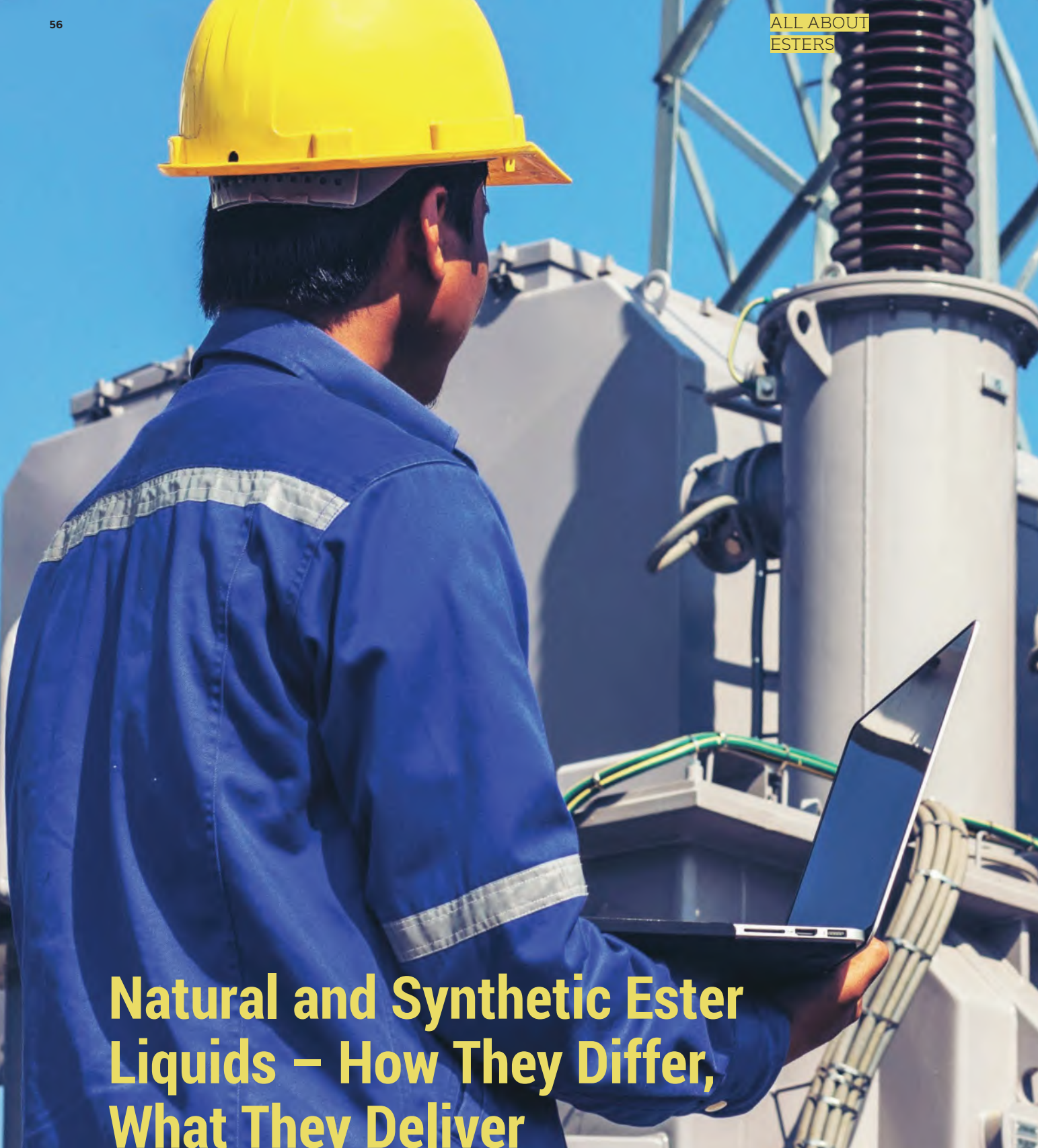
[www.transformercontainmentbag.com](http://www.transformercontainmentbag.com)  
[customerservice@andax.com](mailto:customerservice@andax.com)

to potential spills during transformer changeouts. Even in a situation where a transformer was not leaking when lifted and removed but ended up leaking after being lifted into the back of the truck. It becomes a hazard when you factor the risk and liability of on the job slips and falls.

**Proactive containment is a sound, safe policy for utilities and line crews when lifting and moving transformers.** And given that just about everyone has a smart phone with the ability to post pictures and videos of your crew's actions all over social media or the evening news, proactive containment is a game changer. So how can a line crew be proactive while lifting and moving a transformer during a changeout? First, line crews need the right tools for the job. They need the tools that allow the specific crew members to do their job properly, safely and in compliance with governmental regulations and company policies. In this specific case the line crew needs a tool that provides proactive containment for the transformer and allows for OSHA compliance while lifting, moving and storing the transformer. The transformer containment product has to allow the "Rigger" complete access to the manufacturer's "lifting lugs built into the transformer at time of manufacture" [7]. **The transformer containment product has to contain the transformer, while allowing it to remain balanced and secured when the line crew is lifting, moving and storing it. This ensures 100% OSHA compliance for safe lifting and proactive containment and satisfies even the most stringent company safety compliance guidelines.**

The Transformer Containment Bag™ manufactured by Andax Industries, provides for both complete access to the transformer manufacturer's lifting lugs and complete containment for the transformer, which ensures 100% OSHA Compliance. It is the tool that provides a proactive solution for utilities and line crews. The Transformer Containment Bag™ is also the recipient of the Product of the Year award for Safety from Plant Engineering and Environmental Protection publications. **Use the right tool for the job – The Andax Transformer Containment Bag™.**

As that transformer reaches the ground, containing the spill becomes a high priority. Whether the oil is contaminated with PCBs or not, an oil spill can become a big concern for the line crew and the utility – very quickly. Terms such as "unregulated release" and "waterway contamination" become the starting point of costly fines and expensive cleanups. Containing the transformer as soon as possible, whether leaking or not, is a great way to minimize the potential costs and exposure related

A full-page background image showing a male worker in profile, wearing a bright yellow hard hat and a blue work uniform with reflective silver stripes on the sleeves. He is holding a silver laptop. In the background, there is a large industrial transformer with a grey cylindrical body and a stack of dark purple insulators on top. The scene is set outdoors under a clear blue sky.

# Natural and Synthetic Ester Liquids – How They Differ, What They Deliver

|                         |
|-------------------------|
| by <b>Jinesh Malde</b>  |
| <b>Muhammad Daghran</b> |
| and <b>Attila Gyore</b> |

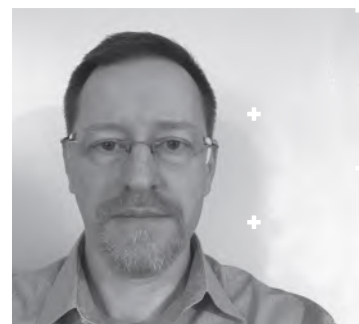
A dielectric liquid is a material used in a transformer to enhance cooling efficiency of active parts and provide electrical insulation. Together, the dielectric liquid and the solid insulation (i.e. paper and pressboards), provide enhanced dielectric withstand strength of the transformer structure. The dielectric liquid also acts as an information carrier on issues related to internal faults within the tank and active parts. Currently, hydrocarbon based mineral oils represent the highest volume of dielectric liquids used in transformer applications. These oils are derived and refined from crude oil and achieve the desired properties



**Jinesh Malde** has worked for M&I Materials Inc. since 2016 as Applications Engineer providing technical support to customers on use of natural and synthetic esters in transformers. He received a Bachelor of Science degree in Electrical Engineering from Lawrence Technological University, Southfield MI. For three years he worked as Transformer Design Engineer at Marcie Electric Inc. followed by six years at Weidmann Electrical Technology Inc. as Distribution Transformer Engineer. He is a member of the IEEE Transformers Committee, participating in several working groups, task forces, and as Secretary of Insulation Life Subcommittee. He is a member of the ASTM Committee D27 – Electrical Insulating Liquid and Gases.



**Muhammad Daghrhah** finished his PhD (2017) in electrical and electronic engineering from The University of Manchester with transformer thermal modelling as the researched subject. He also holds MSc (2013) in Electrical Power Systems Engineering from the University of Manchester and BEng (2010) in Electrical Engineering from Birzeit University in Palestine. Muhammad worked from 2010 till 2012 as a lecturer at Birzeit University at which he was responsible for lab developments and students training on diverse topics including electrical machines, machine drives, wireless communications, and engineering drawings through which he developed strong interpersonal, teaching, and communication skills. In 2018, he joined MIDEL technical team as Applications Engineer with responsibilities involving technical support for customers, leading research in understanding transformer thermal behaviour with alternative liquids, attending exhibitions and technical conferences.



**Attila Gyore** has a PhD from the Budapest University of Technology and Economics (BUTE), with a focus on superconducting transformers. For 10 years he was an Assistant Professor at the Department of Electric Power Engineering at BUTE, and from 2011 he worked with CG Hungary as an active part design engineer of power transformers. Dr. Attila joined M&I Materials in 2012 as a senior application engineer, where he is an expert in the applications of natural and synthetic ester liquids and retrofilling of transformers. Attila is an active participant in conferences worldwide and is a highly engaged member of IEEE, CIGRE D1 as well as IEC TC10 and TC14.



Natural ester dielectric liquids are produced from vegetable oils and their properties are affected by the base vegetable oil from which they are made.

that meet most of the relevant standards. However, despite mineral oil being a good dielectric liquid, it is neither a K class liquid (fire point greater than 300°C), nor is it readily biodegradable (environmentally friendly). As such, over the past several decades, natural and synthetic esters have emerged to meet the K class requirements, are environmentally friendly and improve the life of the insulation system inside the transformer. This article provides information on differences between the various liquids, similarities between natural and synthetic esters and guidance on selection of the most appropriate liquid based on the application.

## Differences Between the Dielectric Liquids

To define the differences between mineral oil and ester based dielectric liquids, it is worth looking at their chemical structures.

### Mineral Oil

Figure 1 shows the basic chemical structure of mineral oil. The hydrocarbon compounds in mineral oil vary and can be categorized into paraffinic, iso-paraffinic, naphthenic, aromatic, and poly-aromatic. These compounds exist in mineral oil with different ratios and thus contribute to slight differences in properties such as flash and fire points, pour point, viscosity, and oxidation stability to name a few.

Figure 1. Mineral oil hydrocarbon structures [1]

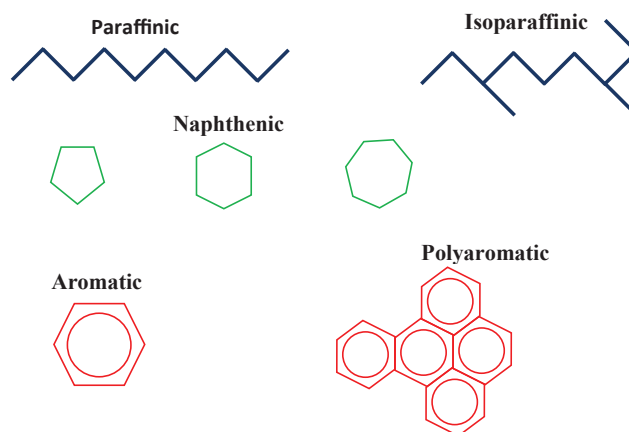
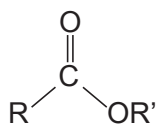


Figure 2. Basic building block of an ester



### Ester Liquids

The basic building block of an ester is shown in Figure 2. It is comprised of carbon (C), oxygen (O), and hydrocarbon chains presented by R and R'. The single and double lines represent a single bond and a double bond respectively. Note that C=O double bonds behave differently from the C=C double bonds found in the R chains of natural esters.

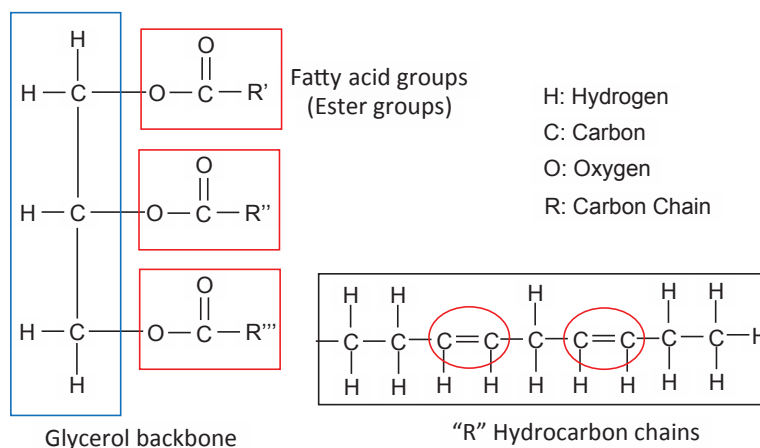
**Natural esters should only be used in sealed systems where there would be no direct exposure to air for elongated periods of time.**



Figure 3. Examples of a chemical structure of natural ester liquid

### Natural Ester

Natural ester dielectric liquids are produced from vegetable oils, which are manufactured from plant crops (soybean, canola/rapeseed, sunflower, etc.). The structure of natural esters is based on a glycerol backbone, to which are bonded 3 naturally occurring fatty acids as shown in Figure 3. Plants produce these esters as part of their natural growth cycle and contain different amounts of double bonds in the fatty acid chain (i.e. R').





### Single and double bonds, saturation and oxidation stability

For the natural ester where all bonds in the 'R chain are single, the liquid is saturated and highly resistant to oxidation. Where double bonds are present, these can be broken as the liquid reacts with oxygen. Liquids which contain these double bonds are therefore referred to as unsaturated and need some degree of chemical stabilization to remain high performing in the presence of oxygen. Just as mineral oil dielectrics require inhibitors, natural ester dielectrics require anti-oxidant stabilizers for this reason and should only be used in sealed systems where there is no direct exposure to air for elongated periods of time.

Natural esters fall on a spectrum with respect to saturation. The spectrum is formally classified into mono, di- and tri- unsaturated (poly unsaturated) components (Table 1) which also carry the names oleic, linoleic and linolenic respectively [2]. While canola oil has a higher proportion of oleic content, this mono-unsaturated content is less susceptible to oxidation than the di-unsaturated linoleics and tri-unsaturated linolenics. Canola-derived esters therefore contain less of the more oxidation-prone fatty acids.

Figure 4 shows several vegetable-based oils with different ratios of poly-unsaturated, mono-unsaturated and saturated fatty acids. The higher the saturated fatty acid content, the higher the pour point of the liquid, which can limit the operational temperature of the transformer. By using specially formulated pour point suppressants, the pour point of the natural ester liquids can be improved.

### Synthetic Esters

A synthetic ester dielectric liquid is designed using carefully selected acids and alcohols. A chemical reaction is created through esterification with heat to produce an ester and then any excess water is removed. The process is illustrated in Figure 5. Synthetic ester dielectric liquids are derived from chemicals and are usually the product of polyol alcohols (a molecule with more than one alcohol functional group)

Figure 4. Percentage of fatty acids in different base vegetable oils

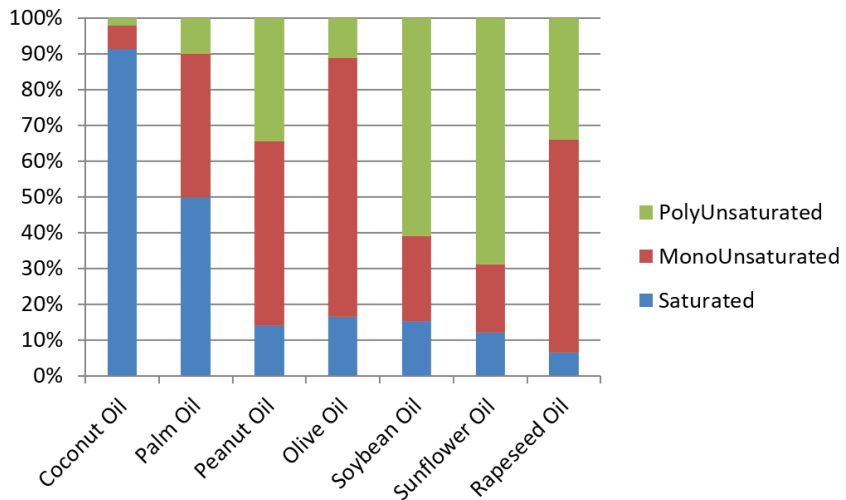


Table 1. Unsaturated fatty acid content in natural ester liquids.

| Natural ester fluids | Less susceptible to oxidation | More susceptible to oxidation |                 | Total |
|----------------------|-------------------------------|-------------------------------|-----------------|-------|
|                      | Mono-unsaturated              | Di-unsaturated                | Tri-unsaturated |       |
|                      | Oleic                         | Linoleic                      | Linolenic       |       |
| Soybean              | 24%                           | 54%                           | 7%              | 61%   |
| Canola               | 62%                           | 22%                           | 10%             | 32%   |

Figure 5. Esterification process for synthetic esters

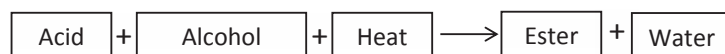
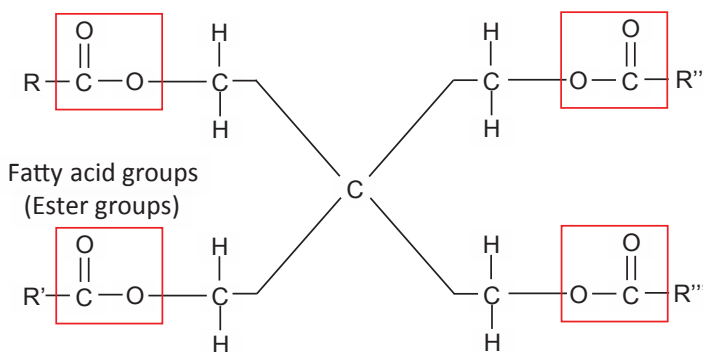


Figure 6. Example of chemical structure of a synthetic ester with a central pentaerythritol hub with four ester groups



**Synthetic ester dielectric liquids are derived from carefully selected acids and alcohols through the chemical reaction of esterification.**



with synthetic or natural carboxylic acids as shown in Figure 6. Chemically, synthetic esters consist of four ester groups where there is no double bond in the R chains between carbons (saturated bonds), which increases its oxidation and thermal stability.

### **Difference Between Natural and Synthetic Esters**

The two fundamental differences in the physical properties of natural esters compared to synthetic ester liquids are oxidation stability and pour point.

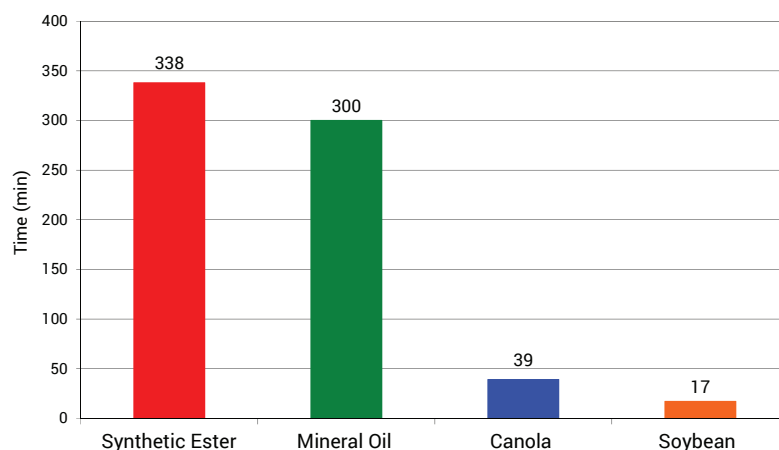
#### **Oxidation Stability**

Figure 7 shows test results for the different dielectric liquids following the ASTM D2112 pressurized vessel oxidation test method. The test is conducted in the presence of copper catalyst, pressurized at 90 psi with pure oxygen and heated to 140°C. The time is measured till the pressure drops to 65 psi due to pure oxygen consumption from the oxidation process. The longer the time, the better the oxidation stability.

**The two fundamental differences in the physical properties of natural esters and synthetic ester liquids are oxidation stability and pour point.**



Figure 7. Results of oxidation stability test according to ASTM D2112 test method



Oxidation stability is an important characteristic in the manufacturing, operation and maintenance of a transformer. If an insulating liquid oxidizes, the physical and chemical properties of the liquid change. In natural ester liquids, the viscosity of the liquid increases, the acid value increases, and the liquid starts to polymerize over time. The oxidation process in a transformer is a slow process that can be accelerated by an increase in temperature. In order to improve the oxidation stability of liquids, oxidation inhibitors are added which can prolong these changes to the chemical and physical properties of the liquid.

## Pour Point

Another key difference between synthetic and natural esters is their pour point temperature. Pour point is defined as the temperature below which the liquid loses its ability to flow and pour down from a beaker. Table 2 shows the pour points of synthetic ester, canola based natural ester, and soybean based natural ester.

A lower pour point indicates better cold temperature performance of the transformer.

## Comparison of Ester Liquids to Mineral Oil in Transformers

The chemical structures of ester liquids are more polar than mineral oil. This polarity has an effect on the moisture saturation limit, power factor and insulation resistance in a transformer. The gases generated (hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide and carbon dioxide) in ester liquids are the same as mineral oil, however the gassing behavior is different [3]. IEEE C57.155 has guidance on the gassing behavior of ester liquids. There are differences in the dielectric and thermal behavior of ester liquids compared to mineral oil. Leading transformer manufacturers are aware of these differences and address them when designing transformers. End users should be cautious in using the same limits set for mineral oil filled transformers as for an ester filled transformer in tests such as power factor, insulation resistance, and DGA.

## Benefits of Using Esters in Transformers

As outlined earlier, the main reasons for adopting an ester as a transformer dielectric liquid include increased fire safety and better environmental protection. Additionally, esters have high moisture tolerance that can improve the life of the insulation system. These features are discussed as follows.

Table 2. Pour point for different types of esters

|                       | Synthetic ester<br>(MIDEL 7131) | Canola natural ester<br>(MIDEL eN 1204) | Soybean natural ester<br>(MIDEL eN 1215) |
|-----------------------|---------------------------------|-----------------------------------------|------------------------------------------|
| Pour point (ISO 3016) | -56 °C                          | -31 °C                                  | -18 °C                                   |

Table 3. Fire classification of dielectric liquids according to IEC 61039:2008 based on fire point and net calorific value

| Class | Fire point               | Class | Net calorific value     |
|-------|--------------------------|-------|-------------------------|
| O     | ≤300°C                   | 1     | ≥42 MJ/kg               |
| K     | >300°C                   | 2     | ≤42 MJ/kg and ≥32 MJ/kg |
| L     | No measurable fire point | 3     | <32 MJ/kg               |

| Liquid          | Flash point<br>ISO 2592 | Fire point<br>ISO 2592 | Net calorific value | Classification to<br>IEC 61039 |
|-----------------|-------------------------|------------------------|---------------------|--------------------------------|
| Mineral Oil     | 160°C                   | 170°C                  | 46.0MJ/kg           | O1                             |
| Synthetic Ester | 275°C                   | 316°C                  | 31.6MJ/kg           | K3                             |
| Natural Ester   | 316°C                   | 360°C                  | 37.5MJ/kg           | K2                             |

## Fire Protection

Dielectric liquids are classified according to their Fire Point and Net Calorific Value, following the IEC 61039:2008 Standard "Classification of insulating liquids" [4]. Table 3 summarizes the classification.

K class liquids are recognized in the industry as "Less Flammable Liquids", which allows reduced separation distances between a transformer and its surroundings when it is installed indoor or outdoor. This is specifically mentioned in the IEC 61936 – 1, "Power installations exceeding 1 kV a.c. – Part 1: Common rules" [5] and FM Global Property Loss Prevention Data Sheets 5-4 [6]. As an example, the distances between a less flammable liquid insulated transformer with enhanced protection and an adjacent transformer or building can be reduced from 15.2 m in case of mineral oil down to 1.5 m in case of less flammable liquid in a transformer with enhanced protection, see table 3 in the IEC 61936-1 for more details [4].

Figure 8 shows a visual demonstration of the benefits of using a less flammable liquid in a transformer. Savings can be achieved on space, concrete, and construction times following the FM Global guidelines [6].

## Environmentally Friendly

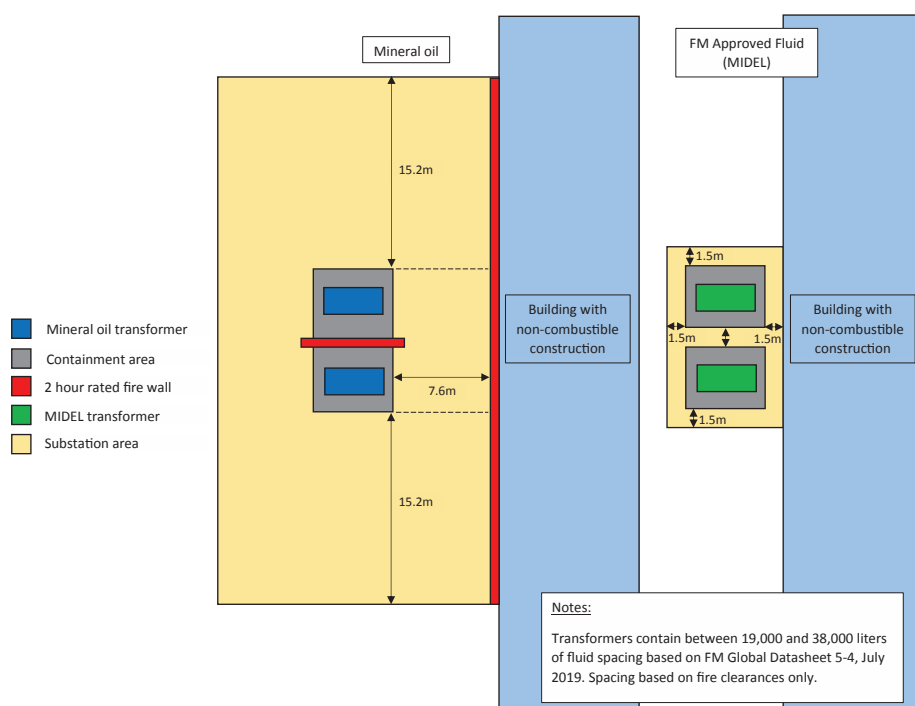
Ester liquids are recognized as environmentally friendly since they are known as "readily biodegradable". Biodegradation is the process by which organic substances breakdown adequately enough for enzymes in soil or water to process them back to hydrogen and carbon (i.e. they become absorbed by the environment.). The biodegradation of ester dielectric liquids has been externally assessed by accredited laboratories using a standard test method developed by the Organization for Economic Cooperation and Development (OECD), a worldwide standard-setting body. To be classified as readily biodegradable a substance must satisfy the following criteria:

The main reasons for adopting an ester as a transformer dielectric liquid include increased fire safety and better environmental protection. Additionally, esters have high moisture tolerance that can improve the life of the insulation system.

■ ■ ■



Figure 8. Example of installation separation distances according to FM Global guidelines [6]



According to test method OECD 301B (test conducted over a 28-day period), in order for a product to be considered “readily biodegradable”, a sample must achieve at least 60% degradation by day 28. Once a sample exceeds 10% biodegradation it must reach 60% within the next 10 days. For test materials that are not soluble in water, such as transformer liquids, measurements are taken of the oxygen consumed, or carbon dioxide produced, to determine the biodegradation percentage.

Figure 9 demonstrates that synthetic ester achieved 10% degradation by day 3, and by day 10 it achieved 61% degradation. On the 28th day, it reached 89% degradation, putting it comfortably in the “readily biodegradable” category. Similarly, soybean and canola based natural esters are superior in their biodegradation behavior; by day 10 they biodegrade to 85%.

Note that ester liquids will not biodegrade in a transformer. This is due to the fact that the conditions within the transformer are too hot and dry to sustain microbial life.

### Moisture Tolerance

Due to the chemical structure, esters are able to tolerate more moisture while retaining higher breakdown voltage in comparison to mineral oil. This is well indicated with the plots shown in Figure 10. This provides advantages in locations of high humidity and remote transformers that are costly to check and monitor for leaks on the distribution network and thus save money in the field and generate better Total Cost of Ownership.

Esters have higher moisture saturation levels due to the free oxygen in the ester linkage which can attract and retain water molecules. In the ageing mechanism of the transformer, moisture is produced during the degradation of the cellulose material. The moisture generated attacks the cellulose chains further, increasing the rate of degradation. Because ester liquids hold more moisture than mineral oil, less becomes available to attack the cellulose chains and thus reduce the rate of degradation. The slower aging rate of cellulose in ester liquids is well documented in aging tests [7].

### Application of Ester Liquids in Transformers

Natural ester and synthetic ester filled transformers have been used in distribution, power, and special transformers since the 1970s. As of today, the largest natural ester filled transformer is rated at 420 kV and the largest synthetic ester filled transformer is rated at 433 kV [8]. As these transformers are used more and more, it is important to understand what the strengths and limitations are of using the ester liquids based on application.

**Ester liquids are recognized as environmentally friendly because they are “readily biodegradable”. However, they will not biodegrade in a transformer since the conditions within the transformer are too hot and dry to sustain microbial life.**



Figure 9. Biodegradation results for synthetic ester and natural ester in reference to mineral oil.

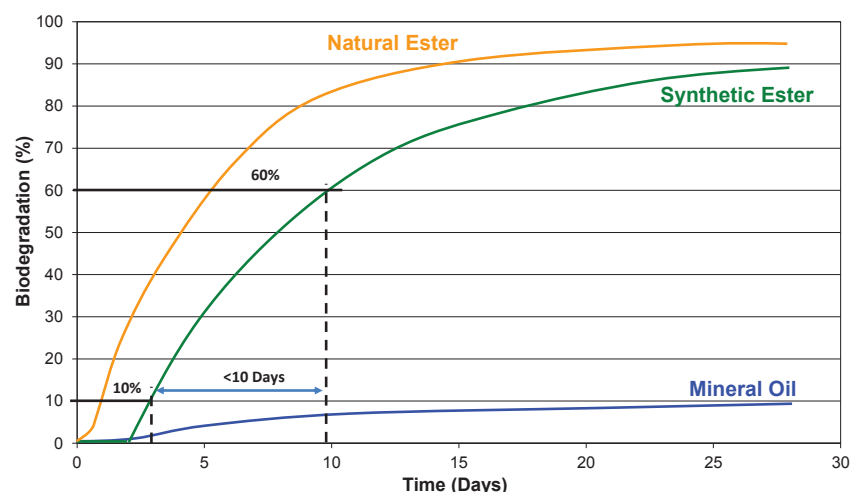
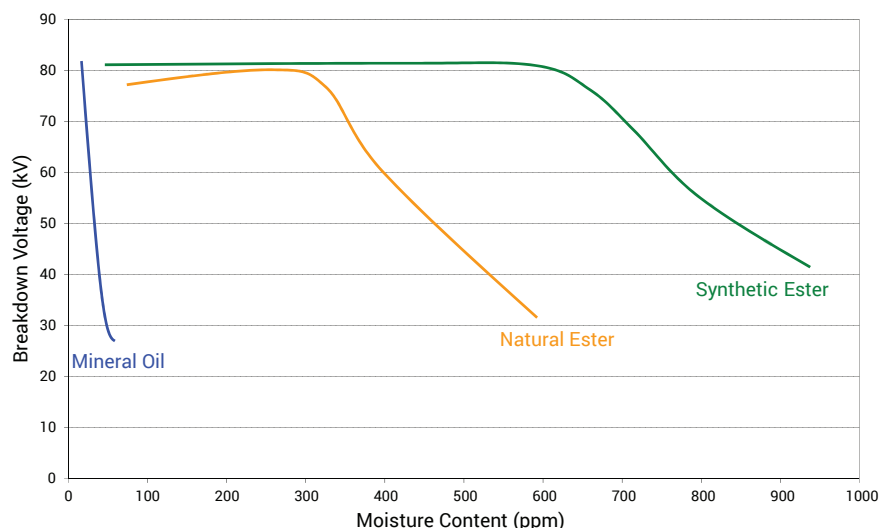


Figure 10. Breakdown voltage (kV) vs moisture content for different dielectric liquids. BDV is measured according to IEC 60156:2018 test method (2.5 mm gap) at 20°C.



### ▼ Breathing and non-breathing transformers

Natural esters are not recommended for use in breathing transformers. Natural ester liquids are prone to oxidation and can solidify over time if used in breathing transformers causing cooling and dielectric issues. Synthetic esters on the other hand are perfectly suited for use both in breathing and non-breathing transformers. There have been instances where breathing transformers have been retrofitted for use with natural ester liquids. However, the long-term maintenance requirements need to be taken into consideration when retrofitting a breathing transformer.

### ▼ Distribution transformer vs. power transformer

Natural esters are perfectly suited for sealed distribution transformers. They are a cost-effective solution that makes the transformers safer, provide an increased overload capability and are environmentally safer. Synthetic esters also work well for distribution transformers but are even more suited for power transformers than natural ester liquids. This is because they have the same benefits as natural ester in improving fire safety, environmental performance and insulation system life, but they can also be managed in a similar way to mineral oil. Because power transformers are more expensive, more attention is given to monitoring of the transformers to make sure that they operate under all circumstances. From a risk mitigation point of view, a synthetic ester can provide a better overall solution.

### ▼ Operating conditions

Transformers filled with ester liquids can work at a higher average winding rise (greater than 65°C rise). This is possible because ester liquids can operate at 90°C top liquid temperature rise compared to 65°C for mineral oil as per the IEEE C57.154 standard as the ageing rate of cellulose material in ester liquids is slower compared to mineral oil at similar

operating temperatures. One thing to be mindful about at the higher operating temperatures is that in the event of a leak, the oxidation rate of insulating liquids increases as well. This would have to be taken into consideration with natural ester liquids as they have higher oxidation rate compared to mineral oil or synthetic ester liquids. In the case studies below, the 400 kV Highbury substation transformer is an excellent example of an innovative project that was designed to operate at high temperatures and the heat generated was captured and repurposed for another application.

- ▼ For cold temperature applications, transformer location, transformer loading profile, and what mechanical operations the transformer is subject to, need to be considered. Due to the difference from seed to seed for natural ester liquids, the proper selection needs to be made based on the conditions listed above. Soybean natural ester has a pour point of -18°C while canola natural ester has a pour point of -31°C. Synthetic esters, due to the pour point being below -50°C, are well suited in all cold temperature applications. If a transformer is operating at full load, the pour point of the transformer is not important, however if the transformer is lightly loaded, the cooling characteristics of the transformer would have to be analyzed to determine the effect on the hotspots of the transformer. The selection of a tap changer needs to be analyzed as a heater would have to be installed if the operating temperatures are below -18°C for synthetic ester and -10°C for natural ester liquids [9].

### ▼ Retrofilling of transformers

The use of ester liquids in retrofill applications is growing due to insurance, fire safety concerns and construction costs to existing transformer sites. Both natural and synthetic ester liquids have proven to be effective in retrofilling of existing transformers to 69 kV. Above this size, retrofilling

decisions become design dependant due to the dielectric property differences between esters and mineral oils. Selection of using natural ester versus synthetic ester is dependent on the end users' needs and capability of handling maintenance requirements of the transformer with respect to oxidation.



**K class liquids are recognized in the industry as “Less Flammable Liquids”, which allows reduced separation distances between a transformer and its surroundings when it is installed indoor or outdoor (further reducing costs).**

■ ■ ■

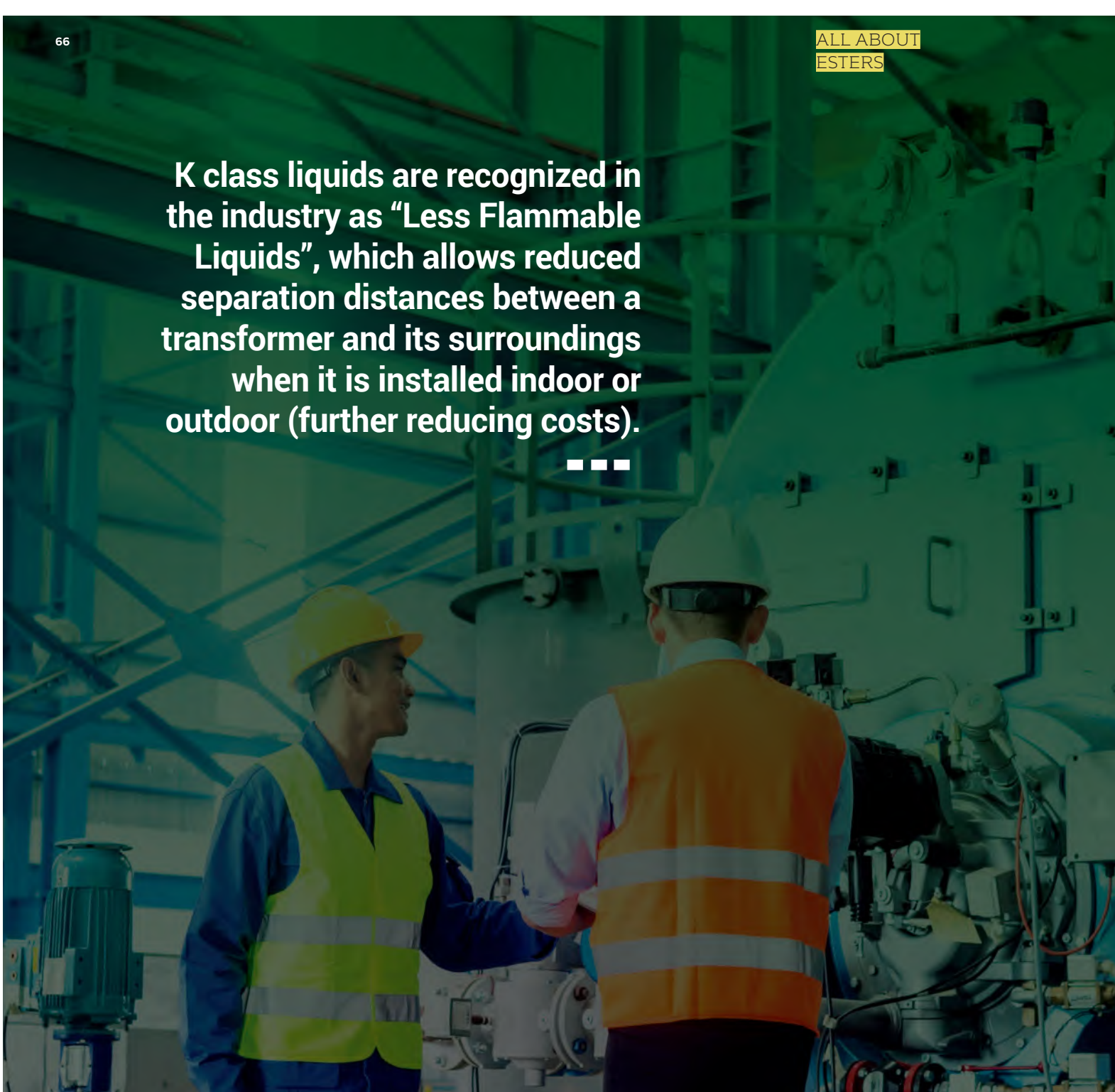


*Figure 11. 28 MVA, 138 kV transformer filled with MIDELE n1204 for a mine in Canada.  
(Photo courtesy of Northern Transformer)*



*Figure 12. 400 kV transformers with MIDELE 7131 synthetic ester for Highbury substation in London, U.K.  
(Photo courtesy of Siemens Transformers)*



## Case Studies and Future Projects

The use of ester based dielectric liquids in transformer applications extend to over 40 years; starting when the synthetic ester MIDEL 7131 was first invented and used to retrofill existing furnace transformers to replace PCB oil at British Steel, in the U.K.

Some recent case studies include:

### First canola natural ester filled transformer in North America rated at 138 kV

A 28 MVA transformer filled with canola natural ester was commissioned for use in a mine in Canada (Figure 11). The end user selected canola over soybean natural ester because the transformer was to be operational in ambient temperature below -25°C.

### Highbury Substation, London, U.K.

Three 400 kV power transformers, filled with synthetic ester, were used to reduce the substation footprint in a highly confined location in London, U.K. The original substation had three old transformers filled with mineral oil and once the substation was due for refurbishment, the utility was restricted in using a limited space for the substation. Synthetic ester allowed reduced clearances between the transformers and adjacent objects/building and this saved considerable amounts on estate, concrete, and construction times without compromising on fire safety or on environmental protection. On top of achieving the primary objectives from synthetic ester use, the utility desired to upgrade the project to extract the heat generated from the transformers from electric losses and heat a nearby school and residential building, in effect significantly reducing the carbon footprint of the substation. Figure 12 shows a picture of one of the transformers used in that substation enclosed with thermal jacket to

control heat dissipation from the transformer to water heat exchanger of the substation.

Some of the upcoming projects with ester filled transformers include:

- a) 400 kV natural and synthetic ester filled transformers in India
- b) 420 kV canola natural ester filled transformer in Germany
- c) Largest wind turbines rated at 12 MW will include transformers filled with synthetic ester
- d) Several 230 – 345 kV synthetic ester filled power transformers for utilities in North America
- e) 230 kV canola natural ester filled transformers in China
- f) Several mines worldwide are retrofilling mineral oil filled transformers and purchasing new transformers filled with natural and synthetic ester liquids. The esters are also being specified instead of silicone liquid for new transformers because ester filled transformers are cheaper to manufacture and operate, easy to source and provide the benefits of less flammability as silicone liquid.
- g) Larger use of natural and synthetic esters in indoor transformers, renewables, and industrial application
- h) Research in use of synthetic ester liquid in transformer rated at 500 kVA and up
- i) Research in use of synthetic esters in HVDC transformers

## Conclusion

From their initial use and through the decades, there have been no reported fires due to the use of ester liquids in transformer fleets. Ester liquids allow for innovations to take place in transformers to make them – fit in smaller footprint, have better return on investment, environmentally friendly and most of all SAFER. Regarding the types of natural or synthetic esters to use in transformers, an end user can make a selection and decision based on the requirements of the project as the various liquids offer different options in each application.

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**Environmental Product  
Declaration No. S-EP-00958  
on TAMINI Green Power  
Autotransformer  
250 MVA 400/135 kV**

This Environmental Product Declaration (EPD) is part of the International EPD System Programme according to the ISO 14025.

|                          |                                                                                             |
|--------------------------|---------------------------------------------------------------------------------------------|
| Programme:               | The International EPD® System<br><a href="http://www.environdec.com">www.environdec.com</a> |
| Programme operator:      | EPD International AB                                                                        |
| EPD Registration number: | S-EP-00958                                                                                  |
| Publication date:        | 09/12/2019                                                                                  |
| Validity:                | 5 years                                                                                     |
| Expiry date:             | 18/12/2024                                                                                  |
| Revision date:           | -                                                                                           |
| Version:                 | 1.0/2019                                                                                    |
| Geographic validity:     | Europe                                                                                      |



## Who We Are

Tamini is the leading globally established Italian company for the design and manufacture of industrial, power and special transformers.

Founded in 1916 in Milan, Tamini supplies its products to most important industrial sectors – steel, aluminum, mining, oil & gas, chemical and transportation – and the most advanced operators engaged in the generation, distribution and transmission of electrical energy.

In 2014, Tamini became part of Terna Group, the Italian Electricity Transmission Grid Operator, which maintained the business partnership of Tamini and TES – Transformer Electro Service, creating one of the most advanced and qualified players in the market of industrial high voltage transformers. With this business partnership, Tamini became a leading market player and is now even stronger to effectively cope with all future challenges.

Tamini operates six production plants in Italy and has branches in USA, North Africa and India. Approximately 80% of the company's turnover comes from exports, particularly to emerging countries.

With 100 years of experience, Tamini combines the quality of its products with the unmatched expertise of Made-in-Italy design and manufacture. More than 9,000 Tamini transformers have been manufactured and installed for customers in over 90 countries around the world.

A large share of our resources is devoted to the development of special transformers for any industrial application, such as furnace transformers, reactors, power transformers for industrial distribution and rectifier transformers.

In the power sector, Tamini has manufactured 400 kV transformers, auto-transformers and reactors for some of the main European utilities and works with the main players in the renewable energy market.

Tamini guarantees its customers high-quality technical assistance in each phase of the transformer life cycle thanks to the team of experienced specialists and a complete service portfolio.

For more information about the company, visit the official website: <http://www.tamini.it>.



## Our Mission

Tamini designs power transformers for application in the distribution, transmission and generation of electricity from both conventional and renewable sources. Our products are designed to provide custom solutions for specific customer needs, effectively responding to ongoing technological progress in electricity generation and transmission systems, meeting the increasing demand for the interconnection of different national networks.

In particular, Tamini Transformers S.r.l. production site in Legnano, Italy is dedicated to the production of large power transformers up to 550 kV and 700 MVA (up to 1800 MVA in the case of phase shifting transformers), their validation and placing on the market.

The materials, components and commercial products are purchased and transported to the production plant, where the components are assembled according to the specifications provided by the technical office. The transformers are assembled, closed and filled with an insulating liquid (such as mineral oil, natural or synthetic ester). The complete and ready to use equipment is then subject to specific tests in accordance with the required international reference standards.



## Tamini Green Transformer – EPD Certified

The green transformer is an innovative, environmentally sustainable and eco-efficient product, filled with natural ester instead of mineral oil. Committed to preserving the environment, the product provides benefits to health and environment, including:

- extended transformer life due to a longer life of the cellulose-based insulation;
- reduced risk of pollution (in case of spillage or loss) since natural ester is bio-degradable and less toxic thus reducing the risk of pollution during operation, installation and end of service life;
- greater safety (toxic and fire safety) as natural ester has a higher flash point – more than double that of mineral oil. This makes it possible to practically reduce the possibility of fire ignition to zero as a result of a fault;
- space saving – reduced impact on the construction site due to smaller distances between transformers, and because collection tank is no longer indispensable although still required by regulations in some countries;
- improved efficiency and environmental performance with the same nominal power.

In 2017, Tamini Trasformatori S.r.l. put the innovative 250 MVA autotransformer filled with natural ester on the national and international markets. This was the first green autotransformer of this high capacity on the market with the **Environmental Product Declaration (EPD)**.

The EPD Certification is a further step towards recognition of the primacy and qualities of innovation, efficiency and sustainability of this product.

To anticipate market demands, improve the environmental performance of the energy transformation process, offer significant environmental benefits and meet the major energy challenges of today and tomorrow (such as energy efficiency, market efficiency, grid reliability and environmental issues), eco-friendly energy-efficient solutions are also under development to advance the process of transformer production.

In particular, the aim is to improve product performance in three phases of the transformer life cycle:

- **Production:** reducing the consumption of natural resources;
- **Operation:** lower emissions, limitation of environmental risk, noise reduction, space saving, increased energy efficiency;
- **End of Life:** possibility to recycle the products or their components.

The product that was born out of this initiative is Tamini's "green transformer" – the 250 MVA autotransformer (ATR) immersed in natural ester fluid instead of mineral oil.



Table 1. Tamini 250 MVA autotransformer characteristics

|                 |                       |
|-----------------|-----------------------|
| Power           | 250 MVA               |
| Voltage         | 400/135 $\pm$ 5x2% kV |
| Frequency       | 50 Hz                 |
| Vector group    | YNa0                  |
| Type of cooling | KDAF                  |

## EPD Certification

This EPD was drafted in compliance with the **International EPD® System** General Programme Instruction of the International EPD® System, version 3.0 dated 2017-12-11, on the basis of PCR 2019:12 "LIQUID IMMERSED POWER TRANSFORMERS (>25 MVA)". The product category corresponds to a subset of UN CPC 46121 "Electrical Transformers".

EPD is a worldwide certification that was developed applying the standard UNI EN ISO 14025:2010, which defines Type III environmental declarations, a tool for communicating objective, comparable, verifiable and credible information on the environmental performance of products, processes and services. These performances must be based on the life cycle analysis, the methodology which is laid down in Standards UNI EN ISO 14040:2006 and UNI EN ISO 14044:2018.

## Life Cycle Assessment

The Life Cycle Assessment (LCA) is a cradle-to-grave study which looks at the impacts of all life cycle stages – from raw materials, through the components production, transport and assembly, to the use of the product for an average lifetime at a certain load with the necessary routine and non-routine maintenance, to dismantling and disposal of the transformer at the end of life.

The LCA study was based on:

1. The functional unit
2. Allocation method
3. System boundaries
4. Cut-off rules
5. Software, database, evaluation method

Table 2 outlines the impact categories and the related methods.

Table 2. outlines the impact categories and the related methods

| Method                                                    | Impact category                 | MU           |
|-----------------------------------------------------------|---------------------------------|--------------|
| Greenhouse gas protocol                                   | Fossil CO2 eq                   | kg CO2 eq    |
|                                                           | Biogenic CO2 eq                 | kg CO2 eq    |
|                                                           | CO2 eq from land transformation | kg CO2 eq    |
|                                                           | Total CO2 eq                    | kg CO2 eq    |
| CML-IA baseline V3.05 / EU25                              | Acidification                   | kg PO4 eq    |
|                                                           | Eutrophication                  | kg CO2 eq    |
|                                                           | Photochemical oxidation         | kg C2H4 eq   |
|                                                           | Ozone layer depletion (ODP)     | kg CFC-11 eq |
| EPD (2018) V1.00                                          | Abiotic depletion, elements     | kg Sb eq     |
|                                                           | Abiotic depletion, fossil fuels | MJ           |
|                                                           | Water scarcity                  | m³ eq        |
| ILCD 2011 Midpoint+ V1.10 / ECJRC Global, equal weighting | Land use                        | kg C deficit |



## Life Cycle Stages

As the cradle-to-grave analysis, the study considers upstream, core and downstream stages. The upstream stage includes components supply – their production, manufacturing treatments and their transport to the assembly site.

The core phase includes the following processes: transformer assembly at the factory, consumption and waste at the assembly factory, tests during the assembly process and partial disassembly in order to be sent to the operation site.

The downstream phase includes distribution, the use phase and the end of life. Distribution process considers the transport of the transformer with its packaging to the site and its installation. The use phase consists of operation losses during the product average life, routine and non-routine maintenance. The end of life includes transformer dismantling and its subsequent disposal.



Figure 1. System boundaries

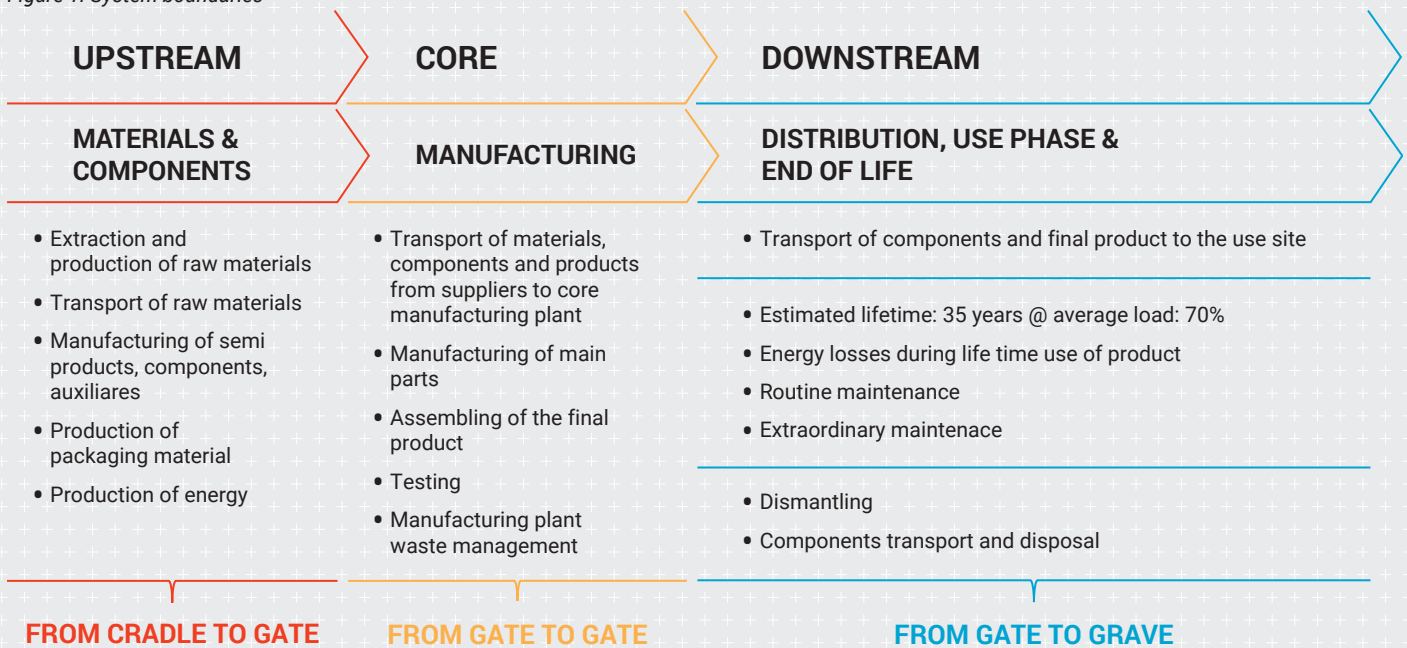
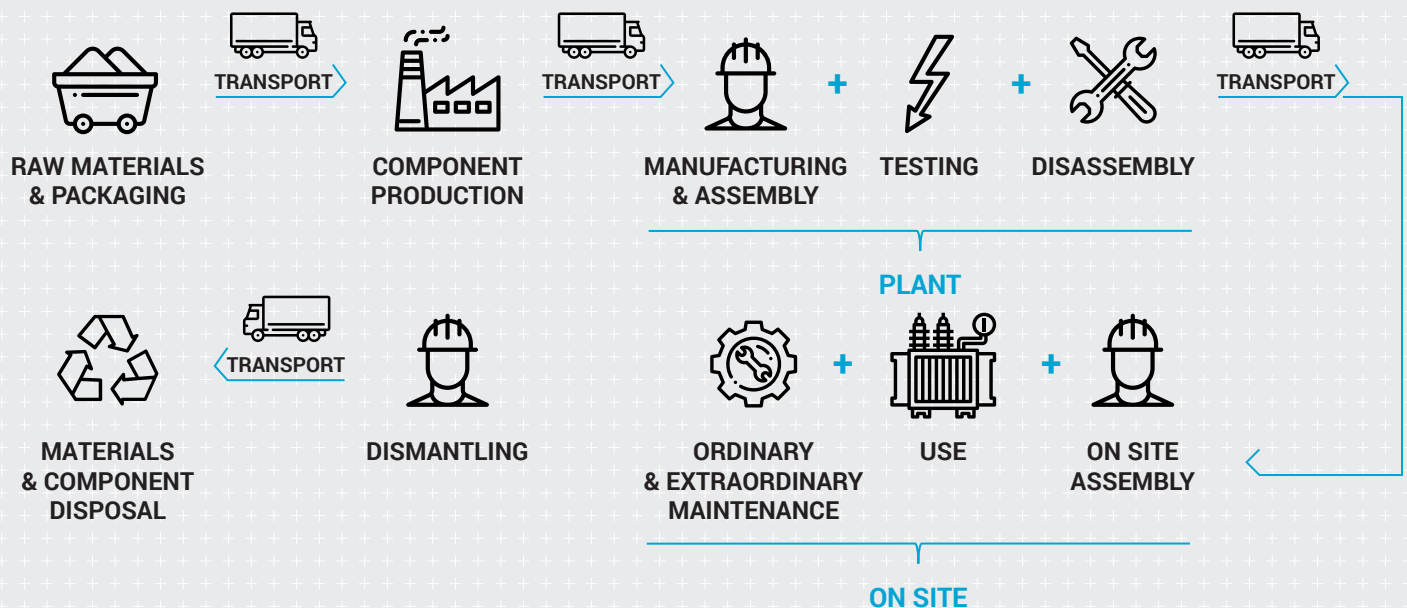


Figure 2. Product phases



## Environmental performances

Tables 3 and 4 outline the environmental impacts of the twelve shown categories. Overall, the core processes, which include activities carried out at the Legnano plant (ATR assembly, testing and partial disassembly before shipment), have a low influence on the overall impacts of the product.

Table 3. Results of the environmental impact analysis of a functional unit

| Impact category                    |                                 | MU                | Total    | Upstream          | Core             | Downstream        |
|------------------------------------|---------------------------------|-------------------|----------|-------------------|------------------|-------------------|
| Greenhouse Warning Potential (GWP) | Fossil CO2 eq                   | kg CO2 eq<br>%    | 5.03E+03 | 1.05E+02<br>2.1%  | 1.00E+01<br>0.2% | 4.92E+03<br>97.7% |
|                                    | Biogenic CO2 eq                 | kg CO2 eq<br>%    | 7.46E+02 | 5.94E+00<br>0.8%  | 8.38E-01<br>0.1% | 7.39E+02<br>99.1% |
|                                    | CO2 eq from land transformation | kg CO2 eq<br>%    | 3.57E+01 | 3.51E+01<br>98.2% | 1.51E-03<br>0.0% | 6.51E-01<br>1.8%  |
|                                    | Total CO2 eq                    | kg CO2 eq<br>%    | 5.49E+03 | 1.19E+02<br>2.2%  | 1.06E+01<br>0.2% | 5.36E+03<br>97.6% |
| Acidification                      |                                 | kg PO4 eq<br>%    | 3.79E+01 | 3.90E-01<br>1.0%  | 5.97E-02<br>0.2% | 3.75E+01<br>98.8% |
| Eutrophication                     |                                 | kg CO2 eq<br>%    | 9.91E+00 | 9.97E-01<br>4.0%  | 1.45E-02<br>0.1% | 9.50E+00<br>95.8% |
| Photochemical oxidation            |                                 | kg C2H4 eq<br>%   | 1.07E+00 | 5.72E-02<br>5.3%  | 1.89E-03<br>0.2% | 1.01E+00<br>94.5% |
| Ozone layer depletion (ODP)        |                                 | kg CFC-11 eq<br>% | 5.90E-04 | 5.49E-06<br>0.9%  | 1.27E-06<br>0.2% | 5.83E-04<br>98.9% |
| Abiotic depletion, elements        |                                 | kg Sb eq<br>%     | 3.33E-03 | 2.05E-03<br>61.5% | 5.37E-06<br>0.2% | 1.28E-03<br>38.3% |
| Abiotic depletion, fossil fuels    |                                 | MJ<br>%           | 6.07E+04 | 7.47E+02<br>1.2%  | 1.32E+02<br>0.2% | 5.99E+04<br>98.6% |
| Water scarcity                     |                                 | m³ eq<br>%        | 3.73E+03 | 1.65E+01<br>0.4%  | 4.29E+00<br>0.1% | 3.71E+03<br>99.4% |
| Land use                           |                                 | kg C deficit<br>% | 5.36E+03 | 7.63E+02<br>14.2% | 1.21E+01<br>0.2% | 4.58E+03<br>85.5% |

Table 4. Use phase impacts compared to total impacts, for each impact category

| Impact category                    |                                 | MU           | Total    | Use phase | % Use phase on Total impacts |
|------------------------------------|---------------------------------|--------------|----------|-----------|------------------------------|
| Greenhouse Warning Potential (GWP) | Fossil CO2 eq                   | kg CO2 eq    | 5.03E+03 | 4.92E+03  | 97.7%                        |
|                                    | Biogenic CO2 eq                 | kg CO2 eq    | 7.46E+02 | 7.37E+02  | 98.8%                        |
|                                    | CO2 eq from land transformation | kg CO2 eq    | 3.57E+01 | 6.48E-01  | 1.8%                         |
|                                    | Total CO2 eq                    | kg CO2 eq    | 5.49E+03 | 5.36E+03  | 97.6%                        |
| Acidification                      |                                 | kg PO4 eq    | 3.79E+01 | 3.75E+01  | 98.8%                        |
| Eutrophication                     |                                 | kg CO2 eq    | 9.91E+00 | 9.50E+00  | 95.8%                        |
| Photochemical oxidation            |                                 | kg C2H4 eq   | 1.07E+00 | 1.01E+00  | 94.5%                        |
| Ozone layer depletion (ODP)        |                                 | kg CFC-11 eq | 5.90E-04 | 5.83E-04  | 98.8%                        |
| Abiotic depletion, elements        |                                 | kg Sb eq     | 3.33E-03 | 1.27E-03  | 38.3%                        |
| Abiotic depletion, fossil fuels    |                                 | MJ           | 6.07E+04 | 5.99E+04  | 98.5%                        |
| Water scarcity                     |                                 | m³ eq        | 3.73E+03 | 3.71E+03  | 99.4%                        |
| Land use                           |                                 | kg C deficit | 5.36E+03 | 4.58E+03  | 85.4%                        |

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**Senior Manager** Laboratory and  
Diagnostic Services at SDMyers

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Interview with **Jason Dennison**

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What makes the SDMyers lab unique are the people. We have a group of people who have created this culture that they are very passionate about doing lab testing and they are very passionate about doing things the right way.

# Jason Dennison



## Alan Ross, our Editor in Chief spoke with Jason Dennison, Senior Manager of the SDMyers Laboratory and Diagnostic Services in Tallmadge, Ohio, where he oversees the largest transformer fluids testing lab in North America.

**Transformer Technology:** Jason, when you graduated from college with a degree in Chemical Engineering, did you ever think you would be doing what you are doing now?

**Jason Dennison:** I really never focused on the electrical world, even in the slightest, so coming out with that degree I wasn't really sure where I was going to end up, but the Chemical Engineering degree can open a lot of doors. I started in the rubber industry and got some exposure and training there as well as Project Management with several companies. It all has culminated into this role with SDMyers and this phenomenal lab environment that we have. It's an interesting blend of chemical engineering and industry knowledge and even the software and systems that underly everything. While it wasn't my career plan, it's been really interesting to see. The depth of my exposure to the electrical world was that I'd walk into a room and I'd flip the light switch on, and the lights came on.

**TT** The same is true for me with a background in Mechanical Engineering. What were some of your early challenges?

**JD** To come here and have an opportunity to try to understand what a transformer does, how is it built, how it works and what are the other assets in the substation that are around it; all of that was the biggest challenge. How does that all manifest itself? And how does that all work so that the lights do come on when you flip on the switch?

I had to marry that with learning about how to know whether a transformer is reliable or not. Additionally, we have this lab and this

diagnostics group who do all of this testing and then they would put together recommendations to present to customers in a way that they can make sense of it and take some action. I think those were my biggest challenges early on.

Through that whole process, you realize this is a really interesting industry. It's a very interesting engineering kind of problem to solve. How do we do this all well? It has proven to be very, very interesting and very satisfying. We talk with people who are very passionate and who care about transformers because that is what they do, but it is just one thing on a long list of things that they have to take care of.

**TT** So many professionals see those transformers behind a fence and see that they have been functioning that way for 50 years, so why should I care about it now?

**JD** It's something I never really thought about actively, but now it's just very satisfying and just a great industry with a lot of great folks in this industry who care.

**TT** You mentioned something about this incredible lab. I am familiar with SDMyers lab. What is it that makes it so unique?

**JD** Most labs are going to tell you a few of the same kinds of things: We follow applicable standards.



We do all this to get high quality analysis and results out. While I don't say that to minimize it but that is a bare minimum competency, I think. Some things do make the SDMyers lab unique and the first that comes to mind are the people. We have a group of people who have created this culture that they are very passionate about doing lab testing and they are very passionate about doing things the right way. That is one of the things that was so interesting for me to step into this area of the business.

As we look to continuously improve ourselves. It's very satisfying to be able to talk to people and say, "Here is what we'd like to do. Here's is a goal we'd like to accomplish," and then just watch them be active in that process because they care. They have also been a big help to me personally. There is so much knowledge in this team that makes it very satisfying.

**TT** Jason, I think I know the difference between diagnostics and analytics and then sometimes I think, isn't it just one thing? Tell me the difference between lab diagnostics and analytics.

**JD** The analysis is creating the test data itself. The diagnostics are looking at that data and saying this data suggests something about the condition or the health of an asset. When we look at that diagnostic process, let's say for example we want to run a Karl Fischer test for moisture content in a liquid. You could read the method, learn how to do it since it's a fairly simple test and you can easily say "there are 15 parts per million of water in this liquid" and call it a day. That's an analysis. You've got to do it right. There's some nuance to it, but you can do that pretty easily. What is difficult and what is complex is to describe how moisture behaves inside a transformer.

Since the solid installation is cellulose, therefore polar, and the water molecules are also polar, they like to be in the cellulose instead of in the oil. Asking "where is the water?" which is dependent on time and dependent on temperature is the question. At the end of the day, what does that mean with respect to the reliability of the transformer? So the analysis portion in some ways is a little bit easier because there are published methods you use, you can buy the instrument, you can run the test, but that wisdom, that knowledge of what does it mean, I think, is the differentiator.

I had to marry the learning about transformers with learning about how to know whether a transformer is reliable or not. And then once you've done the testing, how do you put together recommendations to present to customers in a way that they can make sense of it and take some action? Those were my biggest challenges early on.



**TT** I know that you were instrumental in working with On Now Digital, developing a dashboard that SDMyers uses to take all of this data and now you're working with a whole different world. You are not in a lab environment anymore, you are in a completely different world working with a group of software developers, right. Talk about that experience of sharing the diagnostics through software development and come out with something that I can actually use as an owner of a transformer.

**JD** Developing the Dashboard was a pretty wild experience for me. That was early in my time at SDMyers and the genesis of it learning about transformers, learning about the lab, learning about diagnostics and, critically, learning about the systems underneath that are all serving the purpose of "How do we present a result?" was tremendous for me. What we do has a lot of complexity to it because when you look at a batch of results and you say, "This transformer can be tested again in 12 months," or, is there something imminent, something urgent that we believe you should look at based on the analysis? So how we get that information to somebody who needs it, for decision making, is what the Dashboard is all about.

We have to give it to them in a way that allows them to separate the wheat from the chaff so that they know "this is where I have to spend my time." Because for everybody, time is at a premium. Thinking back to that, it was very interesting because it was a very big learning experience for me.

And in software, sometimes it's difficult, because you want to do everything. The answer in software development is almost always yes. It is all dependent on how much time and money do you have, right? What I think was big for us though is we had a purpose that we still have today and that we want to take things that are pretty complicated and make them simple. How we do that was a good vision that we kept throughout that whole project. It was a very gratifying experience because the feedback that we got after going through that whole process was just tremendously positive.

**TT** People want to know that what they do matters. When the person who runs the Karl Fischer realizes that somebody is looking at that data, making a decision, keeping a plant running, keeping a city running, and keeping the lights on; that has to be pretty gratifying. That's a unique skill set for you to have both the software and lab connection.

I want to switch gears a little bit now. There is a whole world that is changing in terms of the fluids that you are testing. Talk to me about what you've seen with this, with the whole synthetic and natural esters world; what challenges does that give you as a lab to be able to process them?

**JD** We have historically seen mineral oils and their variants as the primary liquid that we test. They are a big part of the testing that we do. They are well known diagnostically and so we know they are a good dielectric liquid. We also see some silicones and those are usually special applications where you require the high flammability (performance). We see them in indoor transformers where mineral oils will have a flashpoint in the neighborhood of 140°C; silicones have a flashpoint over 300°C. Silicone is also more expensive.

We do see the growth of esters as a general category and as you've mentioned, on a year over year basis. We see both natural and synthetic esters. There are some subtle differences between them.

We've developed a Dashboard to help us take all of the data and present it in the right way to those who need it for decision making.



TT Give me a general rate of growth, is it growing 10% a year or 1%?

JD Over the last 10 years or so it has been 2-3% a year. So, what we see is a little bit less in mineral oil and a little bit less silicone. There is a trade-off, but the esters as a general statement, without getting into the particulars, have very excellent flammability and they have the other benefit that they are made from "green" materials and that they are more environmentally friendly.

It's a lot like a vegetable oil in some ways. And I think the other thing is they generally will have a better viscosity at high temperature, which makes them better at cooling. So, I think over time, especially in those kinds of specialized applications, we do see esters growing.

TT Again, switching gears for a bit, tell me about the effort it took to get ISO certified. Every test has to be ISO certified, correct? Talk a little bit about the challenges of bringing that about in your lab.

JD Yes, the ISO effort for us has been exciting, which is a word I would never have thought I would use.

TT It's not a word that I thought you would use either. Exciting! I thought you were going to say it has been a major chore.

JD It was that too. For us it's fundamentally a continuous improvement effort. We don't have people beating down our doors saying, "you shall be compliant". It is that we are looking at ourselves and sit across the table from people and say, "how are we going to do this better?" How do we make ourselves better all for the purpose of making sure that we can safely and accurately do what we do? It has been a challenge for sure. With over 50 years of experience, this is the fun part of our culture. Sometimes it also meant that we had 50 years of baggage as we try to navigate how do we do the right thing and how do we do things better. ISO 17025 is the standard for labs, and I am proud of my team and of those who came along side and helped that happen. I think it brought all of us together even more.

Since we have gone through that it can be looked at in two parts. One is the overall quality management system, which asks, "do we have all the processes in the business process to do a good job?" The second part is, you mentioned is that each test area gets its own basic qualification and certification for ISO. And so that has been a big initiative for us that I think has been really successful as it's just continued to improve the quality of the work that we do.

It is exhaustive because we go through our own internal quarterly audits and we go through annual audits with a third-party certification. They are basically making sure we do what we say we do, that we are meeting our commitments. That is one way we look internally in the lab and allow iron to sharpen iron. It aligns with this idea of reliability that we talk so much about externally, with customers. There is this element of reliability that requires doing the right things repeatably, so it has been a very large effort. Most critically, it has been supported from the very top of the organization and for an initiative this large, I think that's crucial. It has been very well supported and very well received. I think it's done nothing but improve what we do.

TT I know too that an effort like that helps create even more passion in the people that are part of making it happen.

Jason, I know you are a man of many talents and that you have had a great deal of other transformer related experiences we haven't talked about here. Thank you for sharing your lab experience with our readers.



Today our lab is ISO certified. ISO 17025 is the standard for labs, and I am proud of my team and of those who came along side and helped that happen.

# Best Practices for Online Oil Maintenance in Transformer Assets

by **Steve W. Leath**

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**Steve W. Leath** is a graduate of Purdue University with a Bachelor of Science Degree in Mechanical Engineering Technology. He is licensed as a Professional Engineer in the states of Ohio and Indiana. Steve has over three decades of experience in the US electric utility industry serving in technical advisory roles in support of the condition assessment and maintenance of generation, transmission, and substation assets. Prior to joining Filmax, his recent roles and responsibilities were to advise and define asset management programs for power transformers and load tap changers for one of the largest electric utilities in the US. Steve has written and presented technical papers on equipment condition assessment protocols and asset management directives at conferences including ABB Power World, ASNT, and the International Conference of Doble Clients. He is a member of the American Society of Mechanical Engineers (ASME) and the Institute of Electrical and Electronics Engineers (IEEE). Steve is an avid cyclist, hiker/backpacker, and photographer.

**Adopting the more limited maintenance strategies is accompanied by accepting more risk of unplanned equipment outages and premature failures; consequently, it is critical to mitigate as many of these risks as possible.**

## Economic Environment Affecting Utility Maintenance

Today's energy utility industry is experiencing a high-water mark in terms of pressure to reduce Operating and Expense (O&M) expenditures. This pressure extends to the maintenance of generation, transmission, and distribution assets, and the trend shows no sign of waning. The direct result of this financial environment is that utility corporations of all sizes are becoming increasingly creative in reducing O&M spending. Maintenance intervals are being extended and, in some cases, assets are no longer maintained and are therefore classified as "run-to-failure." Assets that may be considered as "run-to-failure" include power transformers below a designated kVA rating and single-phase voltage regulators.

Adopting these more limited maintenance strategies is accompanied by accepting more risk of unplanned equipment outages and premature failures; consequently, it is critical to mitigate as many of these risks as possible. Many utilities accomplish this by making capital investments in online condition monitoring equipment and online filtration of insulating oil, among other approaches. This discussion will focus on continuous online filtration strategies for transformer assets.

## History of Oil Filtration for Substation Assets

Online oil filtration has been recognized as a best practice in the industry for nearly three decades, beginning with the filtration of insulating oil in load tap changers during the early 1990s. This then expanded to voltage regulators and oil circuit breakers, all with the objective of eliminating harmful carbon

particulate produced during the normal “arcing in oil” functionality of these assets. One large US utility conducted a 20-year study (1995-2015) on load tap changer (LTC) maintenance expenditures and authenticated a 72% reduction in maintenance costs per asset over the 20-year period. This was accomplished by requiring

a comprehensive filtration strategy and adopting a condition-triggered maintenance program. Today, increasing numbers of utilities are adopting online filtration programs for power transformers and vacuum LTCs in order to obtain and maintain acceptable moisture levels in the insulating oil.



## Filtration Basics

Oil filtration in general is performed in the interest of removing contaminants. The contamination typically of most concern in insulating oil is particulate, free water, and dissolved water. It is also possible to improve the chemical properties of oil, such as acidity content, by using appropriate filter media. Filtration and conditioning can be performed either offline while the equipment is out of service, or continuously online while the equipment is in service. This discussion will focus on continuous online filtration applications. To understand filtration capabilities, it is necessary to understand the types of filtration media. There are many media types and this discussion will cover only those most relevant to the utility industry. They are as follows:

### Depth Wound Cellulose Media:

This media utilizes a specifically designed paper as the means of removing contamination. These filter elements contain thousands of square feet of cellulose which makes them extremely effective at removing particulate and free water. These filters can also remove a nominal amount of dissolved water. You can envision this filter media as a very high-tech paper towel made from coffee filters. This element is the ideal method for any device that breaks electrical current in oil, such as LTCs.

### Molecular Sieve Media:

This media utilizes a molecular sieve material which is extremely effective at removing dissolved water. It contains microscopic pores ideally sized for capturing water molecules suspended in oil. This is the ideal filter type for removing dissolved water from insulating oil and is the filter of choice for dehydration of transformers. The oil is easily dehydrated to a level that will then remove water from the cellulose insulation, which is critical to the longevity of the asset.

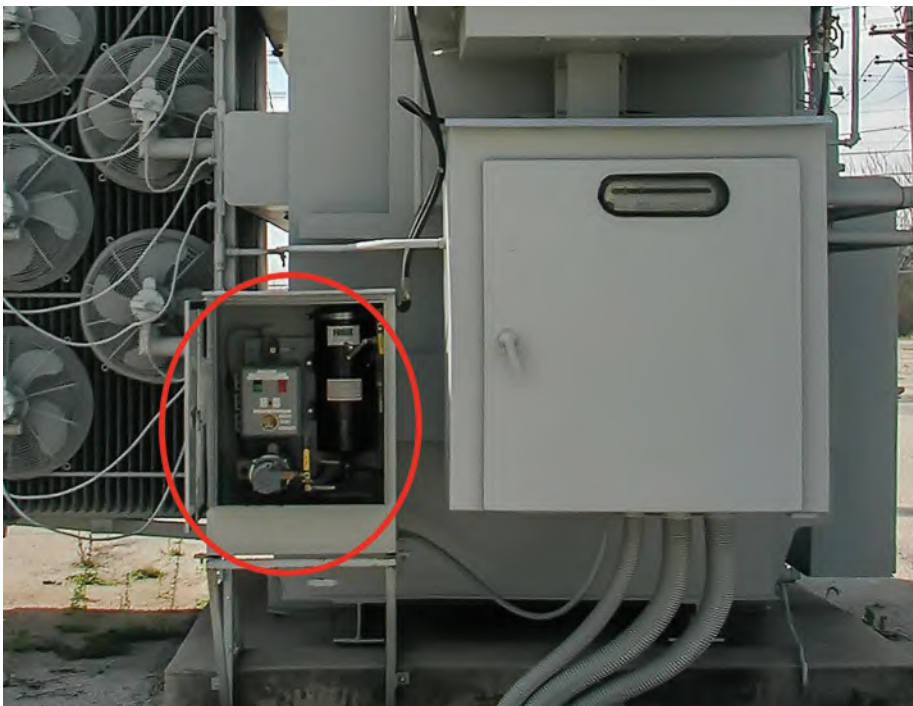
### Pleated Hybrid Media:

This media utilizes a pleated cellulose barrier for particulate and a polymer for water removal. The cellulose barrier contains only a fraction of the surface area of a depth wound filter but can remove particulate, and the polymer is very effective at free water and dissolved water removal. This filter type performs well with higher flow rates, the initial removal of water, and applications where multiple contamination types are present.

### Online Filtration of Load Tap Changer Oil

As mentioned earlier, there is a long history of utilizing online filtration for load tap changers (LTCs), and this practice has proven to significantly reduce required maintenance and consequent associated O&M resources. Oil filtration in LTCs can eliminate time-based maintenance and extend the frequency of oil sampling. Since LTCs are an integral component to many transformers, this is a major element of the transformer maintenance discussion.

Many modern LTCs utilize vacuum technology to interrupt electrical load current during the switching sequence. Bypass switches are necessary to accomplish the required routing of the electrical current through the vacuum interrupters;





these switches are very sensitive to oil conditions where the dielectric strength is compromised. The most likely scenario adversely effecting oil dielectric strength is dissolved water accumulation in the oil. When the oil dielectric strength becomes degraded, abnormal arc intensity across the bypass switches can occur which may result in dissolved gas generation not typical in a vacuum LTC. For this reason, in addition to maintaining proper insulating capacity in general, managing dissolved water content should be considered an important maintenance strategy. Maintaining very low moisture-in-oil content (less than 5 PPM) can easily be accomplished with online filtration and molecular sieve filter media.

While vacuum interrupting technology is common in the modern transformer LTC world, there are still tens of thousands of LTCs in service that interrupt the switching current in the insulating oil media. There are scores of these "arcing-in-oil" designs and all of them benefit from continuous online filtration. When the electric current is interrupted and the subsequent arc is extinguished in the oil environment, byproducts of this process appear. These include generation of dissolved gases and the production of carbon particulate which then becomes suspended in the oil. These particles compromise the dielectric strength of the oil like dissolved water, but also contaminate the switch contacts in the LTC switching components.

As these switch contacts become contaminated, film development on the contact surfaces causes an increase in the electrical resistance across the switches. This increased resistance creates excessive heating in the contacts which accelerates until there is formation of coke (burnt carbon) on the switches. This causes extreme dissolved gas levels in the LTC oil and, if not addressed with proper maintenance, the intense resistance and heating can burn the switching contacts open, resulting in a catastrophic event. This can all be mitigated with online filtration of the oil using depth wound cellulose filter media.



The following case study illustrates the benefits of carbon management in an arcing-in-oil LTCs.

#### Case Study Background

The study involved two transformers identical in design and both equipped with McGraw 550B load tap changers. The transformers were operated in parallel and each LTC performed over 20,000 switching operations annually. For the purposes of the study, each transformer was removed from service and the LTCs were thoroughly serviced. After the inspection and service, each LTC was retro-filled with new oil. On Bank No. 1, a filtration system was installed on the LTC and equipped with a Depth Wound Cellulose filter media. The LTC on Bank No. 2 was without filtration. The transformers were placed in service for six months and then again removed from service to be inspected. Bank No. 1 LTC (filtered) had performed 12,434 operations since the service, and Bank No. 2 LTC (non-filtered) had performed 12,289 operations. The inspection findings were summarized as follows:

- Bank No. 1 LTC (filtered): The oil was clear and bright and the lab analysis indicated that the fluid qualities were still at new oil specifications. There was also a reduction in acid level which was positive in terms of oxidation potential. The switch contacts were free of filming and carbon accumulation (Figure 1).
- Bank No. 2 LTC (unfiltered): The oil was nearly black from carbon accumulation. The lab analysis indicated an increase of acid level, indication the early stages of oxidation. The contacts had significant filming (Figure 2).

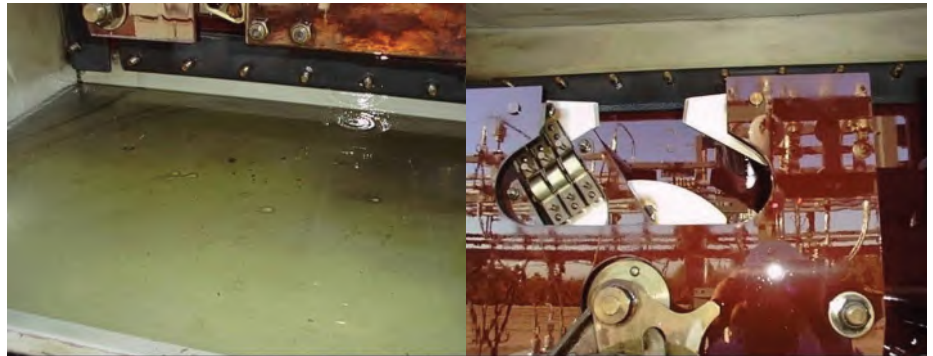


Figure 1. Bank No. 1 LTC (filtered) after 12,434 operations

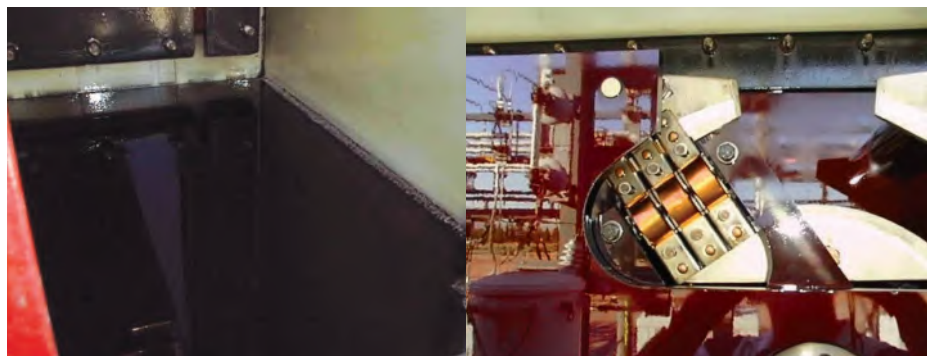


Figure 2. Bank No. 2 LTC (unfiltered) after 12,289 operations

**Moisture concentrations will achieve equilibrium over time.**  
**By dehydrating the transformer oil, it will also effectively dehydrate the cellulose insulation in concert.**  
**Both aspects are key to maximizing the transformer life.**



## Online Filtration of Transformer Main Tank Oil

A primary consideration regarding the life expectancy of a transformer is the proper maintenance of water content in both insulation systems, namely the oil insulation in the main tank and the cellulose winding insulation. Elevated water content has adverse effects on both insulation systems, and it is important to understand the implications. IEEE offers specific guidelines on the water content in both insulation systems.

Regarding oil insulation, the primary measures of water content are concentration in parts per million (ppm), and relative saturation as a percentage (%) of the amount of water in the oil compared to the amount of water it can hold at a given temperature. For example, oil at 40°C will hold about 120 ppm of water. If the actual water content is 12 ppm, the relative saturation is 10%. Maintaining acceptable dielectric strength is the critical concern, and the dielectric strength of the oil is more proportional to the relative saturation than the concentration. Therefore, relative saturation is the ideal measure in understanding the dielectric strength of transformer insulating oil. IEEE provides limits on maximum saturation for oil filled equipment based on primary voltage class. For transformers, the limits are as follows:

- Up to and including 69 kV – Not to exceed 15%
- Above 69 kV and less than 230 kV – Not to exceed 8%
- 230 kV or greater – Not to exceed 5%

It is important to note that reaching saturation levels of 5% or less are generally achievable with continuous filtration using molecular sieve filter media. Some considerations include oil volume and leakage rate of the transformer.

Regarding cellulose insulation in a transformer, the key measure is percent moisture by dry weight. Accelerated aging on the insulation system is a primary concern with elevated moisture in cellulose insulation. Moisture by dry weight in cellulose is generally determined by the relative saturation of the oil. Water concentrations in both systems will become equalized over time and temperature conditions. Water content in the cellulose decreases both the electrical and mechanical strength of the insulation, and in severe cases can cause catastrophic failure due to bubble evolution in the transformer insulation. IEEE also provides guidelines for acceptable moisture by dry weight and these are correlated with the oil relative saturation limits defined above.

The key point is that moisture concentrations will achieve equilibrium over time. By dehydrating the transformer oil, it will also effectively dehydrate the cellulose insulation in concert. Both aspects are key to maximizing the transformer asset life.

The following case study illustrates the benefits of moisture management in power transformers.

## Case Study Background

This case study involved a 300 MVA autotransformer with a primary voltage of 345 kV and a secondary voltage of 138 kV. An online filtration system was installed and molecular sieve filter media was utilized. The transformer contained an oil volume of approximately 18,000 gallons and the initial oil conditions were 61 ppm and 39% relative saturation based on the incorporated moisture in oil sensor included with the system. This represented approximately a 4% moisture by dry weight in the cellulose insulation. In a one-week timeframe, the water in oil content was reduced to 10 ppm and 10% relative saturation. Over the next six months with continued filtration and filter changes, the water content of 5% relative saturation in oil was achieved. It is important to note that this saturation needs to be maintained over time to effectively dehydrate the cellulose.

## Conclusion

It is critical to mitigate the risks associated with reduced maintenance programs driven by the current economic environment of the power utility industry. Online filtration offers a legitimate opportunity to alleviate some of these risks and migrate to a maintenance strategy that is more intelligent and condition-driven, rather than purely extending maintenance intervals.

# Transformer Oil Corrosive Sulfur Problem and Solutions

by **Frank May**

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Transformer operation should be evaluated from three viewpoints: social, economic and environmental. First, transformers must be reliable to provide uninterrupted electrical power to clients. Second, transformer operation should not involve unforeseen expenses. Third, the transformer must run for as long as possible without generating waste products that require special disposal. One of the problems impacting all three of the above is corrosive sulfur and its compounds in insulation oil. As the name implies, it causes premature wear and corrosion and it can make the oil unusable.



The sulfur problem is not as cut and dried as that, however, since some sulfur compounds are known to have a positive effect on transformer oil performance, such as methyl phenyl sulfide and  $\alpha$ -naphthyl thiophane, which improve the oxidation stability of the insulation fluid. It is also known that non-corrosive substances may become such at elevated temperatures.

## The sources of sulfur in transformers

Transformer oil includes complex mixtures of hydrocarbons of various origins, sulfur compounds, a small amount of oxygen and nitrogen compounds, and trace metal organic substances. As far as sulfur is concerned, these compounds can enter the oil both in production

and during use in high voltage equipment. Sulfur compounds are part of any fossil oil type, in varying quantity. The amount may vary from tenths of a percent to as much as 20% by weight [1].

Fractional distillation causes much of the sulfur compounds to concentrate in the oil fractions and residual products.

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**One of the problems impacting transformer operation is corrosive sulfur and its compounds in insulation oil. Corrosive sulfur causes premature wear and corrosion and it can make the oil unusable.**

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**Frank May** is a field service engineer at GlobeCore (Oldenburg, Germany). He has more than 30 years of practical experience in testing, commissioning and maintenance of industrial equipment. Mr. May is currently researching practical and probable corrective solutions of electrical insulation oil purification and regeneration for the purposes of transformer reliability improvement and service life extension. Previously, Frank worked for Fluidex Engineering, a company based in South Africa which was the forerunner of Fullers Earth reactivation process, and for GE Energy. He completed his mechanical technical training in the UK in the 1970s while also having a very good military career over the same period.

The following are the main classes of sulfur compounds in oil:

- mercaptans (RSH), where R is a radical of the corresponding paraffinic hydrocarbon with straight or branching chain, or a cyclic hydrocarbon radical (aromatic or naphthenic);
- sulfides (R-S-R1), where R and R1 are radicals of the corresponding hydrocarbons;
- disulfides (R-S-S-R1);
- thiophenes, compounds based on pentatomic ring with a sulfur atom.

Sulfur can be present in seals (rubber gaskets) used in transformers [2].

Manufacturers of sealing materials have recently been undertaking much effort to remove sulfur at the stage of material solidifying, but occasionally the amount of sulfur in gaskets is still high.

Sulfur can also be contained in glue used in the making of transformer cores and in copper [3]. Only one case of sulfur compounds from such glue

causing serious corrosion problems in a transformer has been registered so far. The content of sulfur in copper is usually low and does not cause any serious problems.

Another possible way for the sulfur to get into the transformer is the human factor. This includes using hoses which have been used before to pump another oil product with increased sulfur content, or hoses made from high sulfur content materials.



it is possible to completely remove this contaminant [9].

The ability of some metals to absorb dibenzyl disulphide has also been researched with the objective of making special filters to reduce the concentration of sulfur in transformer oil. One article [10] states that zircon can reduce the concentration of DBDS in transformer oil from 48 ppm to 9 ppm. The objective of this work is to find a simple, efficient and environmentally friendly process of dibenzyl disulfide removal from insulation oil. We believe it can be achieved with sorbents alone, without other chemicals.

### Researching the abilities of sorbents to remove DBDS from insulation oils

Several samples of transformer oil with sulfur and DBDS content of 11.6 ppm and 88 ppm, respectively, were prepared for the test. The samples were processed in a special laboratory vacuum machine, which consists of a regeneration pod, a vacuum chamber, a vacuum pump, and a vacuum meter to control the pressure in the vacuum chamber. The regeneration pod is equipped with an electric heater and a temperature sensor.

The regeneration pod is filled with adsorbent. The vacuum pump creates vacuum in the vacuum chamber. The regeneration pod is filled with oil, then the heater is engaged to increase oil temperature to 65°C. Then, vacuum pulls the oil through the adsorbent and into the vacuum chamber. Regenerated oil is drained from the chamber through a valve.



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**Corrosive sulfur can react with the silver surfaces of switch contacts, forming silver sulfide, which is accumulated on the contacts and enters transformer oil during OLTC operation. It can cause serious OLTC damage and lead to transformer winding failures.**

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**It seems viable to use a mix of multiple adsorbents for sulfur removal, each component being especially efficient for specific type of sulfurous substances. This means a synthesis of sulfur removal and regeneration technologies, as adsorbents remove not only sulfurous compounds, but also the contaminants resulting from oil aging.**

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The sorbents used were Fuller's earth and a special mineral clay. Elemental sulfur and DBDS content were measured in compliance with IEC 62597-1 ed.1 (2012-08) and IEC TR 62697-3 (2018). The results are listed in Table 1.

The information in the table shows that using the special clay mineral to process oil (150 ml to 150 g ratio of oil to adsorbent) removed DBDS completely. The amount of elemental sulfur in the oil remained unchanged.



**Table 1.**  
*Elemental sulfur and DBDS content in transformer oil samples before and after processing*

| Sample | Purification process                                        | DBDS, ppm    | Elemental sulfur (S <sub>8</sub> ), ppm |
|--------|-------------------------------------------------------------|--------------|-----------------------------------------|
| 1      | Original untreated oil                                      | 88.0         | 11.6                                    |
| 2      | 1.2 liters of oil per 100 g of Fuller's earth (four passes) | 17.8         | 11.6                                    |
| 3      | 200 ml of oil per 50 g of special clay sorbent              | 3.9          | No measurement was made                 |
| 4      | 200 ml of oil per 150 g of the special mineral clay         | Not detected | 11.6                                    |

## Conclusions

The research shows that using the special natural adsorbent makes it possible to completely remove dibenzyl disulfide from the oil in one pass from at least 88 ppm concentration, which is almost nine times of the maximum limit.

Fuller's earth made possible the reduction of DBDS content to 17.8 ppm (after four passes), but not its complete removal. It seems viable to use a mix of multiple adsorbents for sulfur removal,

each component. Our experience in development and construction of oil regeneration equipment allows us to design desulfurization equipment which can run on energized transformers, eliminating the long downtime often required for oil processing. Besides, the suggested technology is more environmentally friendly, as it does not involve chemicals, while the performance of saturated adsorbent can be restored in the process of reactivation directly in the regeneration machine.

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**There are several methods of protecting the transformer against corrosive sulfur and its compounds, including passivation, oil change and adsorption purification.**

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# Moisture in New and In-Service Transformers

by **Mel Wright**

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**Melvin (Mel) Wright** holds BSc degrees in Chemistry and Forensic Science. Mel is a current and past member of IEEE Power and Energy Society and ASTM committee D27 (Electrical Insulating Liquids and Gases). He has 40+ years as an analytical chemist, laboratory manager, consultant and educator on transformer fluids, fault identifications and condition assessment. Mel designed, built, and equipped the transformer fluid laboratory in the GE's Denver transformer service and repair facility (the Denver LIL) in 1980. He performed fluid testing, provided condition assessments, consulted engineers on possible fault conditions, and was involved in many forensic teardowns of transformers. He gained in-depth knowledge in using fluid testing and other data to compare IEEE, IEC and other international guides with actual faults found during testing and teardowns. Mel provides clients with training on fluid sampling, diagnostic interpretation of laboratory tests and on-line oil monitor data. Mel provides intensive training on interpreting DGA, Furans, Fluid Quality test data with transformer operating history in creating "Valid and Actionable Condition Assessments" of transformers.



This is not the typical water in oil discussion about limits, percent saturations and so on. The goal of this article is to give transformer maintenance personnel some points to ponder when dealing with both dissolved and free water in mineral oil transformers. I'll present some real-world experiences and discuss some visual aids or experiments to better understand the gross interactions of water in mineral oil dielectric fluids.

The vast majority of water issues that develop in in-service transformers are due to maintenance oversight or errors.



Never trust that "new oil" means that the fluid, as delivered, meets specifications. Test and verify!

Transformer manufacturers and the producers of mineral oil dielectric fluids go to great efforts to ensure their products are as free of water as possible. There are many tests performed to validate that both the transformer and the fluid meets ASTM, IEEE and IEC specifications. The question becomes: How does water get into transformers compromising both the fluid and the cellulose insulation? Let's review some real-world examples.

### **How does water get into new or in-service transformers?**

#### **Transport Tankers**

Over the years numerous transformers have been filled on-site with "new oil" with high levels of dissolved water and a few with free water. The source was found to be free water in the tanker compartments. Neither the supplier or the commissioning team were aware that the transporter's procedures for providing a "clean tanker" involved steam cleaning the interior tanker walls to removed gasoline, diesel fuel or other petroleum products previously transported.

The fluid from the supplier's tanks were tested and found to be excellent in quality, so the commissioning personnel did not question the quality of the oil delivered in the tanker. In addition, during this time period, several transformer service facilities' new oil storage tanks were contaminated. Not until the utility performed annual oil testing was the high dissolved water discovered. Widespread testing of transformers, storage tanks, pumping equipment and hoses finally led to the source of the water. Needless to say, remediation costs were very high. Examination of the tankers revealed that each of the three tanker compartments could have between 5 to 20 gallons of free water. Oils with this amount of water had been pumped into storage tanks and transformers with each shipment.

Lesson:

**NEVER TRUST oil in tankers.**



**While it is true that water does not magically appear in transformers, we also know that there are cases where water can increase from circumstances other than leaks.**

### Compromised Gaskets

Several N2 sealed transformers showed trending increases in dissolved water, and DGA tests showed excessive O2 content. Inspection of the transformer found the headspace pressure gauge reading zero psi, confirming that the N2 blank was compromised. Improperly installed and damaged gaskets on the top allowed rainwater and snow melt to enter the unit. Drops of free water were found hanging from under the top plate, while drops or puddles of water were found on some of the horizontal surfaces and at the bottom. The transformers were sent to a repair facility for untanking, testing of windings, oven drying of the core and coils and tank cleaning.

### Maintenance Errors

A common error in maintaining the oil preservation system of free breathing transformers, especially in hot, humid climates, is maintaining the silica gel media. Missing canisters, saturated silica gel media, especially in tropical areas is common. Some of these units have large amounts of free water in the bottom of the



tank, high dissolved water and highly oxidized oils. Fortunately, most are lightly loaded (less than 40%) and thus the risk of cellulose insulation failure from water and oxidation degradation is low. However, as nearby infrastructures expand and the loading increases, so does the failure rate. There are many other operator and servicing errors that can introduce water into transformers in addition to these common ones.

### Interactions of Water and Oil

Water is a unique fluid – a small molecule with interesting interactions due to its polar nature. Oil, on the other hand, is composed of hundreds of various, large, non-polar molecules which are devoid of attraction to each other or water. This hydrophobic (water hating) nature is one of many reasons that mineral oil dielectric is the universal fluid of choice. However, oil that is highly contaminated with polar oxidation products (identified by Fluid Quality tests results: very low IFT, high neutralization number and dark color) will be able to hold large amounts of dissolved water.

## Filtration to remove dissolved water

Some interesting issues have occurred as a result of filtering units high in dissolved water and having free water using cellulose filters. Here are a few examples of how corrective actions to remove water can go bad.

### Not Understanding Changes in Solubility with Fluid Temperature

The process of using cellulose cartridges to remove dissolved water from oils requires a basic understanding of the changing affinity of water between the fluid and the cellulose as the temperature of the fluid changes. Heating oil as it

a number of ways to achieve this before passing the oil through the cellulose filters. The cooler the oil, the lower the solubility of the water in oil, thus increasing absorption and removal by the filters. Think of it in this way, the ratio of absorption of water by the filters increases compared to the decreasing water holding capacity of cooler oil. Hot oil holds more water, which is perfect for extraction from the tank; however, hot oil can greatly reduce the exchange ratio of water from the oil into the filters. In some cases, if the filters are nearing saturation and the oil is hot, there can be a zero exchange or even a transfer of water from the filters to the oil.

**Awareness of the issues presented in this article, by conscientious samplers and maintenance personnel, are critical to maintaining transformers with acceptable levels of moisture, based on industry standards.**

### Rush to Complete Filtration

Time constraints at facilities commissioning large numbers of distribution class units, with filtration end points determined by the volume filtered, might force the operators to speed up the process, against good practices, by increasing the filtration flow rate. Increasing the flow rate will increase the head pressure on the filters. If the filters absorb a lot of water, the resistance increases reducing the flow rate and increases the pressure on the filters. In some cases, the point is reached where water saturated cellulose fibers start breaking off and enter the transformer. It is easy to determine when this happens by testing the oil for dielectric strength. The series of 5 or 10 tests (voltage flow) on the sample will vary drastically from high to low. High dielectric breakdown results for the oil, but when water saturated fiber floats between the electrodes, a low dielectric breakdown occurs. The labs will report "a failed standard deviation result" per ASTM D1816 as well as, in this case, each of the 5 or 10 test results, the mean. The maintenance personnel receiving a report like this should evaluate the results, consider resampling for confirmation. If similar results are obtained on the resample, review maintenance records to determine if the source can be determined or what actions to take.

*Cartridge style cellulose filter is used to remove dissolved water in oil*



goes into the transformer increases the solubility of water in the oil, facilitating the removal of water. However, pulling this oil directly from the tank and passing this hot oil directly through the filters can be harmful to the process. Hot oil may have a higher affinity for the water than the cellulose filters, depending on temperature, the dissolved water content of the oil and the amount of water that has built up in the filters. When possible, the oil should be allowed to cool, and there are

### End Point for Filtration

If testing for dissolved water is not available, a common practice is to end filtration based on filtering a set multiple volume of the main tank. For the transformer holding 1,000 gallons of oil the filtration process would stop after 5,000 gallons passed through the filters. If the units did not have free water in the bottom of the tank, this was found to be a reliable filtration end point with the oil meeting dissolved water limits.

### Transformers with Free Water

Free water will settle to the bottom of the tank. Sample/fill/drain valves are from 1 to 6 inches above the bottom of the tank. Thus, free water could be that depth and not be detected in a type fluid sample. If the visual examination of the previous oil sample did not identify the existence of free water, it is unlikely that anyone is aware of the large reservoir of water below the sample port. Filtration, even using hot vacuum, will not remove the majority of the water. The filtered oil above it will meet the desired specification for dissolve water content after filtering, but the reservoir of free water will still exist on the tank bottom. Due to the core and coil support structure at the bottom of the tank, pools of free water can be trapped in areas so that even if you could tilt the unit, you would not be able to pump out or solvate the water from the unit. If six months after filtration to remove water the oil shows increasing trends of high dissolved water, you can be fairly confident that the source is this undetected reservoir of free water below the sample/drain valve, trapped at the bottom of the tank.

Decision time for the transformer owner: leave it and filter to remove dissolved water every couple of years or address a permanent solution.

### Conclusions

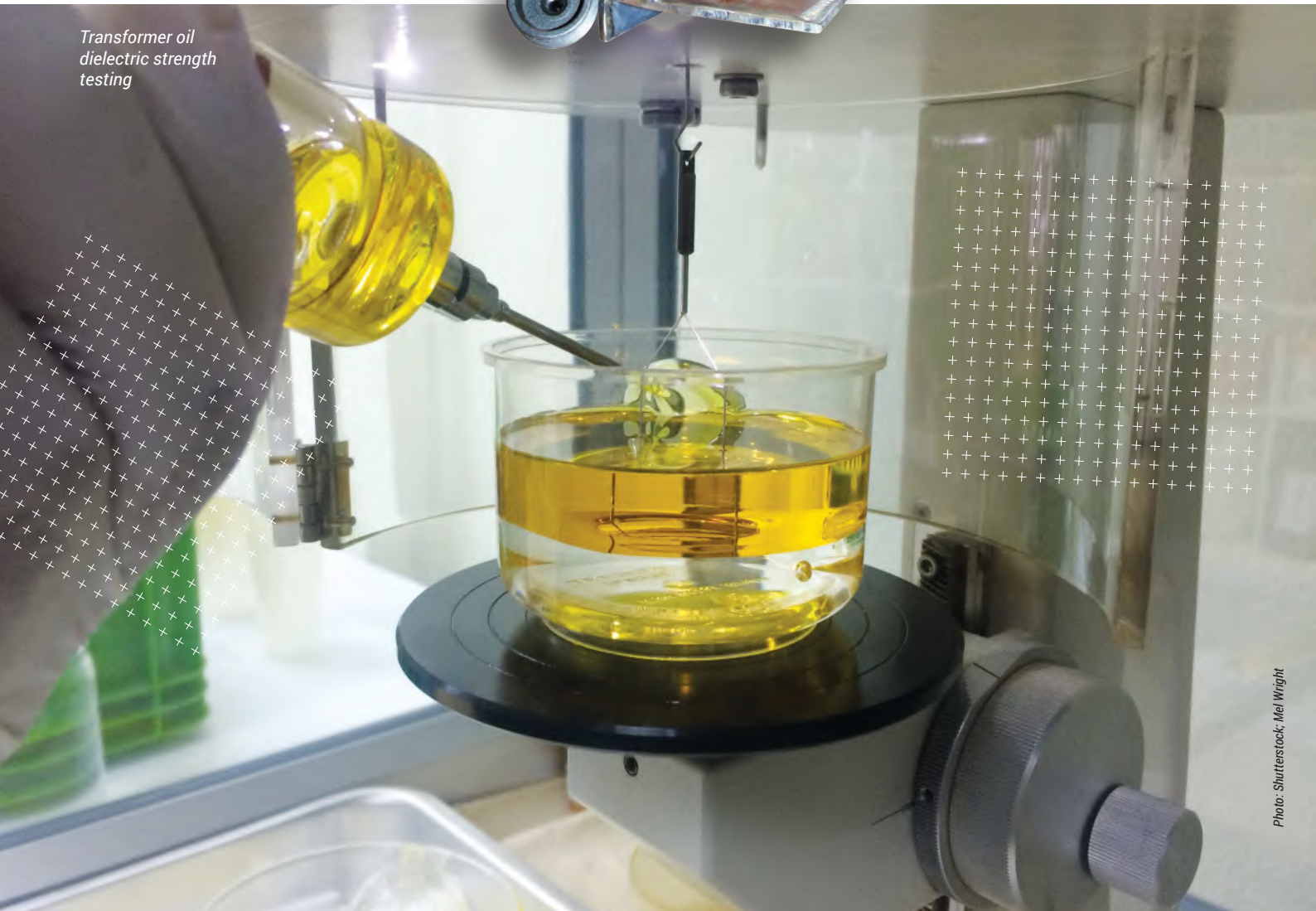
New transformers and fluids are as dry as technology allows when shipped. Water should never be an issue in operating transformers if commissioned correctly. Never trust that "new" means that the fluid, as delivered, meets specifications. Test and verify!

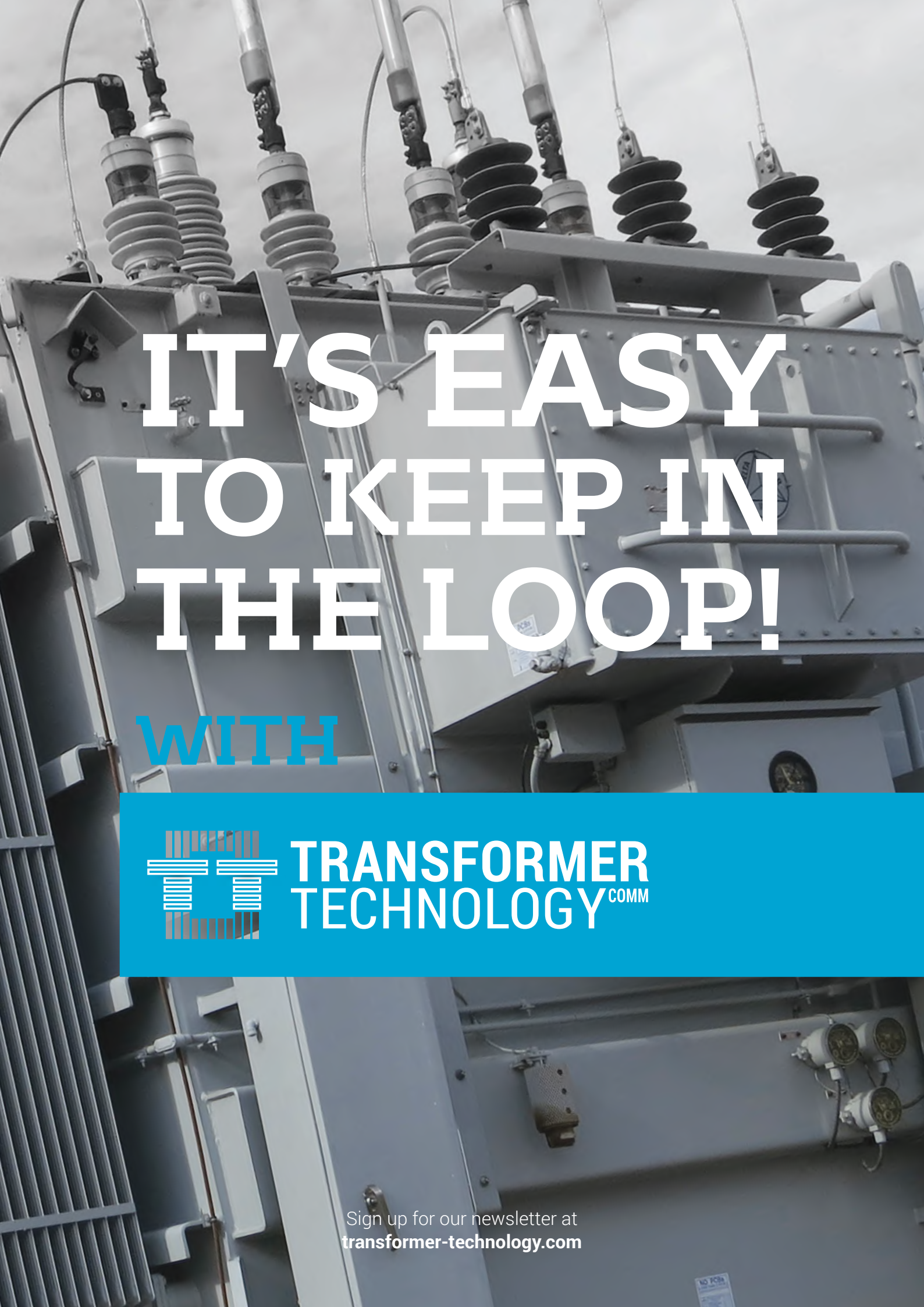
Always flush fluid pumps, hoses and filtration units with three times the total "dead" volume of the equipment. Capture the last flush fluid and test to validate that the quality of the oil did not change. Only after this pumping filling equipment validation test should you use it to fill or top off a transformer. The vast majority of water issues that develop in in-service transformers are due to maintenance oversight or errors. Examples are water ingress via damaged gaskets, compromised fluid preservation system, damaged conservator tanks, bladders, etc. While it is true that water does not magically appear in transformers, we also know that there are cases where water can increase from circumstances other than leaks. Awareness of the issues presented in this article, by conscientious samplers and maintenance personnel, are critical to maintaining transformers with acceptable levels of moisture, based on industry standards.



*Bottom valve from a small distribution transformer. Note height off the bottom.*

*Transformer oil dielectric strength testing*





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# Don't Just Go with the Flow: How Fluid Testing Helps Accomplish Operational Goals

by **Mark O'Brien**

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The high-level goal is to better understand the condition of  
seek and what you do with it can vary widely based on your



**Mark O'Brien** is the business manager at On Now Digital, a software solutions provider serving electrical utilities and fluid testing laboratories. Prior to this role, he gained 5+ years of experience in digital project management and quality control at the largest transformer fluid testing lab in North America where he was responsible for implementing ISO 17025:9001 and other improvements.

Quick, don't think, just answer – why are you testing your transformer fluid? Is it because your insurance requires annual testing? Or, because that's what your operation has always done? Perhaps you know it improves reliability... in some abstract way. If you can't answer the question succinctly and immediately, there's a good chance you're not getting the most out of your fluid testing protocol. **Routine testing can be time-consuming, cut into your maintenance budget and even pose potential safety issues, so identifying your operational goals and creating a fluid testing plan that supports them is essential.**

Photo: On Now Digital

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**What's necessary to understand is that establishing clear goals is the mandatory first step in determining proper fluid testing, analysis and maintenance protocols.**



*Figure 1. An Interfacial tension test, as part of a liquid screen, can help indicate the integrity of the liquid insulation*

You wouldn't let your doctor's office draw a blood sample if you went in for a flu shot, would you? And I'm guessing you wouldn't undergo an invasive scan if you suspected you might have poison ivy. Just like your doctor's focused health assessment, your fluid testing plan should be strategically tied to your business goals. The high-level goal is to better understand the condition of your equipment. However, the specific information you seek and what you do with it can vary widely based on your organizational goals.

### **What Can You Learn from Fluid Tests?**

Before you start pinpointing goals, it's important to understand that fluid testing ultimately gives you two types of information. The first relates to the degradation of your transformer's insulation, and many annual fluid tests, such as an interfacial tension test (Figure 1), track this. The second results from fault probing within your

unit. This is most valuable if done on an instantaneous basis, but when performed over time, these test types can also indicate your equipment's operating condition. In either case, the fluid is simply an indicator of the equipment's condition. Ensuring the liquid insulation is in good shape is important, but the solid insulation should be your true concern. When the solid insulation goes, end of life is imminent. With that understanding, let's look at how you can make fluid testing an active player in your maintenance plan.

#### **Goal Setting: Identify Your Operational Aims**

Don't think about fluid testing specifically when you assess goals; rather, consider the overall aims you're trying to accomplish. Common aims for industrial and commercial operations include:

- Decreasing capital expenditure
- Extending asset life/reliability
- Improving safety
- Limiting downtime

- Increasing efficiency
- Maintaining compliance

What's necessary to understand is that establishing clear goals is the mandatory first step in determining proper fluid testing, analysis and maintenance protocols. This is because your goal affects the test types and tools you'll need to be successful.

If, for example, your organization's only goal is compliance, your service provider will most likely limit the testing scope and depth of analytics and keep follow-up actions minimal. However, if your goal is improving reliability while limiting capital expenditure, your equipment will require more stringent testing. You may even consider using AI to uncover optimal operating conditions. It's a completely different task, using completely different tools. **There is a full spectrum of goals and outcomes. And depending on which you choose, your approach will vary wildly.**

**More data leads to more insight if you have the right tools. Just bear in mind that without the right tools, it often results in chaos and confusion.**



Figure 2. Laboratory technicians preparing testing samples for MaxLife analysis

### Process Definition:

#### What, When and How Often?

Once you've set your goals, you'll face a new set of questions, mainly: what pieces of equipment are you going to test, and how frequently are you going to test them? **A strategic fluid testing plan is rooted in implementing a result-oriented process.**

First, determine which pieces of equipment you receive the most value out of testing. You can accomplish this completing a basic criticality analysis. This enables you to start testing the most critical pieces of equipment first. Just note that in many cases, you may be required to test all pieces of equipment above a certain voltage per your insurance provider.

Next, think about testing frequency. Depending on your goals and criticality, you may test your equipment anywhere from annually to hourly. If you think back to our compliance example, annual testing might suffice; however, if your program

is based on maximizing the reliable life of an asset, you may consider a continuous monitoring approach.

The value of continuous monitoring is that you decrease the testing interval in order to catch issues well before they compound. Usually this approach looks for dissolved gas (DGA) and occasionally moisture as well. Continuous monitoring also helps you understand how to optimize your asset health on a day-to-day, hour-to-hour basis, directly tying your testing to loading conditions, ambient temperatures, production conditions and more. You simply don't have that granular level of detail with an annual sampling program.

However, even with real-time monitoring, you may want to perform a full suite of additional tests on an annual basis to determine how quickly the liquid insulation is aging and therefore how quickly the solid insulation is deteriorating. Tests such as moisture, liquid power and acid

all play major roles in the breakdown of the solid insulation, and an online dissolved gas monitor is going to have almost no insight into those realms (unless the condition quickly leads to an active event).

In practice, the more robust strategy involves placing a DGA monitor on a unit with readings every 12 or 24 hours, paired with an annual oil sample including a Liquid Screen, Karl Fischer Moisture Test, Liquid Power Factor, Dissolved Metals (or ICP), Oxidation Inhibitor, Furanic Compounds and Dissolved Gas Analysis. This increases the availability of data from a single data point annually to potentially 730 annually. More data leads to more insight if you have the right tools. Just bear in mind that without the right tools, it often results in chaos and confusion.

Once you identify your testing plan, you can select a laboratory. Be sure to identify which test methods they use – preferably the Standard ASTM test

**A presentation mechanism may not seem important, but in practice, whatever system you use can be the lynchpin for success.**

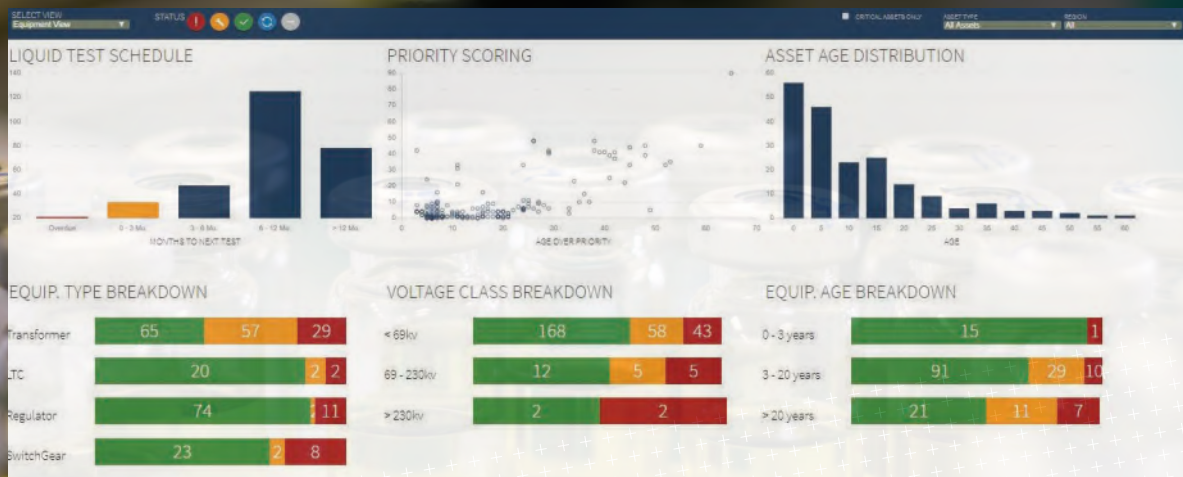


**Figure 3. Presentation dashboards offer color-coded data visualizations to make testing results understandable at-a-glance.**

methods as referenced by IEEE. It's also smart to evaluate the credentials and certifications of the laboratory. Most testing labs carry ISO 17025:9001 certifications that ensure a commitment to quality, objectivity and standardization.

### Analysis and Presentation:

#### Get the Right Information Quickly

You've completed fluid tests... now what? To keep in line with your goals, you must determine what to do with your test results. Are you going to use the IEEE limits, parameters recommended by your testing lab or your own limits on the data? You can also utilize machine learning algorithms that link test results to failure probability. All of these are viable options. Here are just a few distinctions:

**IEEE** – IEEE limits are tried and true guidelines relating to the safe operation of electrical assets. They group test values into four conditions ranking from normal operating

condition to serious active fault condition. More importantly, however, is understanding the framework behind these limits. IEEE limits are built around the serviceability of the liquid insulation. In laymen's terms that means, you are testing the oil to see if it can still perform its primary functions: dielectric insulation, heat transfer, diagnostic. When testing the liquid, IEEE is only concerned with whether the fluid can provide these three functions.

**Provider limits** – Your testing lab may implement its own limits to reflect the criteria it values. For example, a well-known North American transformer maintenance and testing provider, proliferated an approach called "MaxLife," which aims at maximizing the reliable life of the asset (Figure 2). The difference between this approach and IEEE is that Maxlife focuses more on the solid insulation than the liquid, with the thought process being that if the liquid insulation cannot perform its function, the solid insulation has

already been damaged irreversibly. This more holistic approach aims more conservatively at catching and eliminating threats.

**Custom limits** – If you have specific equipment purchased from the same manufacturer, you have been tracking test results for years, and you have experienced a few failures, you may be interested in setting custom limits. This requires that your team has done the analysis before and understands that certain gas profiles, acid levels or moisture percentages indicate unreliable equipment. You can use software to help customize those limits for your testing program to ensure that any time test results hit your pre-determined limits, you get a notification. This solution is best for teams who have engineering staff on hand and frequently use data analytics.

**Machine learning and AI** – Machine learning and AI algorithms can find anomalies or trends that lead to



Figure 4. Oil samples prepared for DGA test

unreliable assets. The trouble here is the most effective AI systems have neural networks that work best if trained to fixed outcomes using supervised learning – meaning, you need to have failure data available so the system can look back and see what conditions previously led to failure. That's how AI detects anomalies that a diagnostics technician may miss. The cool part here is that, depending what system you are using, the algorithms constantly learn as the system gathers more information. An AI system coupled with a real-time DGA gas monitor would be your most powerful early detection tool.

**Once the fluid analysis is complete, there are different methods for viewing your testing data.**

You can print paper reports and cross reference them with your analysis, but please note that this method is incredibly time-consuming and leaves a wide margin of error. Similarly, you can

use an Excel file provided by your testing company, which at least puts your data in a digital format. However, spreadsheets still require additional legwork in terms of viewing limits. You may want to consider a dashboard or software system that allows you to aggregate your data to your preferred method. These systems do the analysis automatically, and hopefully present you with a clear picture of which assets require your attention first.

A presentation mechanism may not seem important, but in practice, whatever system you use can be the lynchpin for success. How the information is presented to you has a direct impact to your ability to make wise decisions with the data. When considering a dashboard, look for options with visually presented data, clear priority lists, and easy-to-understand graphs (Figure 3). This allows you to quickly make decisions using your testing data to contribute to your predetermined goals.

**Game Plan:**

**Create Clear, Sustainable Action Items**

Whatever system you use should lead to some type of action step. This should be based upon two primary factors:

- The equipment's criticality within your system
- The condition of the asset

Ideally, you would have enough time and money to fix every issue every time. However, in the real world, you have to prioritize your maintenance staff and dollars to fix your most crucial piece of equipment first. Then prioritize the rest of equipment accordingly. These decisions should reflect both your previously performed criticality assessment and your top-level goals. Your engineering staff, or a qualified engineering contractor, can assist you in crafting your action plan.

Like every good action plan, you need a feedback loop. Implement a process whereby you follow up with your equipment through visual inspection or

verification of the work or testing done. Usually this can take place during your next testing cycle, but it remains a best practice to review any work done as quickly after completion as possible. This includes anything from inspecting the asset for proper reassembly to re-testing for improved results to rating the accuracy of the analysis system or contractors you employed in the process. Anything uncovered here should be included as an improvement in the next annual testing and maintenance cycle. **This system enables continuous refinement**

as organizational goals change.

**Sounds Great!  
But How Does It Really Work?**

Understanding and executing a plan are often two very different things. Here are a few practical examples that may help make this process achievable. These sample plans show the types of goals you can tie to fluid testing and the steps you should take to begin addressing them. Please note that these are examples only. In all cases, the appropriate test recommendations will vary by fluid and equipment type.

**Conclusion**

Whether you are a large organization or a small startup, a proper testing and maintenance plan is key to a reliable electric system. How you accomplish that is up to you, but there are tools available to simplify the process, streamline the data and execute a strategic vision in light of your organization's goals. The tools are numerous, and the challenge is large, but with the right direction, you can be the hero every organization needs.

**Example 1:**

**I aim to decrease capital expenditure for a better return on assets.**

**Goals:**

- Decrease capital expense
- Extend current asset life
- Eliminate unplanned downtime

**Plan:**

- Complete fluid testing bi-annually
- Conduct the following tests:
  - Liquid Screen (Acid, IFT, D1816, Color, Specific Gravity, Visual, Sediment)
  - Karl Fischer Moisture Titration
  - Liquid Power Factor
  - Oxidation Inhibitor Content
  - Dissolved Gas Analysis (Figure 4)
  - Dissolved Metals (ICP)
  - Furanic Compounds
  - PCB
- Use MaxLife parameters to evaluate the data
- Complete criticality assessment of equipment
- Pro-actively service five most critical maintenance items
- Acquire feedback from all involved parties

**Example 2:**

**I aim to increase the reliability of my equipment by optimizing my system.**

**Goals:**

- Increase condition visibility
- Utilize best in class tools
- Eliminate unplanned downtime

**Plan:**

- Complete criticality assessment of equipment
- Commission online dissolved gas monitors on all critical equipment, sampling in 8-hour intervals
- Limit fluid sampling to an annual basis
- Conduct the following tests:
  - Liquid Screen (Acid, IFT, D1816, Color, Specific Gravity, Visual, Sediment)
  - Karl Fischer Moisture Titration
  - Liquid Power Factor
  - Oxidation Inhibitor Content
  - Dissolved Gas Analysis
  - Dissolved Metals (ICP)
  - Furanic Compounds
  - PCB
- Use AI algorithms to analyze data for anomaly detection and pre-failure warning via a dashboard
- Pro-actively service five most critical maintenance items
- Acquire feedback from all involved parties

**Example 3:**

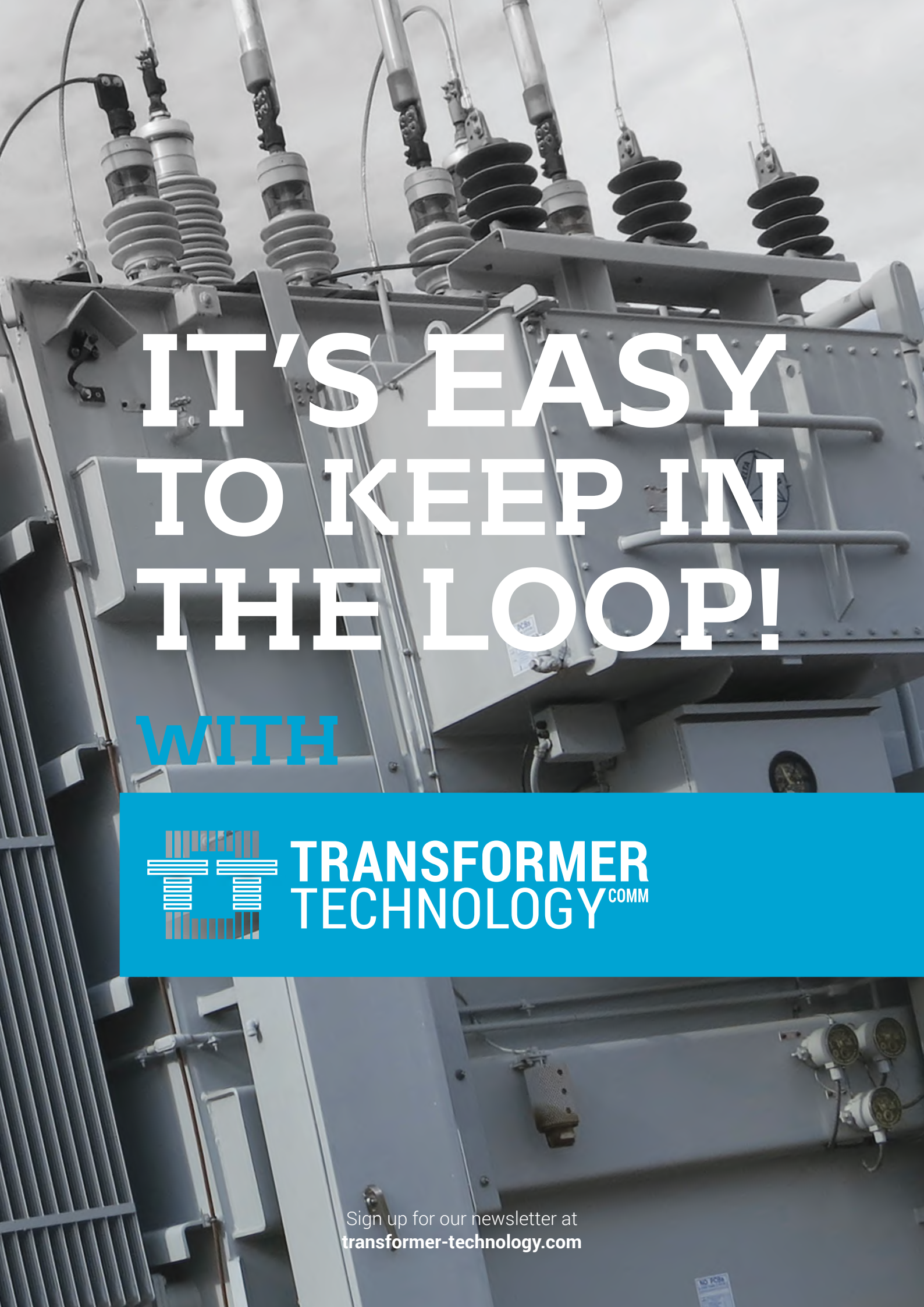
**I aim to stay compliant with my testing program.**

**Goals:**

- Remain in compliance
- Limit expense

**Plan:**

- Complete fluid testing annually
- Complete the following tests:
  - Liquid Screen (Acid, IFT, D1816, Color, Specific Gravity, Visual, Sediment)
  - Karl Fischer Moisture Titration
  - Liquid Power Factor
  - Dissolved Gas Analysis
- Use IEEE parameters to evaluate the data
- Acquire feedback from all involved parties



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