

# Green Insulating Fluids provide some Challenges.

By

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## Abstract.

As the world transitions to more sustainable technologies it is no different in the Electrical power industry and more specifically, in the Insulation fluids used in power transformers. This presents some challenges as this head-long rush to install more transformers, and Retro fill existing units has outstripped the usual developmental learning curve where new technologies mature by a process of trial and error.

## Introduction

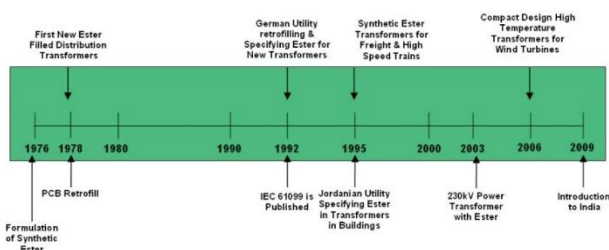
For the majority of transformer applications, mineral oil is an acceptable, cost-effective insulating fluid, and this situation is likely to continue well into the future. However, in applications where fire safety and protection of the environment are important considerations, transformers based on alternative fluids can be a more viable option. The use of alternative fluids in transformers is not new technology; these fluids have been used for many years, mainly in distribution transformers. Lately there has been a clear trend to use these fluids at ever increasing voltages and power ratings, and now there are many examples of these fluids being used in high voltage and high-power transformers.

This Article is designed to provide an overview of some advantages and limitations that exist for *synthetic and natural esters*. (*Green Insulation Fluids*)

## Synthetic esters.

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

**Figure 1 – Timeline of events in the development and application of synthetic ester dielectric fluids**



Unused synthetic esters are supplied in accordance with IEC 61099 and a maintenance guide is available as IEC 61203 Edition2.

## Natural esters.

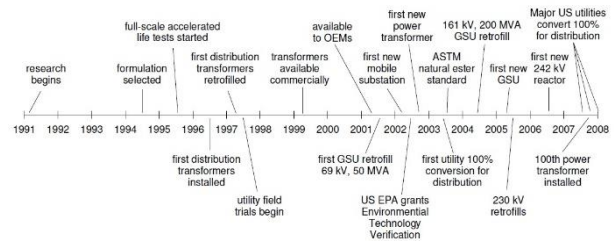
Since the beginning of the 1990's, because of increasing environmental concerns, companies started to develop vegetable oils as transformer fluids. These natural ester fluids have been commercially used since 1999.

Nowadays, natural esters are widely used in the distribution transformers.

Unused Natural esters are supplied in accordance with IEC 62770 Edition1, and a maintenance guide is available as IEC 62975 Edition1.

**Note: The use of natural esters is recommended only for equipment that is not open to the atmosphere, e.g. sealed transformers and reactors because these fluids are prone to rapid oxidation.**

**Figure 2-Timeline of events in the development and application of natural ester dielectric fluids**



## Physical and Chemical Differences between the Ester Fluids and Mineral Oil.

An overview of the different properties of insulating liquids is presented in Table.1

**Table1– Overview of properties.**

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

## Fire classification for transformer fluids

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

**Table 2 – Fire classification of fluids.**

Class	Fire Point °C	Class	Net Calorific Value MJ/kg
O	≤300	1	≥42
K	>300	2	≤42 and ≥ 32 MJ/kg
L	No Measurable Fire Point	3	<32

## Advantages and Disadvantages.

To date, there has been much research in both industry and academia to discover and document the properties and behaviour of these fluids and the items discussed below are an attempt to help readers understand the complexity around these fluids.

### Advantages:

1. Natural Esters are biodegradable and have a lower environmental impact compared to mineral oil. They are derived from renewable resources, making them more environmentally friendly.
2. Some synthetic esters are designed to be biodegradable, offering similar environmental benefits.
3. Natural Esters: Typically have higher fire points and are less flammable than mineral oil, contributing to improved fire safety.
4. Synthetic Esters: Depending on the specific type, synthetic esters can also offer improved fire safety characteristics.
5. Reduce the aging rate of the paper insulation.
6. Reduce the moisture content of the insulation paper, which improves the dielectric strength.
7. Eliminating the bubble formation due to sudden overload, which reduces the risk of partial discharge.
8. Eliminating the oil sludge formation, which improves the cooling efficiency.

### Disadvantages:

1. Higher initial cost of ester fluids compared to mineral oil( ± 5 Times the price).
2. Compatibility issues with some materials such as paints, gaskets, and seals.
3. Viscosity and pour point issues at low temperatures.
4. Additional filtration or drying equipment to maintain the quality of ester fluids.
5. The regeneration(reclaiming) avenues and possibilities of the regeneration of esters are still a challenge that needs to be explored.
6. Possible need for additional testing and monitoring to ensure the performance and safety of retro filled transformers.
7. The Diagnostic for Condition monitoring is not fully understood.

## Design Considerations.

The purpose of this section is to highlight the importance of viscosity in Transformer design along with other some other considerations.

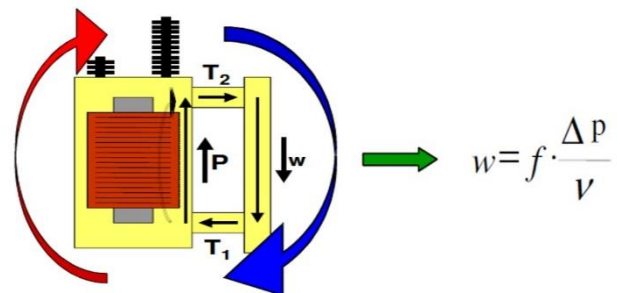
The specific transformer design (everything from gasketing systems to LTC's, bushings and the cooling system performance) must be evaluated to determine suitability for a synthetic or natural ester. This is just one of the many things that must be evaluated in the design review.

Viscosity differences may cause the transformer power delivery rating to change. Also, oil preservation systems may need modified to deal with the oxidation characteristics of the ester fluid. Other considerations include bushing, tap changer and other components & systems.

### Virtual Oil Wheel (Viscosity)

Calculation of the natural oil circulation speed on basis of the Laws of Bernoulli, Newton, Reynolds and Prandtl.

Figure 3- Virtual Oil Wheel



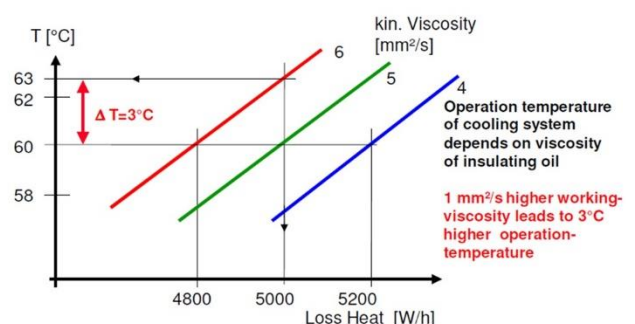
W= Oil flow speed  
f= Calculation factor  
n= Kin. viscosity at operation temperature  
p= force from buoyancy.

### Influence of Viscosity to Heat Dissipation.

Operation temperature of cooling system depends on viscosity of insulating oil, as Ester fluids have much higher viscosities this factor needs consideration in transformer design and the impact on retro filling.

**1 mm<sup>2</sup>/s higher working viscosity leads to 3°C higher operation temperature.**

Figure 4- Influence of Viscosity to Heat Dissipation



### Additive Question.

Many esters contain additive packages consisting of chemicals to reduce the pour point and aid in oxygen stability, and, in some cases, they have an antimicrobial agent or copper deactivators. This contrasts with mineral oil which has either no additives or merely oxidation inhibitors. It is not known if any adverse characteristics exist when esters are used in transformers over a long period. Ideally these additives require monitoring, as with any additive package there will be depletion over time.

Furthermore, for compliance with IEC Standards the supplier with mutual consent should declare the generic types of all additives, and their concentrations but unfortunately this far from the case.

### Dissolved Gas Analysis (DGA) as a diagnostic tool.

There is limited information published concerning the analysis of combustible gases in Ester fluid, as the DGA data for mineral oil filled transformers is far greater than Ester filled units.

IEEE and CIGRE have developed General Guidelines for the interpretation of gasses generated in Ester immersed transformers. It's recommended to establish base line data when a new transformer is first placed in service. A weekly or monthly DGA analysis is recommended when a Transformer is energised on load to establish the Gas Generation rates (Rates of Gas rise). Note: The interpretation of DGA is empirical in nature and the most widely used methods, for fluid insulated transformers are based on the identification of key gases and various Gas concentration ratios. Threshold concentrations for each of the key gases and for the total fault gas concentration must also be empirically established.

**Table 3 -Threshold value for transformers with no previous sample history (IEEE Std C5-155-2014).**

Ester Fluid Type	Number of Records		H <sub>2</sub>	CH <sub>4</sub>	C <sub>2</sub> H <sub>6</sub>	C <sub>2</sub> H <sub>4</sub>	C <sub>2</sub> H <sub>2</sub>	CO
			Soybean	4,378	90th Percentile 95% C.I.	112 (105-118)	20 (19-22)	232 (219-247)
High Oleic Sunflower	476	90th Percentile 95% C.I.	35 (24-45)	25 (18-30)	58 (36-84)	16 (12-23)	0 (0-0)	497 (314-583)
Synthetic	157	90th Percentile 95% C.I.	64 (52-82)	104 (49-135)	124 (105-362)	150 (79-215)	13 (0-33)	1344 (937-1526)

Since industry looks to companies for diagnostic solutions and technical knowledge, we devote time and resources to research and development, furthermore through our participation in IEC and CIGRE we have been able to adapt to the challenges in understanding the dynamics of Ester fluids for the benefit of our clients.  
(As per the following case study)

### Case Study 1: 132 kV Main Transformer located at a Data Centre.

The case of a 30 MVA, 132 kV transformer, with an OLTC. Manufactured in 2021 and designed for a Natural Ester insulating fluid.

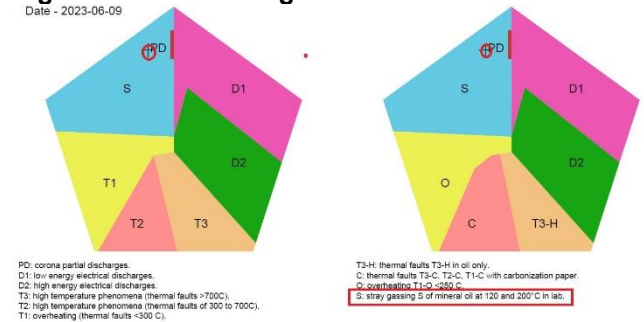
We were tasked with providing an expert 2<sup>nd</sup> opinion on the DGA results as the initial Testing Laboratory had diagnosed this transformer with a high temperature fault, with the recommendation to remove from service for Inspection and repairs. It was requested that a further sample be taken to confirm the results from the other Laboratory.

**Table 3-Summary of the DGA results**

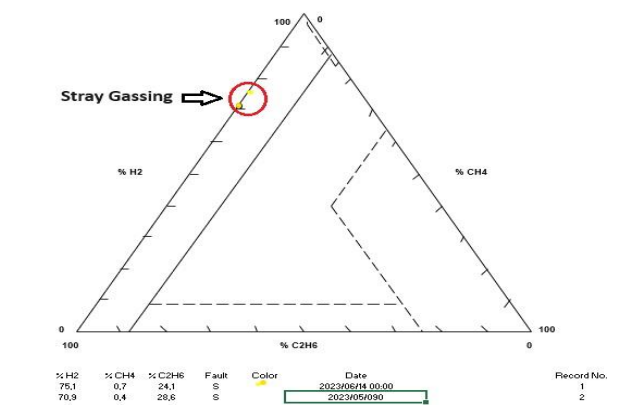
Date	H2	CH4	CO	CO2	C2H4	C2H6	C2H2
2023-06-14	1950	19	131	517	15	626	0
2023-05-09	1921	12	150	1033	25	775	0
2021-09-15	138	0	14	103	0	44	0

Although the DGA levels exceed the IEEE Std C57.155-2014 threshold values, the Gas rates of rise are not significant for a Natural Ester and the correctly applied Duval Triangles and Pentagons showed Stray gassing(No fault condition).

**Figure 5-Duval Pentagon.**



**Figure 6-Duval Triangle 6**



**Figure 7-Oilwatch Report-DGA(IEEE-adapted)**

INTERNAL OPERATION (DGA)	UNITS	RATES OF GAS RISE RESULT	CONCENTRATION RESULT	IEEE C57.115-2014 98TH PERCENTILE
Hydrogen	µl/l (ppm)	341	1950	78 to 482
Oxygen	µl/l (ppm)	N/A	425	N/A
Nitrogen	µl/l (ppm)	N/A	24766	N/A
Methane	µl/l (ppm)	82	19	40 to 210
Carbon Monoxide	µl/l (ppm)	0	131	894 to 2093
Carbon Dioxide	µl/l (ppm)	0	517	
Ethylene	µl/l (ppm)	0	15	43 to 54
Ethane	µl/l (ppm)	0	626	147 to 230
Acetylene	µl/l (ppm)	0	0	1 to 14

## Retro Filling

Before deciding to retrofit a transformer, it is crucial to conduct a thorough analysis, considering factors such as cost, environmental impact, safety, and compatibility with existing equipment. Consulting with transformer manufacturers and experts in the field is advisable to ensure a successful and effective retrofit.

Based on experience of manufacturer and operator the following concerns regarding dielectric behavior, thermal design, material compatibility and ester approved components should be discussed prior to the use of ester liquid in a transformer application.

Draining and flushing cannot remove all the dielectric liquid from a transformer, particularly from insulating paper.

The cellulose (paper) insulation can hold as much as 10% of the total volume of the nameplate Litres.

Over time the leach back of mineral oil could lower the fire point to less than specification.

A design review for the specific transformer should be conducted by someone competent that can determine the impact of replacing mineral oil with an ester fluid.

**Note-This requires a holistic approach not limited to Fire safety and environmental issue.**

### Case Study 2: 11 kV Plant Transformer located at Mine.

The case of a 630 KVA transformer (Category C). Manufactured in 2005 and Retro filled with a Natural Ester insulating fluid, approximately one year prior to a Routine oil test.

### Figure 8-Oilwatch Report: Fluid condition.

TRANSFORMER OIL ANALYSIS	UNITS	RESULTS	NATUR. ESTER Cat. C
Moisture *	ppm	337	200 to 400 (FAIR)
Moisture @20°C	ppm	N/A	
Total Acid Number *	mgKOH/g	0.37	>0.50 (POOR)
Breakdown Voltage (Dielectric Strength)	kV	58	>42 (GOOD)
Oil Colour		2.5 (Yellow)	-
Appearance		Clear	-
PCB	ppm	0	50 (MAX)
TAN Ratio *		N/A	<0.1 (GOOD)
Reactivity *		N/A	>10 (GOOD)
Interfacial Tension *	mN/m	N/A	-
Convulsive Sulphur		-	-

The oil had deteriorated (Oxidised) within a year to a state that replacement was required.

### Case Studies following Retro Filling.

Table 4-Provides a summary of results following Retro Filling of Transformers: Category C

Case Study	No1	No2	No 3	No 4	IEC 62975 Ed 1 Natural Esters	IEC 61203 Ed 2 Synthetic Esters
Fluid Type	Ester-NS*	Ester-NS*	Ester-NS*	Ester-NS*		
Water content (mg/kg)	1929	Free water	1037	6993	Poor >400	Poor >400
Breakdown voltage (kV)	20	8	23	29	Poor < 30	Poor < 30
Acidity mg KOH/g oil	2.57	Not Tested	0.13	0.03	Poor >0.50	Poor >1.0
Fire point °C	Not tested	Not tested	Not tested	Not tested	Poor < 300	Poor < 300

Ester-NS\* designates Not specified as a Natural or Synthetic insulation fluid

Note-The above data is not specifically Oilwatch results by was supplied from Clients and is a reflection on the issues related to Retro filling.

## CHALLENGES FACING Southern Africa.

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

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

However local transformer manufactures need to be mindful; a system can only be as reliable as the reliability inherently built into its design.

Lack of knowledge on the Recognised international bodies such as CIGRE, IEEE and the IEC that now have several working groups dedicated to furthering the knowledge and application of these fluids.

CIGRE have formed a new working group (Retro fill of Mineral Oil in Transformers – Motivations, Considerations and Guidance), which is long overdue.

### Figure 9-CIGRE working group JWG 1N° A2/D1.72



CIGRE Study Committee A2/D1

#### PROPOSAL FOR THE CREATION OF A NEW WORKING GROUP

JWG 1N° A2/D1.72	Name of Convenor: Roberto ASANO (BRAZIL) E-mail address: roberto.asano@yahoo.com
Strategic Directions #2: 2, 3	Sustainable Development Goal #2: 9
The WG applies to distribution networks: <input checked="" type="checkbox"/> Yes / <input type="checkbox"/> No	
Potential Benefit of WG work #2: 1, 3, 6	
Title of the Group: Retrofill of Mineral Oil in Transformers – Motivations, Considerations and Guidance	

In the meantime, it might be prudent to wait for working group to complete its work and rather concentrate on sound Predictive/Reliability Centred maintenance of the existing Mineral oil transformers.

### About Ian Gray

Ian Gray is a member of the South African Chemical Institute and the South Africa mirror committee for IEC TC 10(International Electro technical Commission)/CIGRE (SA-Regional Advisory Group). He also serves on the SANS 290 committee (Mineral insulating oils - Management of polychlorinated biphenyls (PCBs)). His over 35 years of experience includes transformer oil testing, diagnostics and internal inspections coupled with the ISO17025 Quality management system.

#### Normative References (Abridged)

CIGRE TB 436, TB 443, Study Committee A2/P2-ID11064  
IEC 61099 / 61203Ed2 / 62770 / 62975  
IEEE C57.147-2006 / C57.147-2008 / C57.155-2014