Benefits of Ester Fluid Technology

Kevin Rapp
Fluid development

*Basic MO Transformer invention* 1990's

*1st generation Silicone oil & LFH* 1970's

*2nd generation Synthetic esters* 1980's

*3rd generation Natural esters* 1990's

Pioneers
Developed by transformer manufacturers – not chemist!
FR3™ TIMELINE

- 1994: Formulation selected
- 1996: Utility field trials begin
- 1998: Full scale accelerated life tests completed
- 2000: Global Patent 3rd generation
- 2002: Natural esters
- 2004: Environmental technology verification
- 2006: ASTM, IEEE & IEC natural ester standard
- 2006: Brazilian fluid production
- 2006: Cargill production of FR3 fluid
- Other production sites
Estimated FR3™ fluid filled units globally
## Fluids overview

<table>
<thead>
<tr>
<th></th>
<th>Mineral Oil</th>
<th>Natural Ester (FR3 fluid)</th>
<th>Synthetic Ester</th>
<th>Silicone Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Fluid</strong></td>
<td>Petroleum Oil</td>
<td>Vegetable Oil</td>
<td>Hydrocarbons</td>
<td>Polydimethylsiloxanes</td>
</tr>
<tr>
<td><strong>Dielectric Capacity</strong></td>
<td>Reference</td>
<td>Equivalent (better for PD's)</td>
<td>Equivalent (PD is a weak spot)</td>
<td>Lower (usage limited to 44kV)</td>
</tr>
<tr>
<td><strong>Diagnostic Capability</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Less</td>
</tr>
<tr>
<td><strong>Fire point</strong></td>
<td>160°C</td>
<td>360°C</td>
<td>315°C</td>
<td>340°C</td>
</tr>
<tr>
<td><strong>Biodegradability</strong></td>
<td>Low</td>
<td>High</td>
<td>Moderate</td>
<td>Very Low</td>
</tr>
<tr>
<td><strong>Biobased</strong></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Oxidation</strong></td>
<td>Good</td>
<td>Good (non-free breathing)</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td><strong>Aging</strong></td>
<td>Average</td>
<td>Best</td>
<td>Better</td>
<td>Average</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$</td>
<td>$$</td>
<td>$$$</td>
<td>$$$$$</td>
</tr>
</tbody>
</table>
COMPARISON OF INSULATING LIQUIDS

Mineral Oil Molecules

Natural Ester Molecule

Synthetic Ester Reaction

Structures reproduced from IEEE PC57.166 interim working draft October 2021
Natural Ester Reaction

CH₂─OH  +  HO─C─C₁₇H₃₅  →  CH₂─O─C─C₁₇H₃₅  +  3H₂O

CH₂─OH  +  HO─C─C₁₇H₃₅  →  CH₂─O─C─C₁₇H₃₅  +  3H₂O

glycerol (1 molecule)  stearic acid (3 molecules)  glycercyl tristearate (a triglyceride—1 molecule)

Alcohol  +  Acid  ↔  Ester  +  Water
Comparaison of insulating liquids

Natural ester and fatty acids structures

Glycerol backbone

\[ R_1 = \text{HOOC}(\text{CH}_2)_{14} \text{CH}_3 \] palmitic acid

\[ R_2 = \text{HOOC} \] oleic acid

Or \[ R_2 = \text{HOOC} \] linoleic acid

\[ R_3 = \text{HOOC} \] α-linolenic acid

Saturated fatty acid

Unsatuated Fatty acids

Triacyl groups
Properties correlate with fatty acid content

% Fatty Acid Distribution versus Viscosity

<table>
<thead>
<tr>
<th></th>
<th>palmitic</th>
<th>stearic</th>
<th>oleic</th>
<th>linoleic</th>
<th>linolenic</th>
<th>Viscosity</th>
<th>Pour Point</th>
<th>Gassing Tendency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Ester</td>
<td>C16:0</td>
<td>C18:0</td>
<td>C18:1</td>
<td>C18:2</td>
<td>C18:3</td>
<td>mm²/sec</td>
<td>°C</td>
<td>µl/min</td>
</tr>
<tr>
<td>Soybean</td>
<td>10.4</td>
<td>3.1</td>
<td>24.1</td>
<td>57.0</td>
<td>5.0</td>
<td>33</td>
<td>-15</td>
<td>-78</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>4.5</td>
<td>3.0</td>
<td>59.0</td>
<td>20.0</td>
<td>8.3</td>
<td>37</td>
<td>-15</td>
<td>-65</td>
</tr>
<tr>
<td>Canola</td>
<td>4.8</td>
<td>2.8</td>
<td>61.5</td>
<td>18.8</td>
<td>7.8</td>
<td>40</td>
<td>-9</td>
<td>-66</td>
</tr>
<tr>
<td>HO Sunflower</td>
<td>3.2</td>
<td>2.5</td>
<td>84.3</td>
<td>6.9</td>
<td>0.9</td>
<td>42</td>
<td>-12</td>
<td>-65</td>
</tr>
<tr>
<td>Palm</td>
<td>45.0</td>
<td>4.0</td>
<td>40.0</td>
<td>10.0</td>
<td>0.2</td>
<td>45</td>
<td>23</td>
<td>-</td>
</tr>
</tbody>
</table>

Relative Oxidation Stability: 1 1 10 100 200
How was FR3® developed?

Developed by a transformer manufacturer for its transformers, surpassing the challenges from mineral oil and synthetic esters.

- Over 5 years of lab research → best balance of properties
- Gaining internal confidence was their first challenge. Lockie test was a “due diligence” test.
- No risk to corporate image and reputation of OEM.
- Extensive testing and validation was required.
Comparison of Aged Paper
Results of a Sealed Vessel Study

Ester liquids reduce the aging rate of insulation paper via superior capability of managing water
Moisture Saturation of Mineral Oil, FR3 fluid and Envirotemp 360
Dielectric strength of ester liquids acceptable at high water content
Water migrates to the fluid and hydrolysis converts the ester + water into fatty acids.
Aging Vessel after 2000 hrs at 170°C

Natural Ester Fluid

Mineral Oil

Fatty acids produced by hydrolysis of FR3 fluid stay in solution versus plating out on heat generation surfaces as in mineral oil.
Fluid-Cellulose Interaction

Cellulose Protected by Long-Chain Ester Linkage

CELLULOSE - OH + R - C - OH ⇌ R - C - O - CELLULOSE
Superior moisture tolerance

Ester liquids have an exceptional ability to remove water that is either generated by the aging of transformer insulation paper or that is present due to the intrusion of moisture into a sealed transformer.

- 5x-8x Lower paper degradation rate
- 5x-8x Longer paper lifespan
- 1.5x-3x Longer asset lifespan
Ester Fluids Provide Life Extension

- IEEE C57.154 (IEC 60076-14) High temperature transformer standard
  - Current standard 110°C hot spot with 65 AWR limits transformer capability
  - Natural ester fluid-based insulation systems can be run 20°C warmer without degrading life
  - Using current standards transformers can be upgraded to provide loading capability (Thermal Rise Ratings)
  - Design new transformers with higher temperature ratings, achieve smaller footprint with same or more load capability

\[
\text{life}(T) = A \cdot e^{\frac{-15000}{T+273}}
\]

- Envirotex™ FR3™ fluid: \( A = 7.25 \times 10^{-17} \)
- Mineral Oil: \( A = 9.8 \times 10^{-16} \)
Loading capacity vs. High temperatures

+20°C

Operational temperature

+20%

Added capacity
Same lifespan
Reliability & Resilience

vs. Transformer size 250 / 340 kVA (dual rated)

- Extended loading capacity
- Higher permissible hot spots
- Higher paper thermal classes
- Lower initial cost than the larger mineral oil unit

FR3™ fluid transformers
Transformer liquids classified as “Fire Resistant” (K Class) must have Fire Point minimal of 300°C.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Flash Point</th>
<th>Fire Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral Oil</td>
<td>155</td>
<td>165</td>
</tr>
<tr>
<td>Synthetic Ester</td>
<td>270</td>
<td>308</td>
</tr>
<tr>
<td>Silicone</td>
<td>300</td>
<td>343</td>
</tr>
<tr>
<td>Natural Ester</td>
<td>330</td>
<td>360</td>
</tr>
</tbody>
</table>
Transformer Installation Risks

Overall failure rate (from Cigre TB 642) indicates failure rates:

- Substation transformers = 0.53% / year
- Generator step-up transformers = 0.95% / year
- External effects on ~25% of failures

Each 400 - 800 transformers = At least one fire / year!

FM Global (insures 7% of the world’s generating capacity) reported ~1 Billion USD losses in 10 years
Fire Safety – How to evaluate?

Flammability Tests - FM Global (Factory Mutual/1994)

• Target
  – Determine if the ignition of internal arcs in transformers with fire resistant fluids results in fires

• Summary
  – A low energy failure heats up the transformer insulating liquid.
  – The failure results in a rupture of the pressure relief valve, releasing oil to the ambient
  – The fluid deposits around the transformer on the floor
  – The arc is kept and causes a high energy fault and, probably, an explosion breaking the tank, resulting in the discharge of the hot fluid on the floor
Fire Safety – Flammability Test – Mineral Oil

- Oil Temperature
  - Tank 128°C
  - Channel 133°C
- Current 3784A
- Arc duration 7.77s
- Spray of hot oil and fire over the oil in the channel
- No external ignition source
- Self ignition ~350°C
Fire Safety – Flammability Test – K-Class Fluid

- Oil Temperature
  - Tank 140°C
  - Channel 133°C
- Current 3831A
- Arc duration 7.56s
- Disc open, no ignition
- No external fire ignition source
Fire Safety – Flammability Test – K-Class Fluid

- Oil Temperature
  - Tank 133~188°C
  - Channel 135°C
- Current 2939A
- Arc duration 10s
- Disc open, ignition of the gases at the external ignition source
- External flame extinguished after 3.5s
Fire Safety – Flammability Test – Conclusions

• The internal arc in a mineral oil insulated transformer can cause a fire (even without external ignition source)

• The internal arc in a transformer insulated with fire resistant K-Class fluid has no ignition

• Discharged gases from the transformer with fire resistant K-Class fluids, in spray form, can burn if there is an external ignition source (but no liquid fire)

• Since the quantity of energy from the initial fire is not enough to maintain the fluid temperature, the fire is self extinguished
Fire Safety – Flammability Test – Open Tank Test
- Designed by FM Global 2002

• Goal
  – Determine the possibility of reducing the distances and containment from FM standards, **without any additional protection or fire extinguishing system.**

• Summary
  – External and internal failures of high energy and/or induced currents from the system that can heat up metal pieces to glowing red (stray flux).

• Procedure
  – Quickly insert a metal plate heated red hot (750°C) in a tank with fluid heated at 130°C. Measure the temperatures and verify the occurrence of fire.
Fire Safety – Flammability Test – Open Tank Test
- Mineral Oil
Fire Safety – Flammability Test – Open Tank Test
- FR3 Natural Ester (NE) Fluid
Fire Safety – Flammability Test – Open Tank Test
- FR3 NE Fluid 95.5% + 4.5% Mineral Oil
Mineral oil containment and suppression rocks

Automatic fire suppression system

Reduced clearances

FR3™ fluid simplified border

Building

Fire wall

Natural & Synthetic
Mineral oil transformer
Ester K-Class transformers

FR3fluid.com
Oxidation of natural ester liquid important for biodegradability

Biodegradation Rate of Dielectric Fluids

Aerobic Aquatic Biodegradation

CO₂ Evolution (% of theoretical max)

Elapsed Time (days)

Biodegradation Rate (%)

OPPTS 835.3100
10% + 10 days

Biodegradation Rate of Dielectric Fluids

sodium citrate reference material
(EPA “ultimate biodegradability”)

test performed per EPA OPPTS 835.3100 by
Thomas A. Edison Technical Center
Franksville, WI 53126 USA
Wisconsin DNR Laboratory #252201770
report issued April 23, 1999

Envirotemp FR3 fluid
conventional transformer oil
sodium citrate reference material
(EPA “ultimate biodegradability”)

silicone
mineral oil
synthetic ester
natural ester
Acute Aquatic and Oral Toxicity

Acute aquatic toxicity of Envirotemp FR3 fluid

<table>
<thead>
<tr>
<th>Test</th>
<th>Method</th>
<th>Dose (mg/L)</th>
<th>Mortality (# of fish)</th>
<th>LC$_{50}$ (mg/L)</th>
<th>NOAEC (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute Aquatic Toxicity</td>
<td>OECD 203</td>
<td>1,000</td>
<td>0</td>
<td>&gt; 1,000</td>
<td>&gt; 1,000</td>
</tr>
<tr>
<td>Lethality Using Rainbow Trout</td>
<td>Environment Canada</td>
<td>1,000</td>
<td>0</td>
<td>&gt; 1,000</td>
<td>&gt; 1,000</td>
</tr>
<tr>
<td>Acute Aquatic Toxicity</td>
<td>ASTM D608, OECD 203</td>
<td>10,000</td>
<td>0</td>
<td>&gt; 10,000</td>
<td>&gt; 10,000</td>
</tr>
</tbody>
</table>

*Lc$_{50}$ = lethal concentration killing 50% of fish
NoAEC = no observable adverse effect concentration

Acute oral toxicity of Envirotemp FR3 fluid

<table>
<thead>
<tr>
<th>Method</th>
<th>Test</th>
<th>Animals</th>
<th>Dose (mg/kg)</th>
<th>% Mortality Total</th>
<th>14 Day Average Body Weight (g)</th>
<th>7 Day</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>OECD 420</td>
<td>Sighting</td>
<td>1 F</td>
<td>2,000</td>
<td>0</td>
<td>226.0</td>
<td>251.2</td>
<td>259.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main</td>
<td>5 F</td>
<td>0</td>
<td>221.5</td>
<td>265.0</td>
<td>280.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 F</td>
<td>0</td>
<td>285.3</td>
<td>352.0</td>
<td>378.8</td>
</tr>
</tbody>
</table>

a

b

LC$_{50}$ = lethal concentration killing 50% of fish
NoAEC = no observable adverse effect concentration
Environmental Advantages

FR3® and other natural ester liquids are developed from renewable feedstocks

Non-toxic, non-hazardous, readily biodegradable

▪ OECD oral and aquatic toxicity tests – zero mortality
▪ >98% vegetable oil
▪ Carbon Neutral

FR3 can help minimize potential damage from spills

▪ Readily biodegradable
▪ Less likely to permeate soil and reach water table
▪ Cleanup using bioremediation can be an advantage
DIELECTRIC PERFORMANCE

Electrical performance of FR3 natural ester fluid is equal or better than mineral oil

- More than seven series of tests have confirmed performance:
  - Basic dielectric tests AC, LI, SS, CW
  - Testing gaps up to 65 mm and evaluation of Kappeler Curve
  - Evaluation of Interfacial Creep
  - BDV at low temperature conditions
  - Long gap tests up to 150mm (1800kV) with inhomogeneous field
  - Tap Changer testing
  - Partial Discharges Inception Voltage
Permittivity affects field distribution

Calculation with MO

Calculation with NE

Uniform in the center
Higher concentration in the corners
Dielectrics of FR3 fluid and Mineral Oil were equivalent
Long gap tests confirmed equivalent breakdowns

**Long gap tests confirmed equivalent breakdowns**

**DIELECTRIC PERFORMANCE**

**LI 1.2µs x 50µs – negative polarity**

**Stress between Tap Changer contacts**

**FR3 fluid results for MR OLTC were better than MO**
Partial Discharge Inception of NE higher than SE or MO

> Partial Discharge Inception Voltage (PDIV) for different temperatures and water contents (needle – disc) for Natural Ester, Synthetic Ester, and Mineral Oil.
Thank You

Email: Kevin_Rapp@Cargill.com