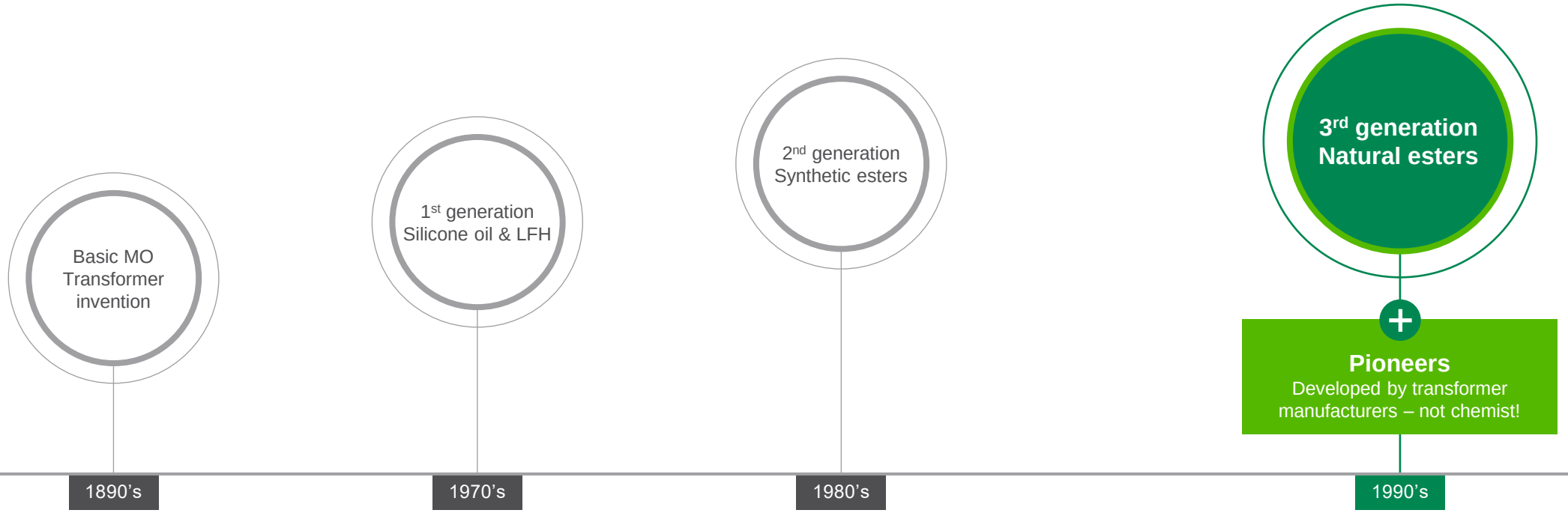
FR3™

a Cargill brand

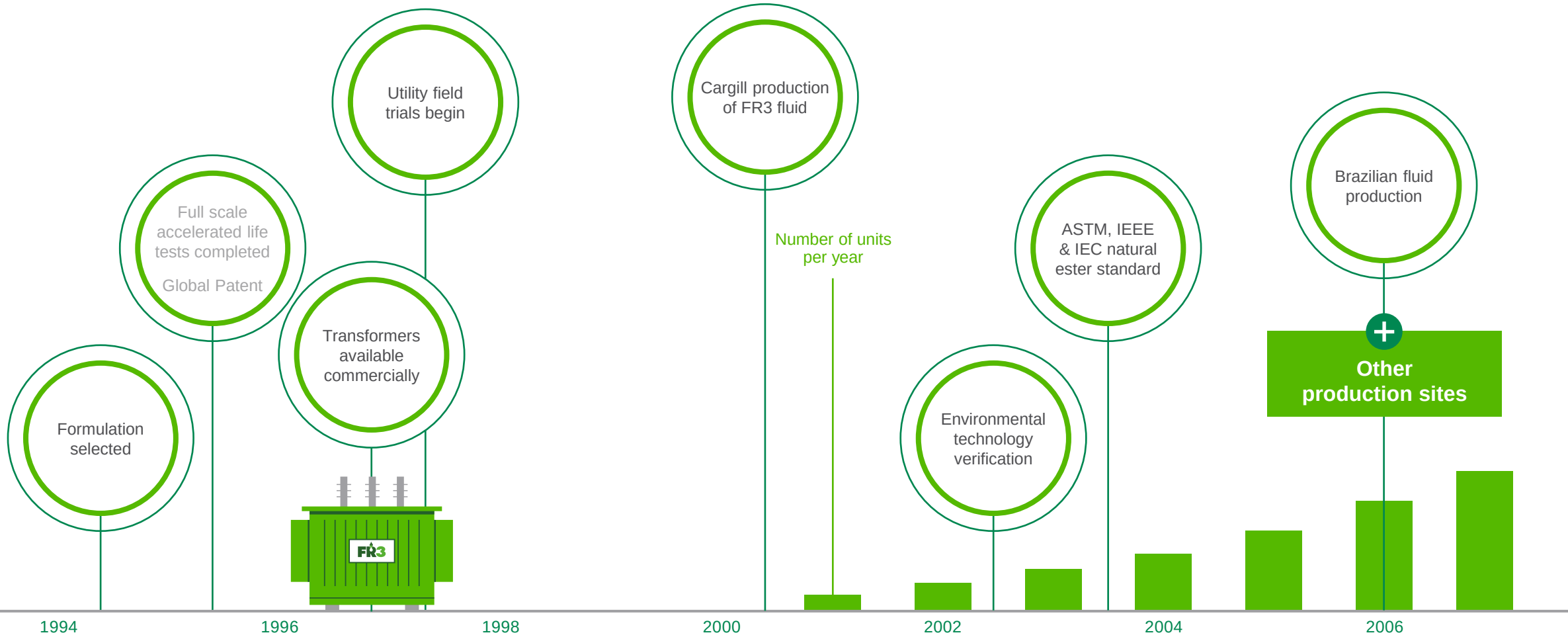
Benefits of Ester Fluid Technology

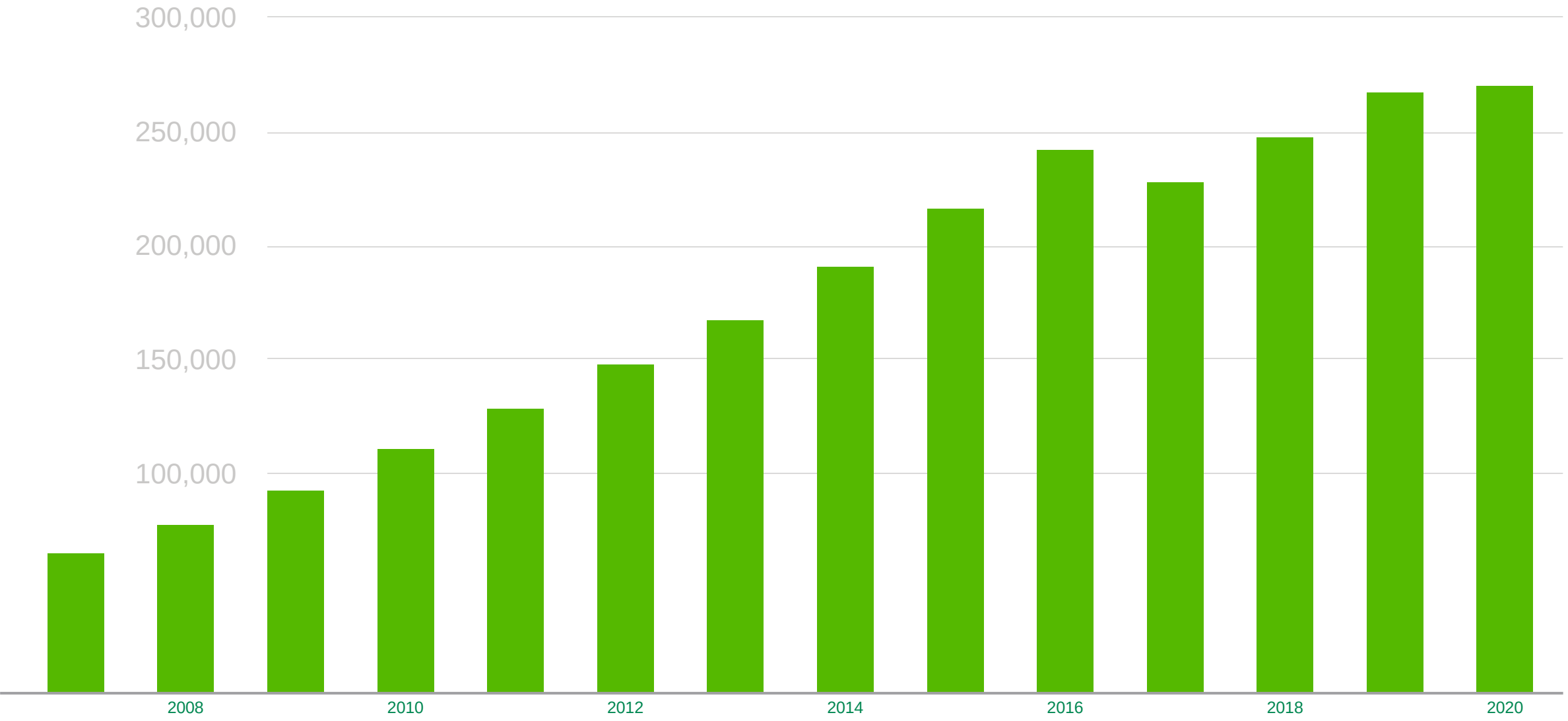
Kevin Rapp

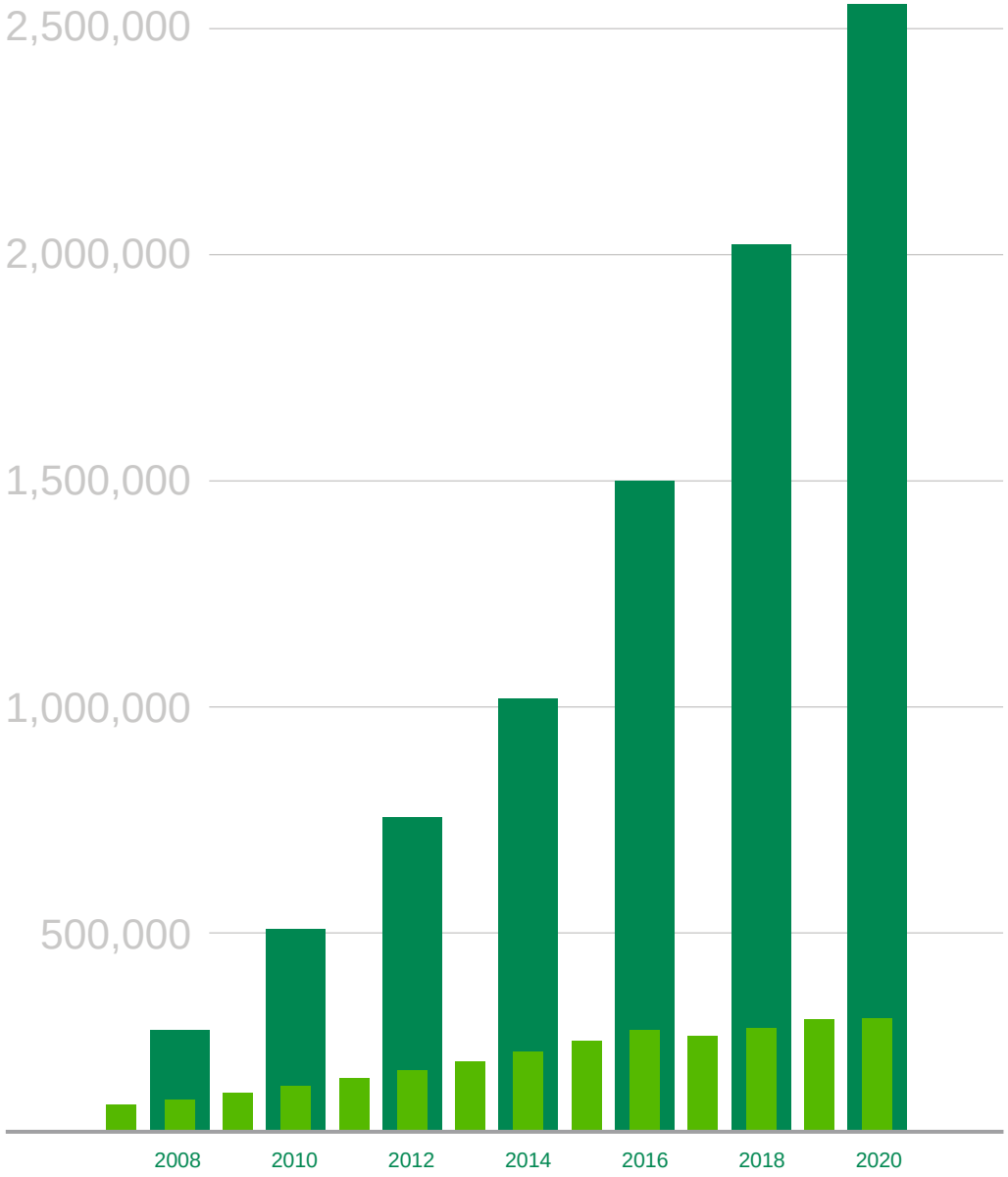
Fluid development



FR3™ TIMELINE




300,000
250,000
200,000
150,000
100,000
2008
2010
2012
2014
2016
2018
2020



+2,5 Million

accumulated units

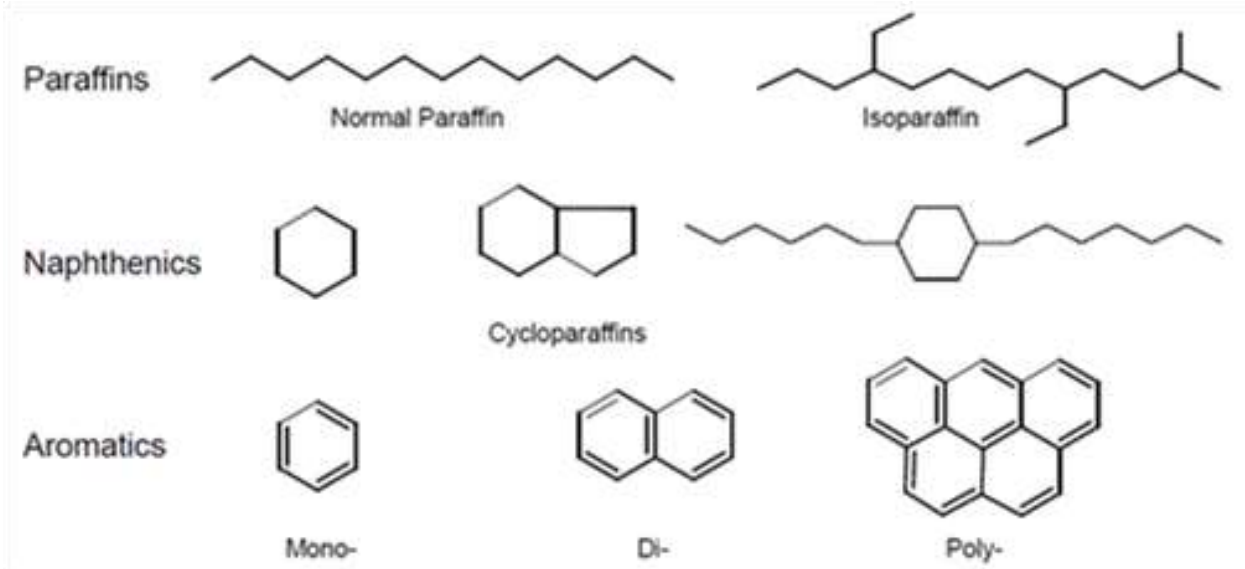
New units per year

Estimated FR3™ fluid filled units globally

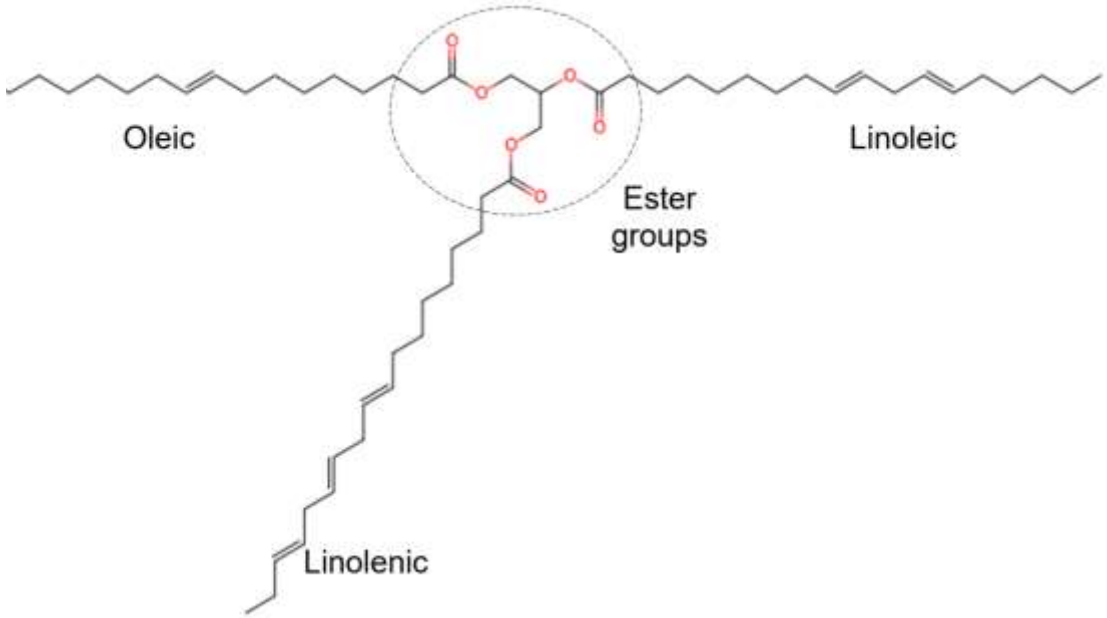
Fluids overview

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

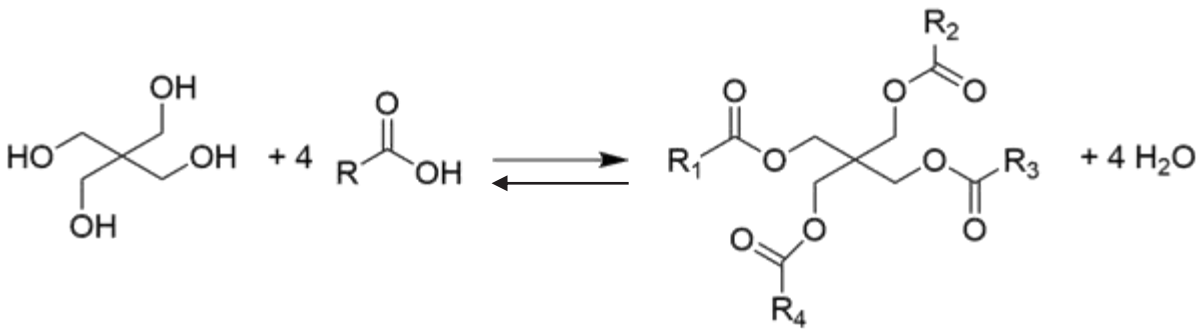
Mineral Oil Molecules



Natural Ester Molecule

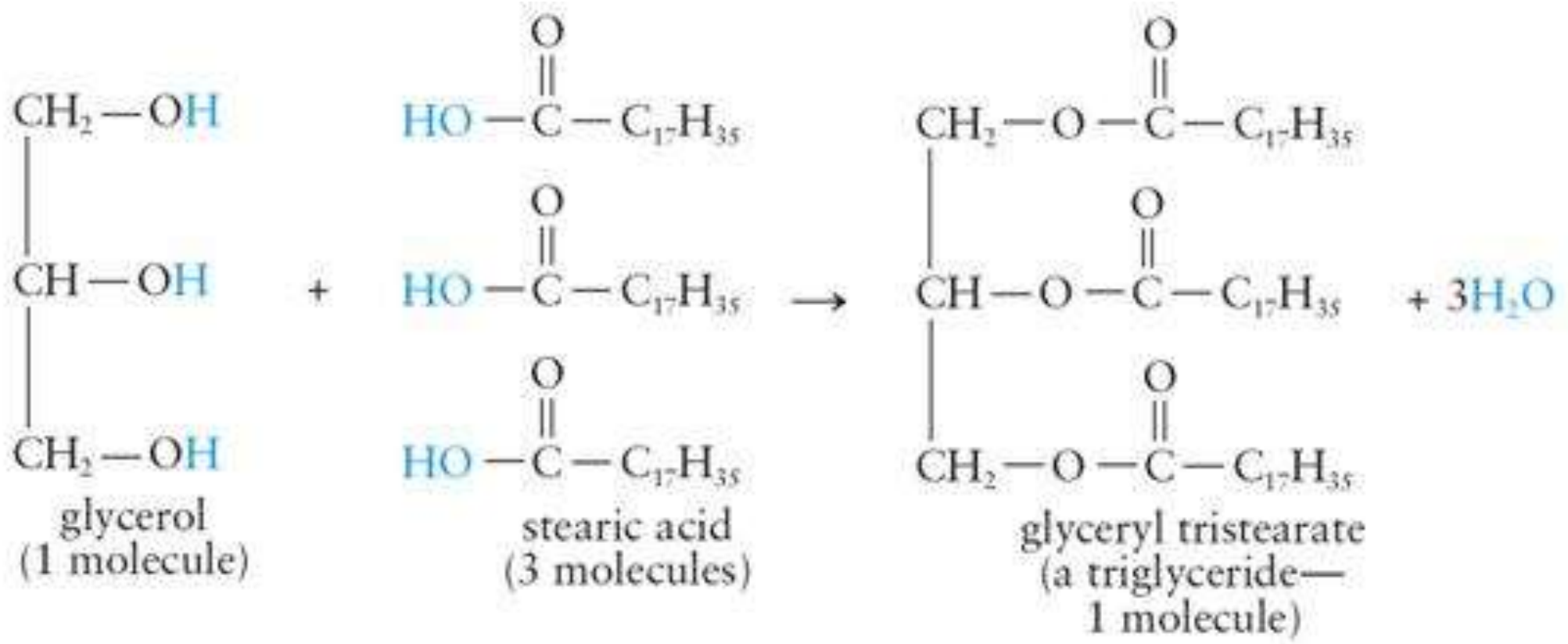


Synthetic Ester Reaction



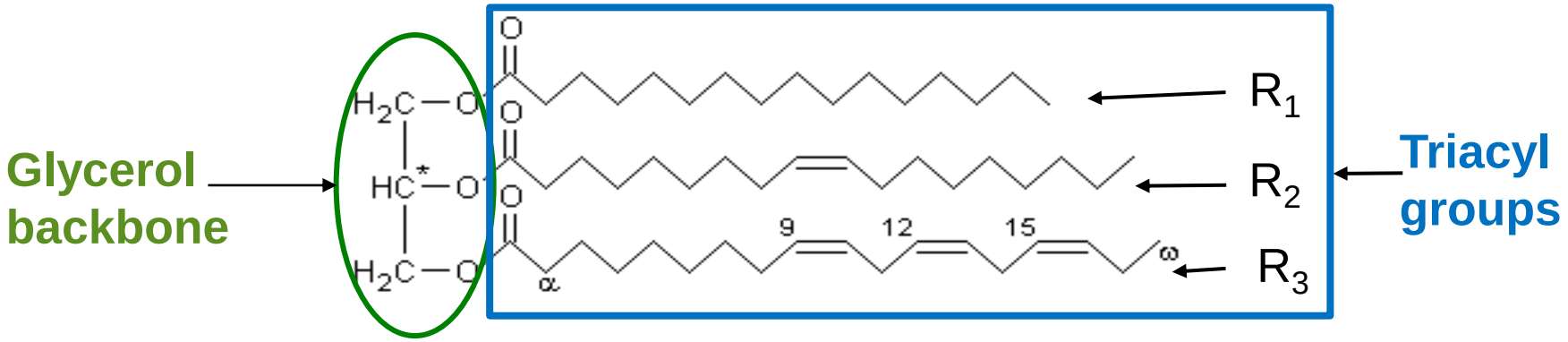
Structures reproduced from IEEE PC57.166 interim working draft October 2021

Natural Ester Reaction



Alcohol + Acid ⟷ Ester + Water

Natural ester and fatty acids structures



R_1 = $HOOC(CH_2)_{14}CH_3$ palmitic acid — Saturated fatty acid

R_2 = HOOC oleic acid

Or R_2 = HOOC linoleic acid

R_3 = HOOC α-linolenic acid

Unsaturated Fatty acids

Properties correlate with fatty acid content

% Fatty Acid Distribution versus Viscosity

	palmitic	stearic	oleic	linoleic	linolenic	Viscosity	Pour Point	Gassing Tendency
Natural Ester	C16:0	C18:0	C18:1	C18:2	C18:3	mm^2/sec	ºC	µl/min
Soybean	10.4	3.1	24.1	57.0	5.0	33	-15	-78
Rapeseed	4.5	3.0	59.0	20.0	8.3	37	-15	-65
Canola	4.8	2.8	61.5	18.8	7.8	40	-9	-66
HO Sunflower	3.2	2.5	84.3	6.9	0.9	42	-12	-65
Palm	45.0	4.0	40.0	10.0	0.2	45	23	-
Relative Oxidation Stability	**1**	**1**	**10**	**100**	**200**			

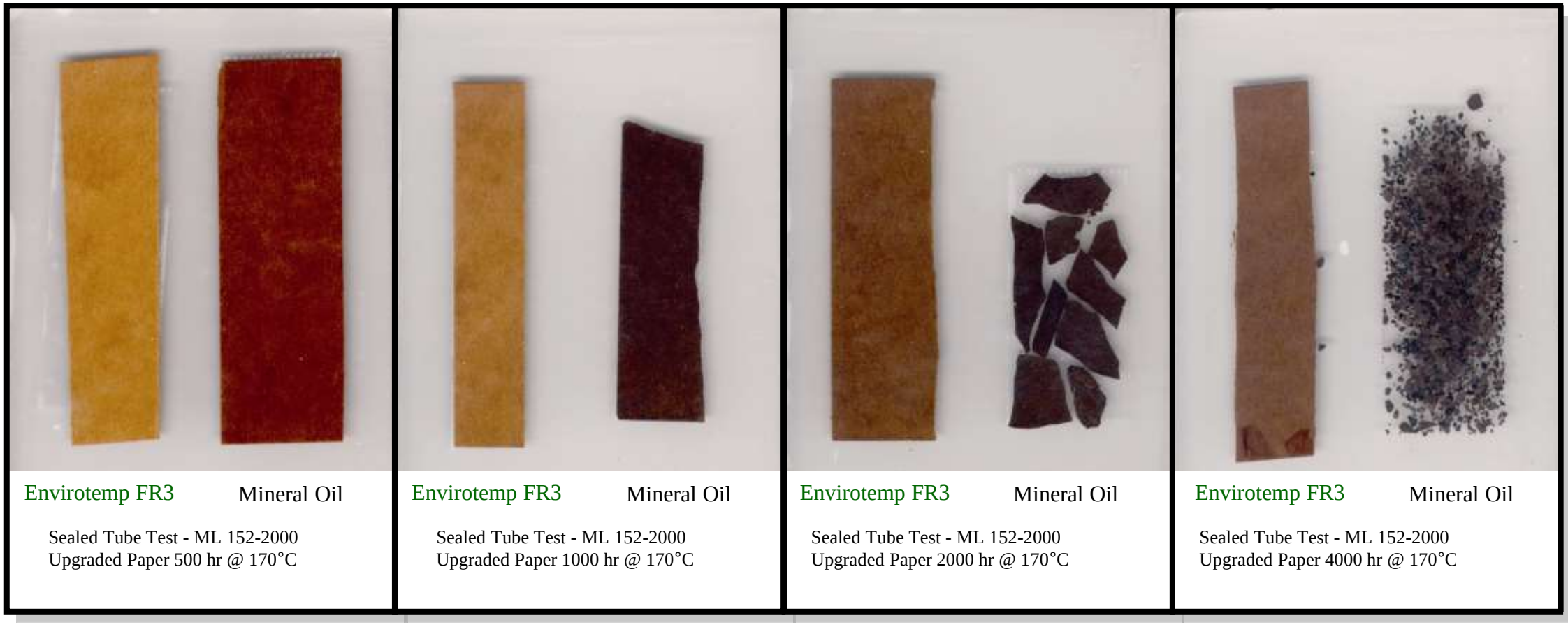
How was FR3® developed?

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.

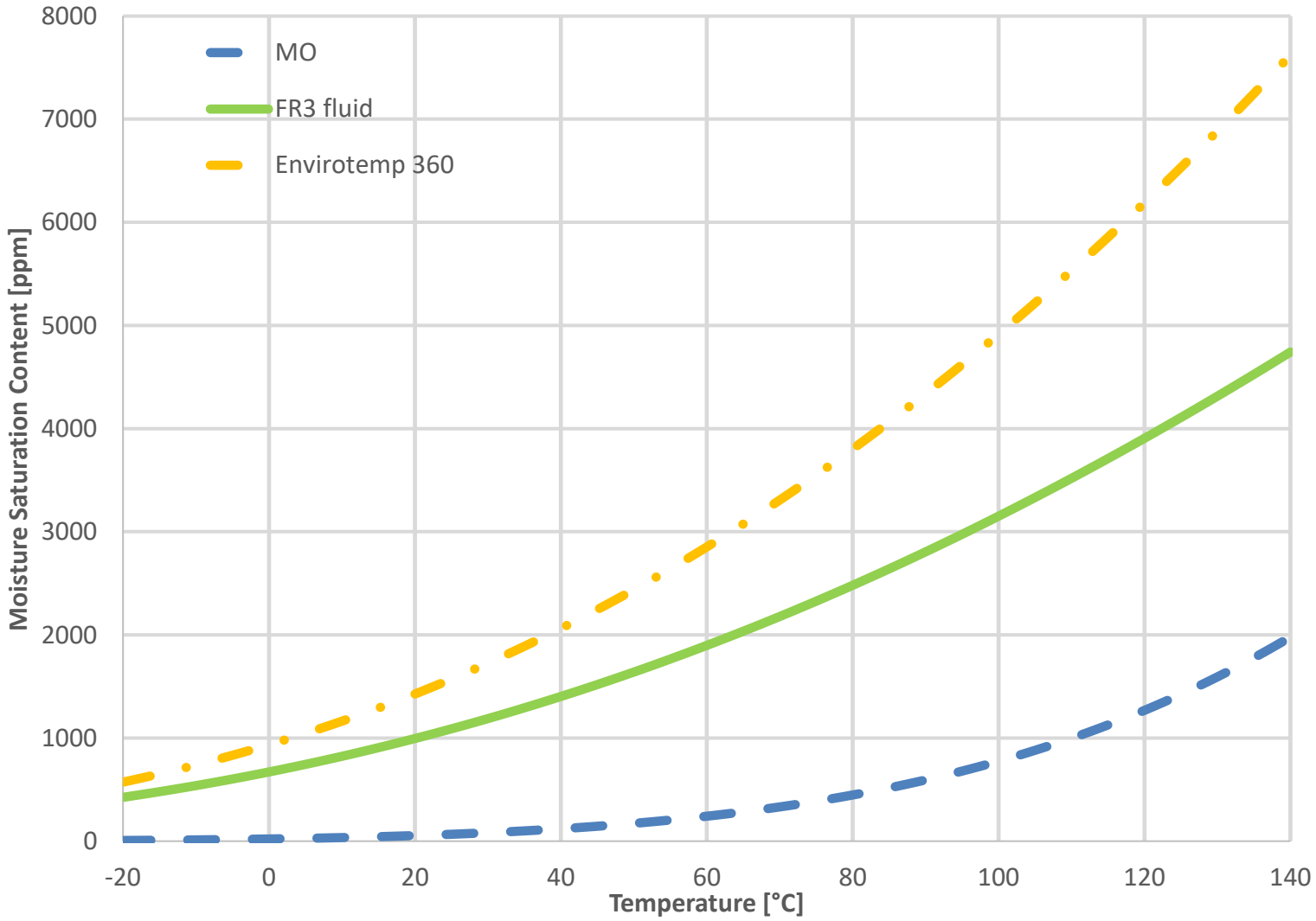
Comparison of Aged Paper

Results of a Sealed Vessel Study

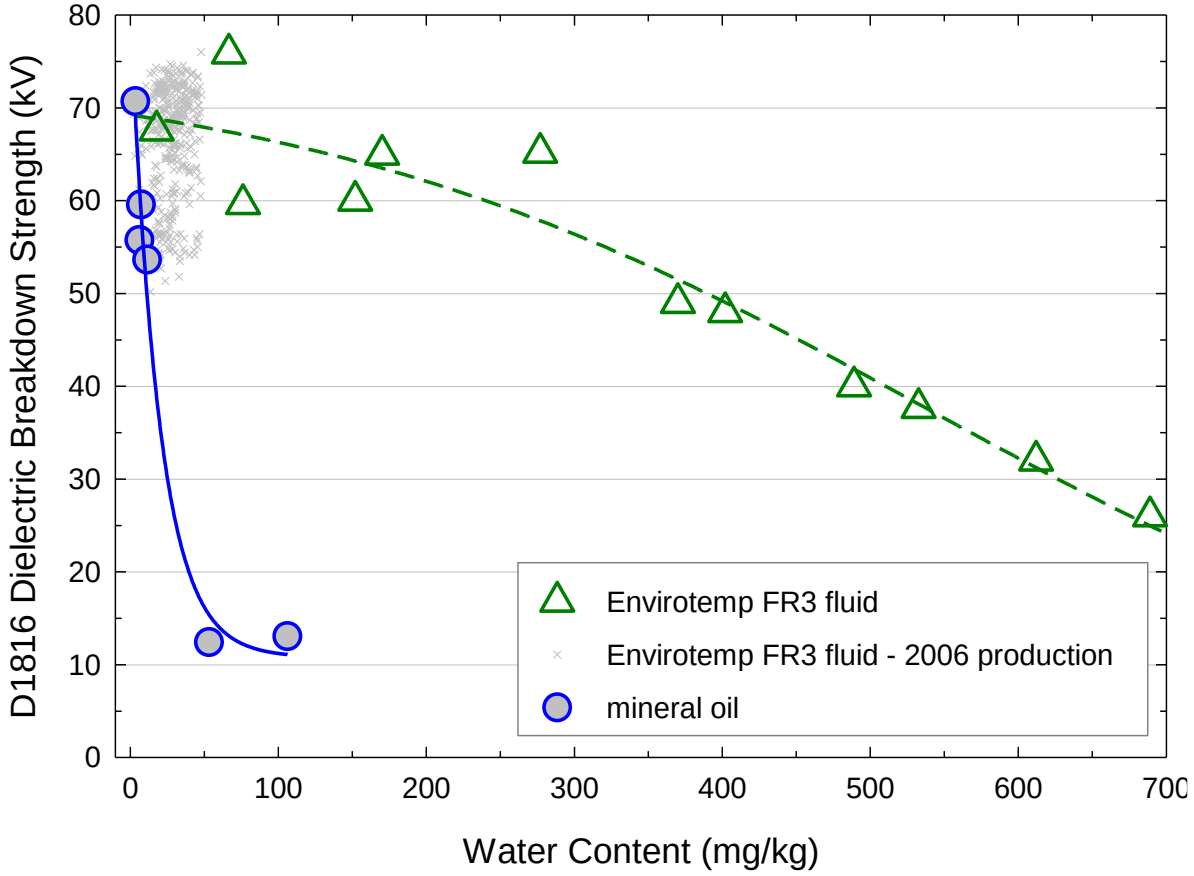


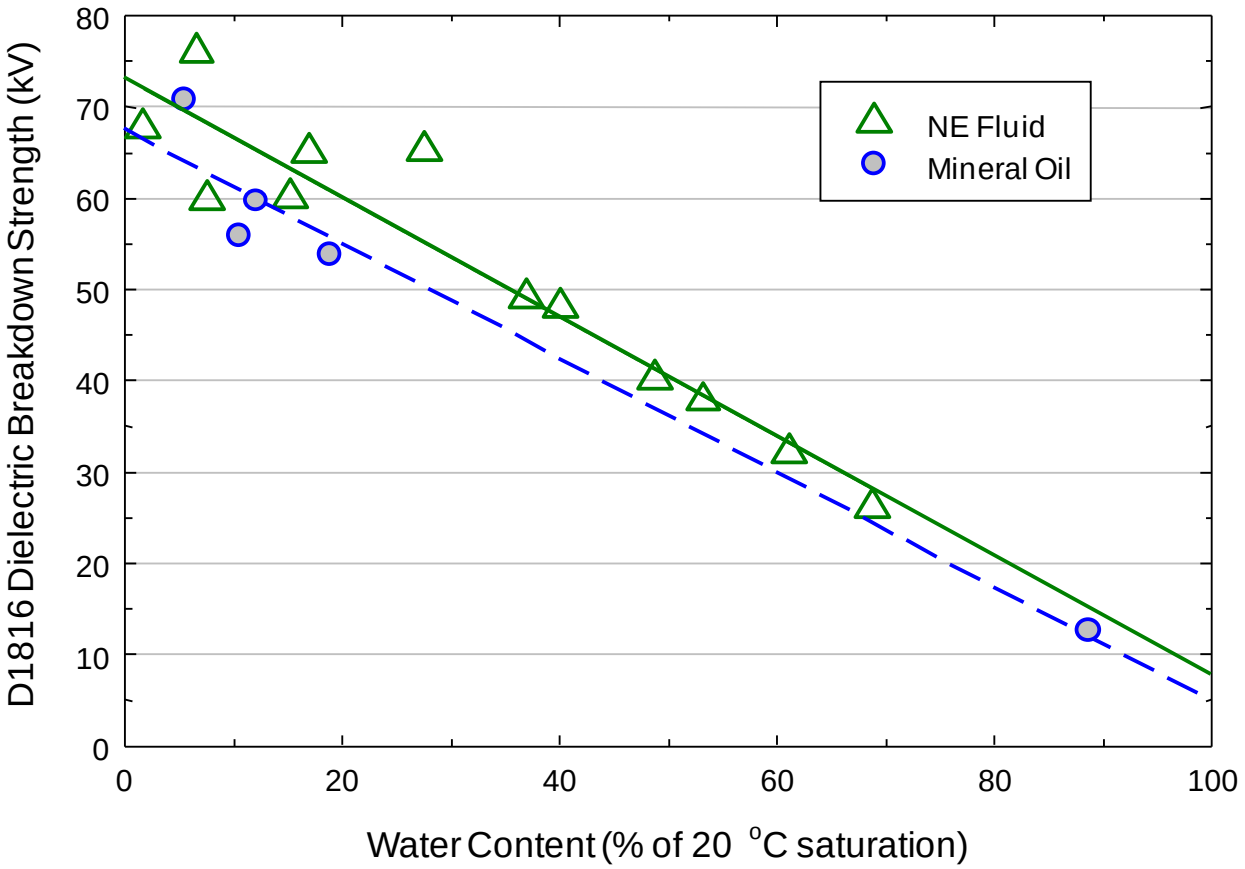
Ester liquids reduce the aging rate of insulation paper via superior capability of managing water

Moisture Saturation of Mineral Oil, FR3 fluid and Envirotemp 360

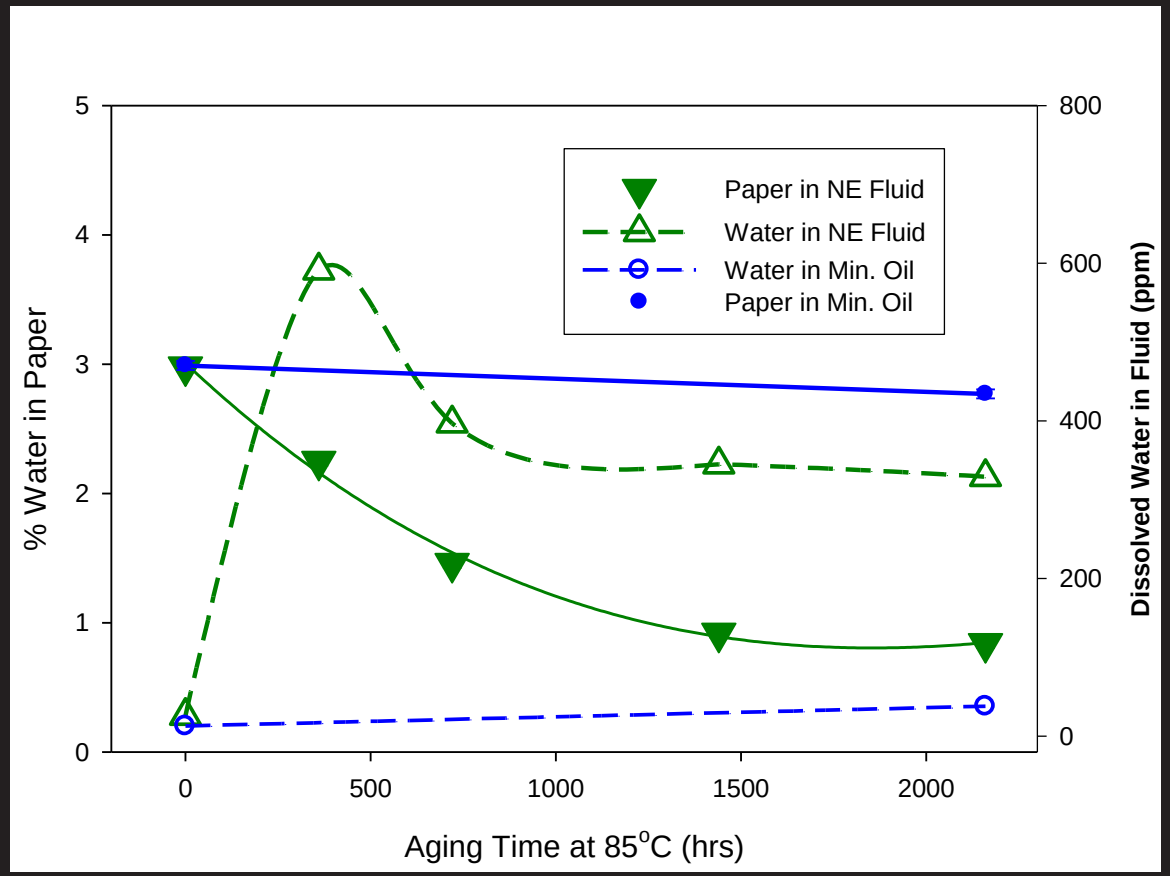


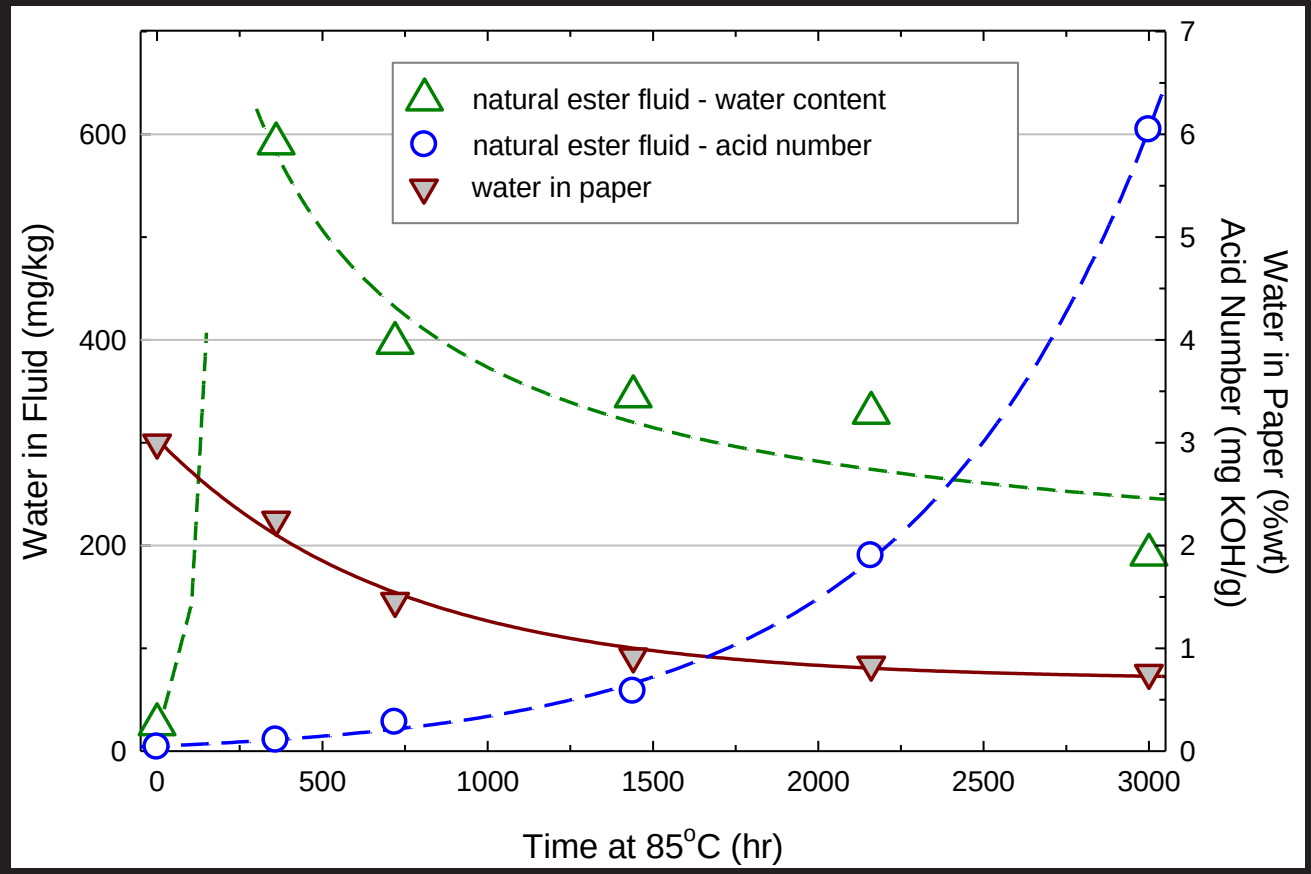
Dielectric strength of ester liquids acceptable at high water content





Water migrates to the fluid and hydrolysis converts the ester + water into fatty acids





Aging Vessel after 2000 hrs at 170ºC

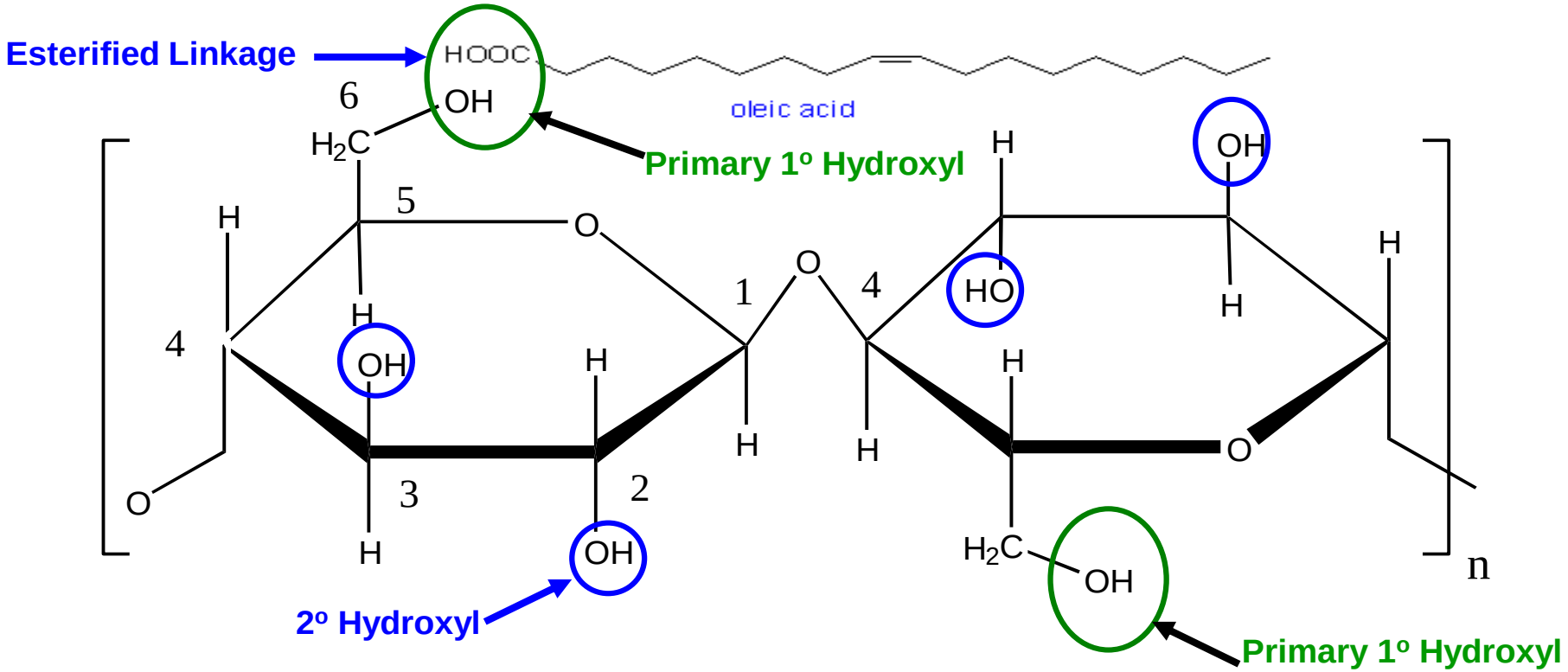
Natural Ester Fluid

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



$$\text{CELLULOSE - OH} + \text{R - C(=O) - OH} \rightleftharpoons \text{R - C(=O) - O - CELLULOSE}$$

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

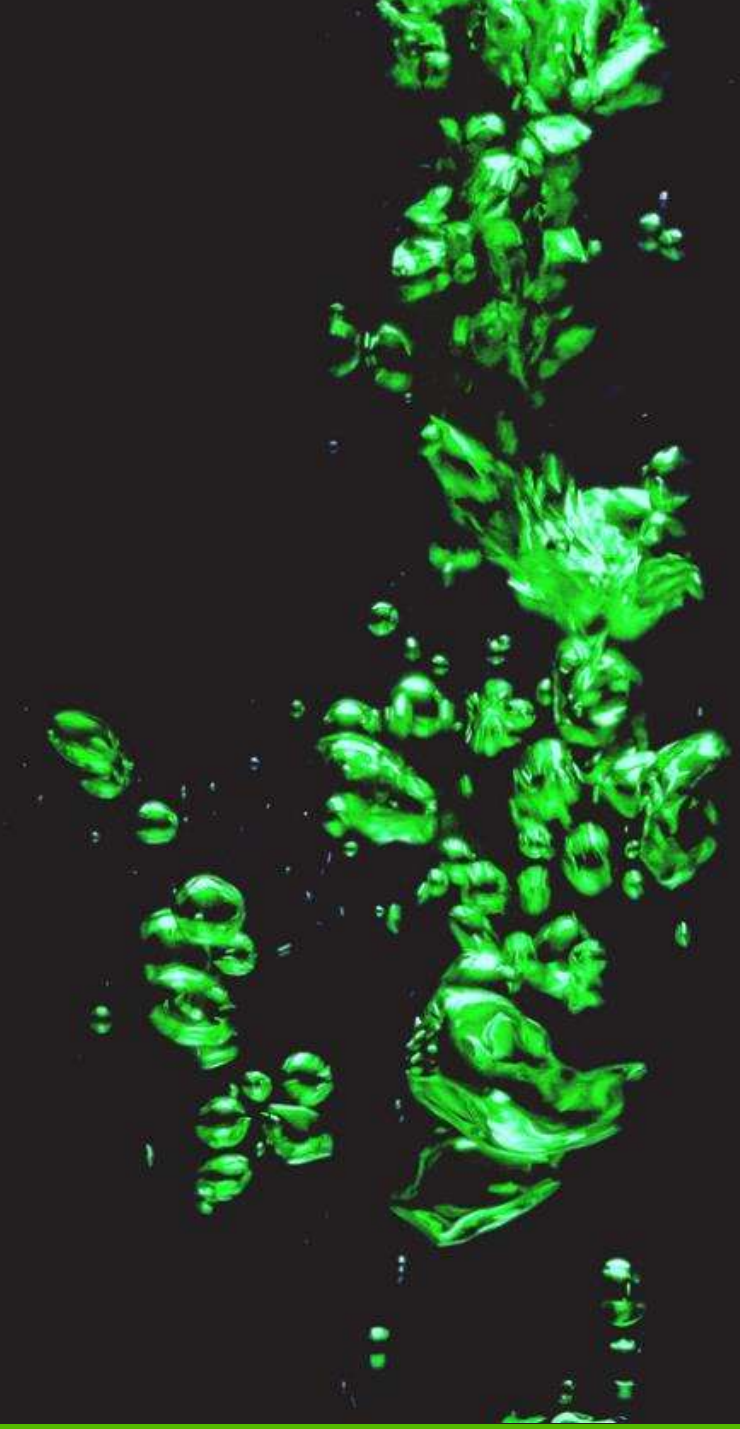
Lower paper degradation rate

5x-8x

Longer paper lifespan

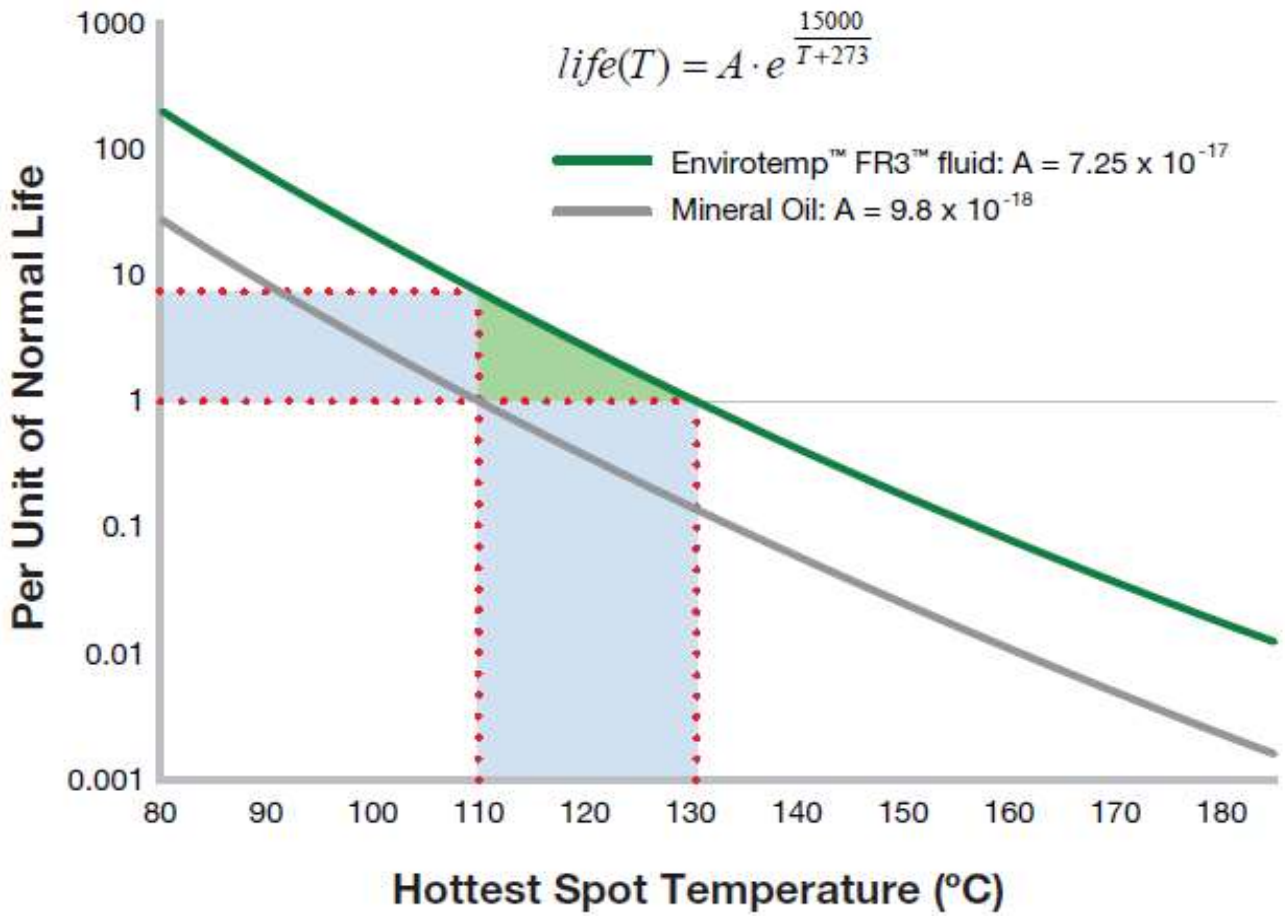
1.5x-3x

Longer asset lifespan



Ester Fluids Provide Life Extension

- **IEEE C57.154 (IEC 60076-14) High temperature transformer standard**
  - Current standard 110ºC hot spot with 65 AWR limits transformer capability
  - Natural ester fluid-based insulation systems can be run 20ºC 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**



RELIABILITY & RESILIENCE

Loading capacity

vs. High temperatures

+20°C > **+20%**

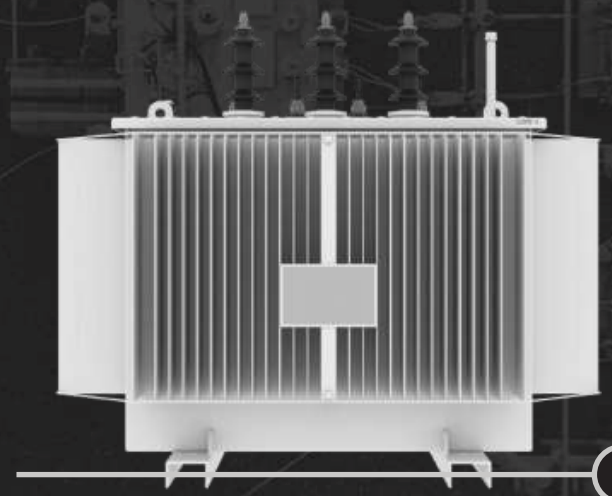
Operational temperature

Added capacity
Same lifespan

Reliability & Resilience

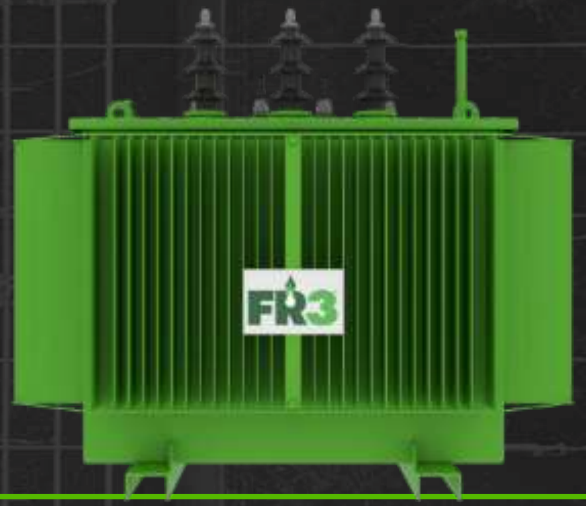
vs. Transformer size 250 / 340 kVA (dual rated)

250 kVA



Mineral oil transformers

250 / 340 kVA

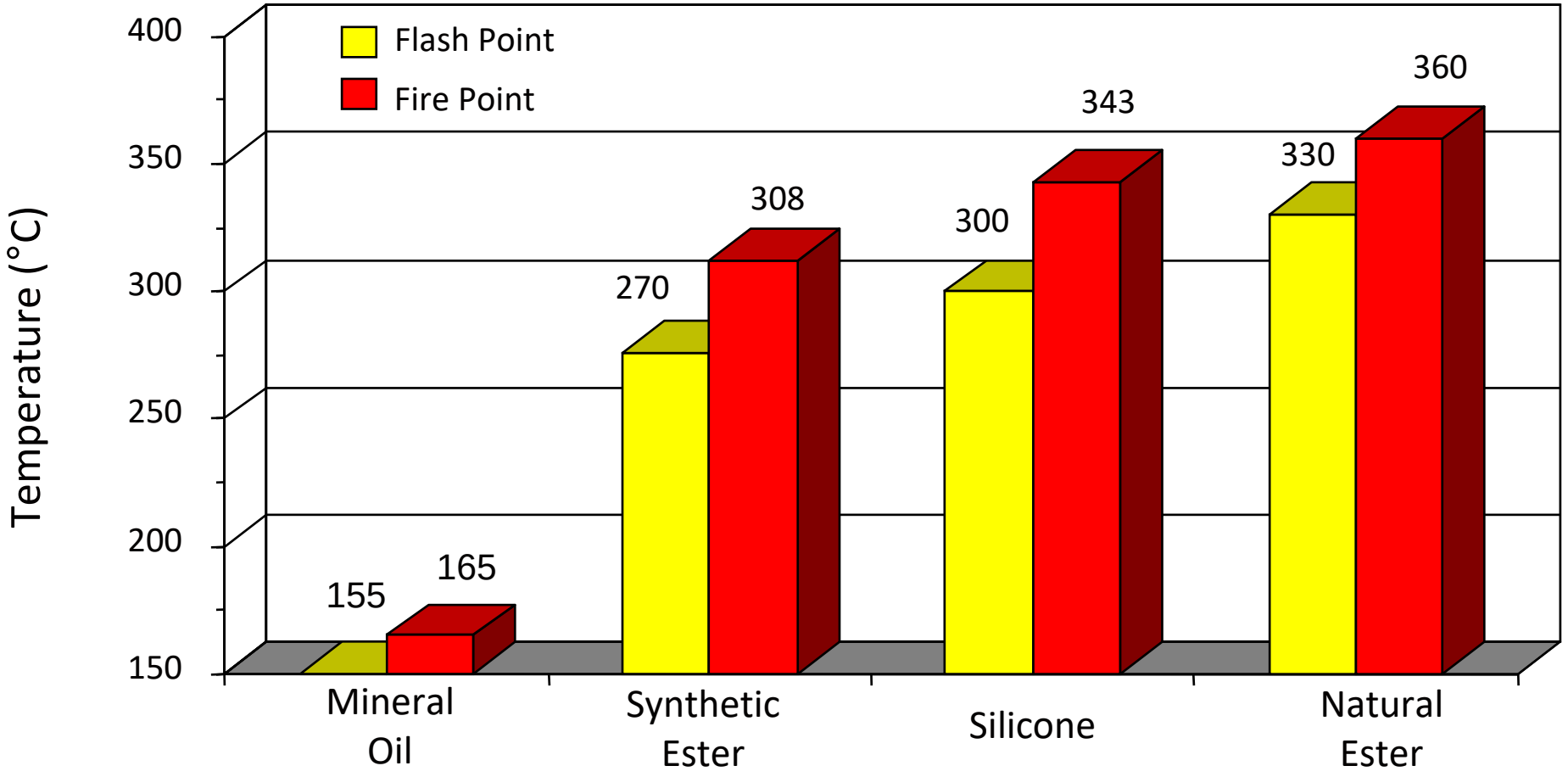


FR3™ fluid transformers

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

Fire Safety

Transformer liquids classifieds as “Fire Resistant” (K Class) must have Fire Point minimal of 300°C



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?

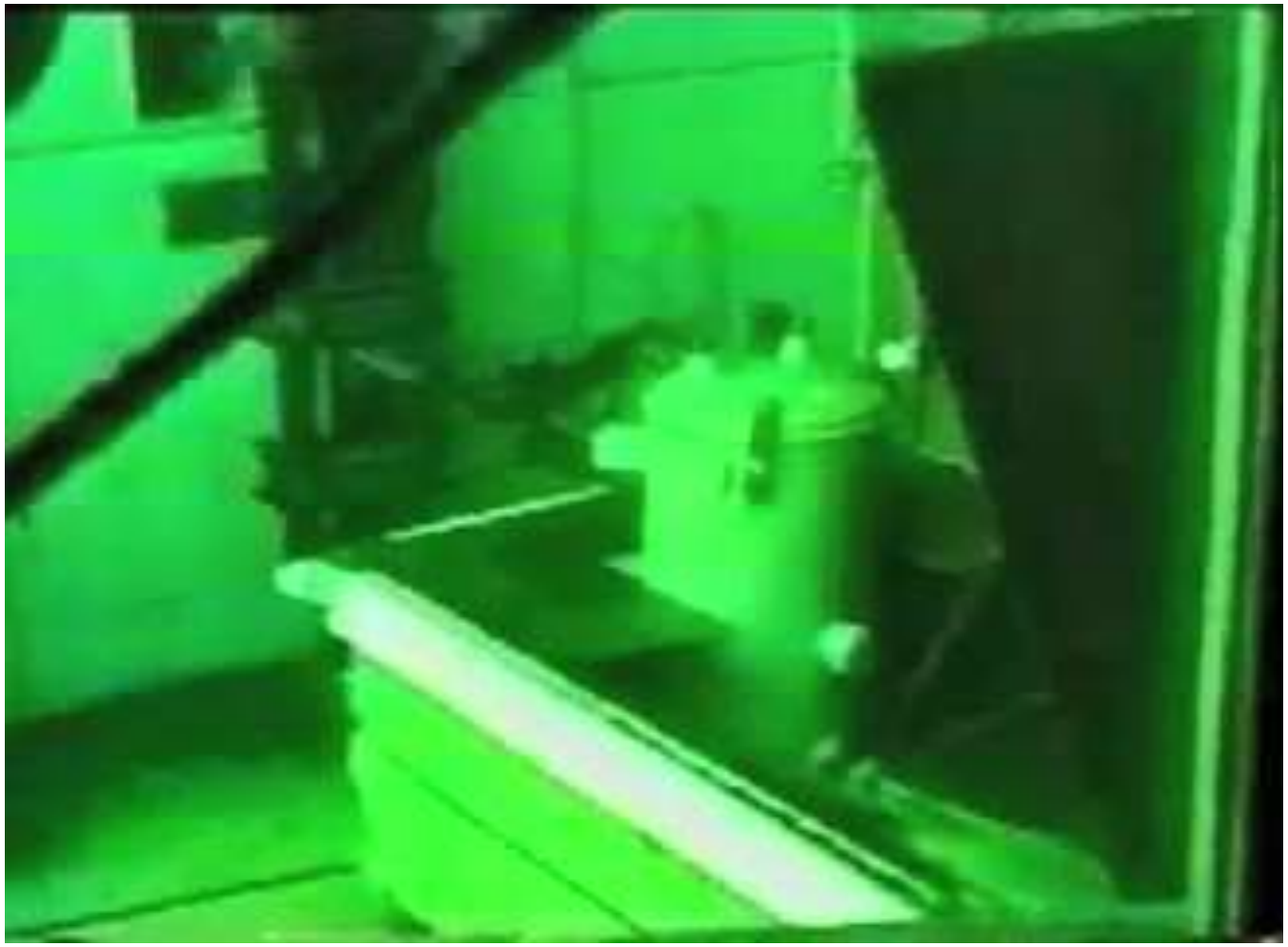
Flammability Tests - FM Global (Factory Mutual/1994)

- 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).

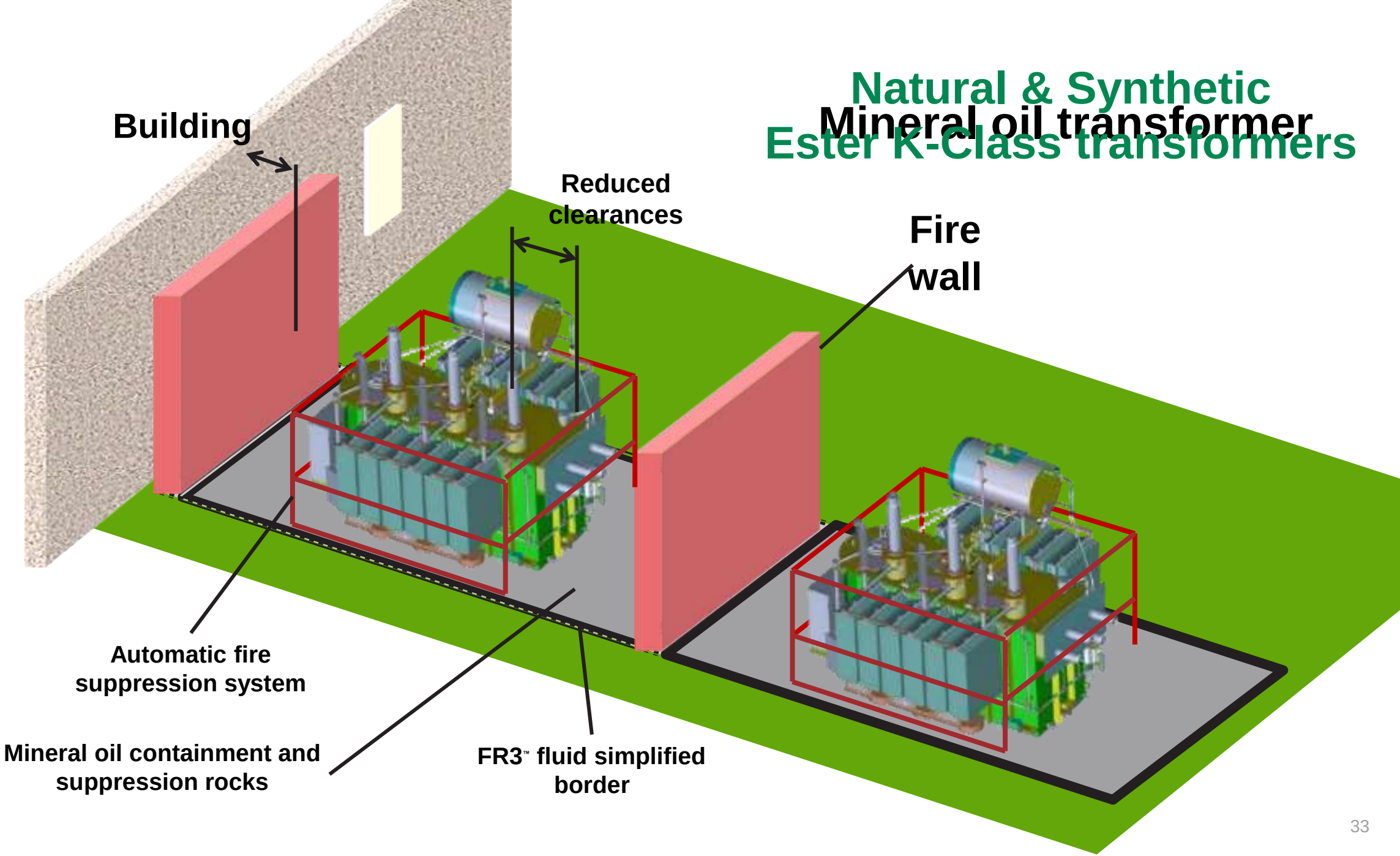
- Procedure
  - Quickly insert a metal plate heated red hot (750°C) in a tank with fluid heated at 130°C. Measure the temperatures and verify the occurrence of fire.

Fire Safety – Flammability Test – Open Tank Test - Mineral Oil

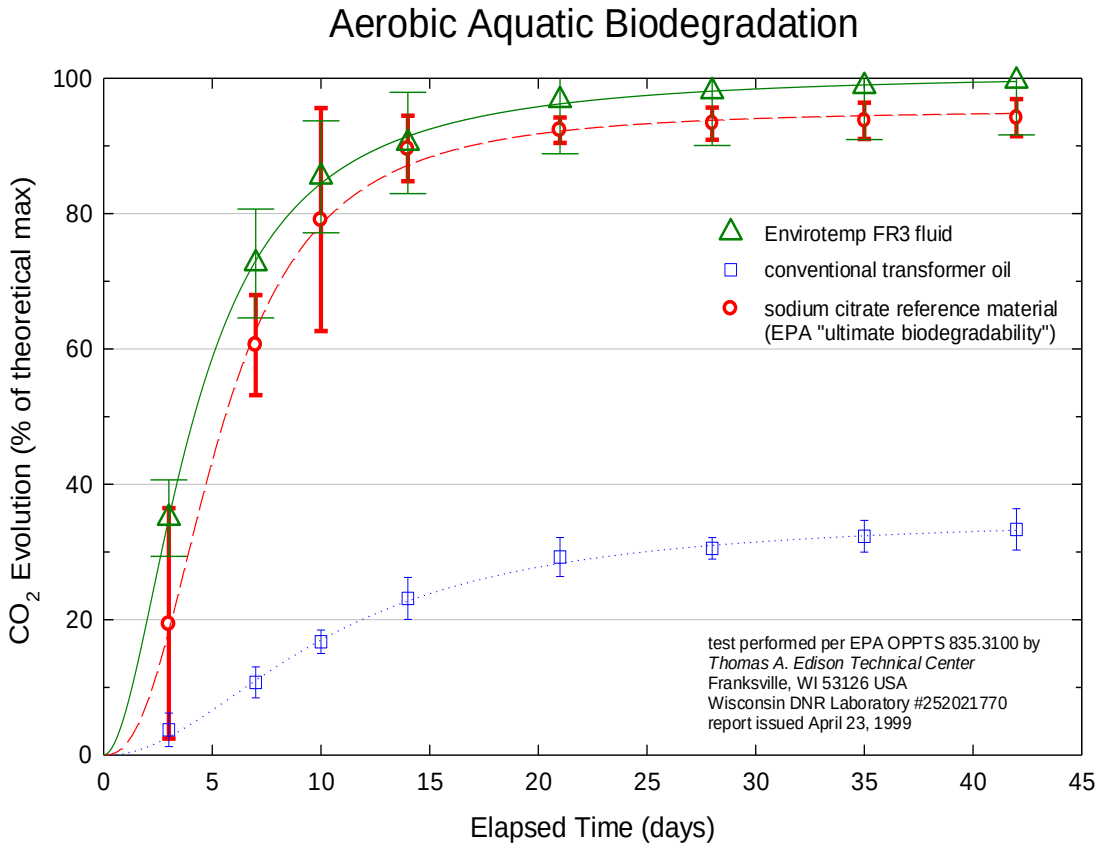
Fire Safety – Flammability Test – Open Tank Test - FR3 Natural Ester (NE) Fluid

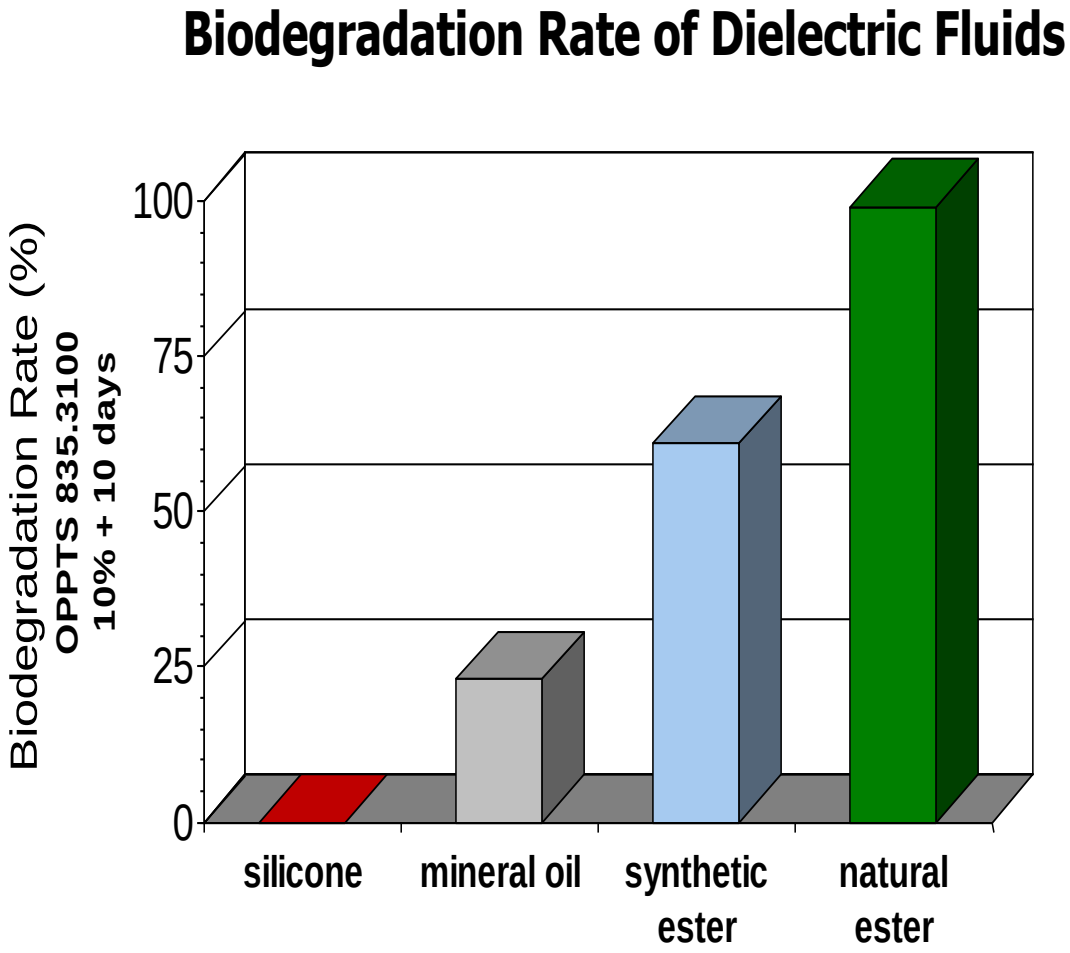
Fire Safety – Flammability Test – Open Tank Test - FR3 NE Fluid 95.5% + 4.5% Mineral Oil

Natural & Synthetic
Ester K-Class transformers



Oxidation of natural ester liquid important for biodegradability





Acute Aquatic and Oral Toxicity

Acute aquatic toxicity of Envirotemp FR3 fluid

Test	Method	Dose (mg/L)	Mortality (# of fish)	LC_{50} [a] (mg/L)	NOAEC [b] (mg/L)
Acute Aquatic Toxicity	OECD 203	1,000	0	> 1,000	> 1,000
Lethality Using Rainbow Trout	Environment Canada	1,000	0	> 1,000	> 1,000
Acute Aquatic Toxicity	ASTM D608, OECD 203	10,000	0	> 10,000	> 10,000

[a] LC_{50} = lethal concentration killing 50% of fish
[b] NOAEC = no observable adverse effect concentration

Acute oral toxicity of Envirotemp FR3 fluid

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

Environmental Advantages

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

Non-toxic, non-hazardous, readily biodegradable

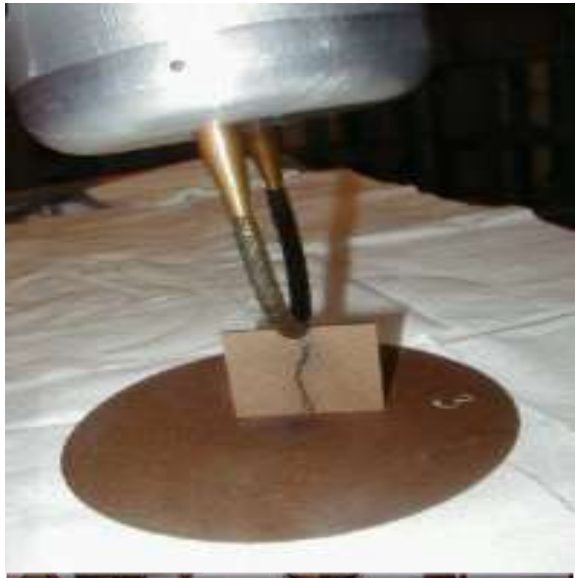
- OECD oral and aquatic toxicity tests – zero mortality
- >98% vegetable oil
- Carbon Neutral

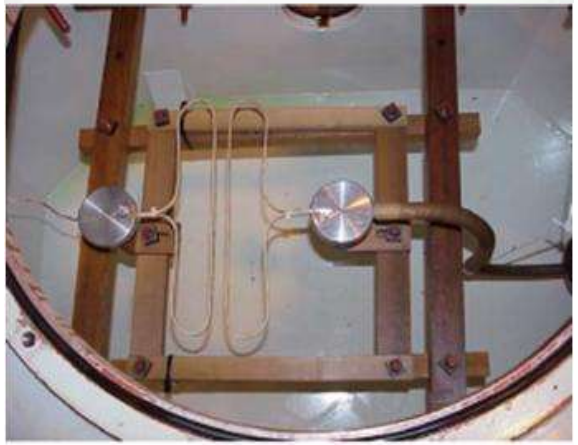
FR3 can help minimize potential damage from spills

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

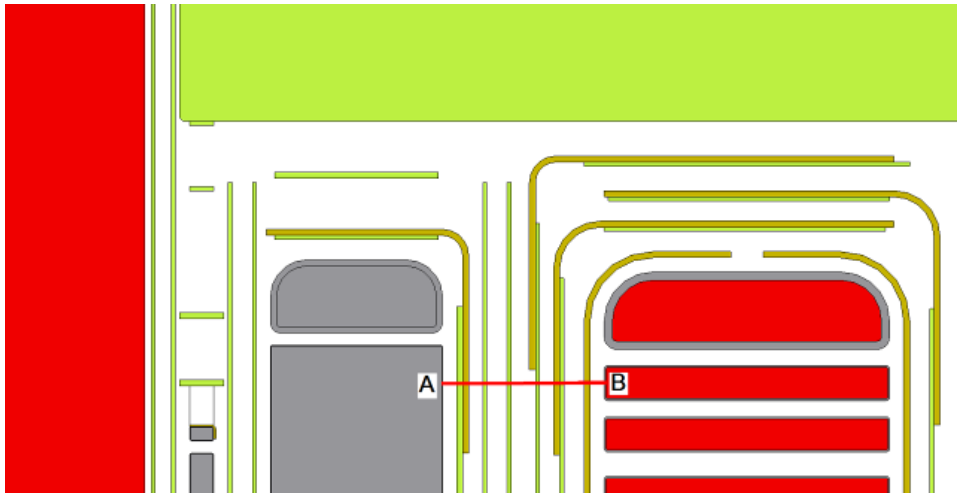
Electrical performance of FR3 natural ester fluid is equal or better than mineral oil

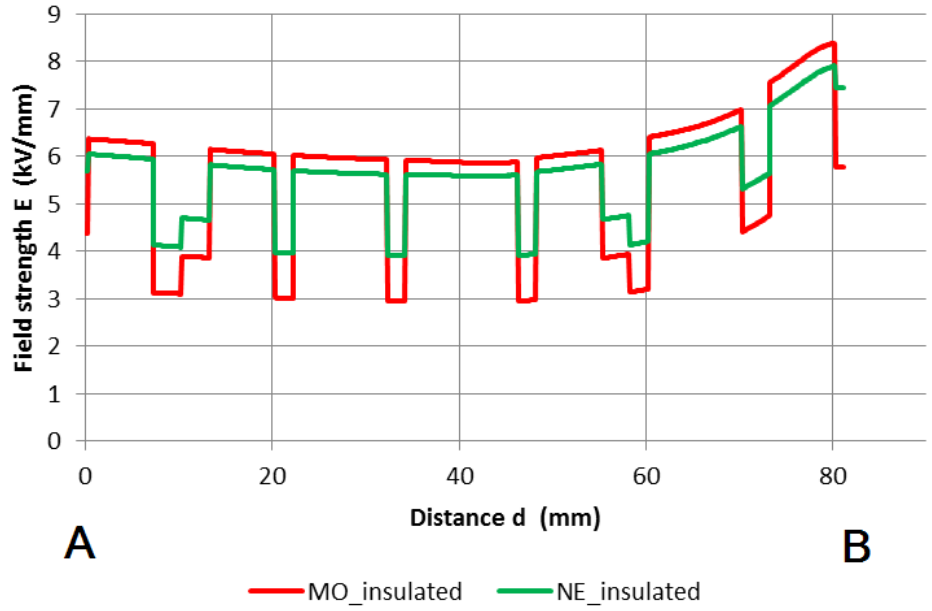
- **More than seven series of tests have confirmed performance:**
  - Basic dielectric tests AC. LI, SS, CW
  - Testing gaps up to 65 mm and evaluation of Kappeler Curve
  - Evaluation of Interfacial Creep
  - BDV at low temperature conditions
  - Long gap tests up to 150mm (1800kV) with inhomogeneous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

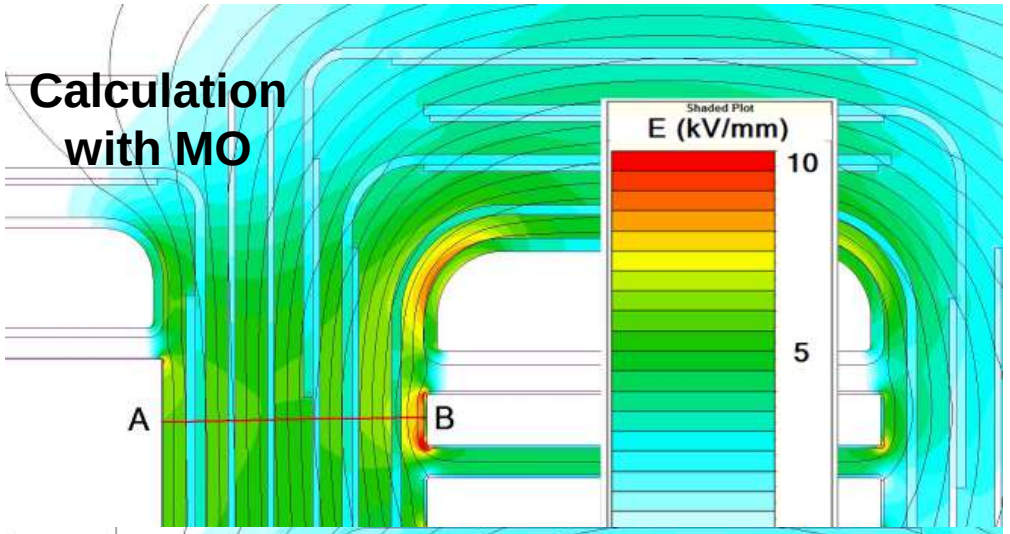


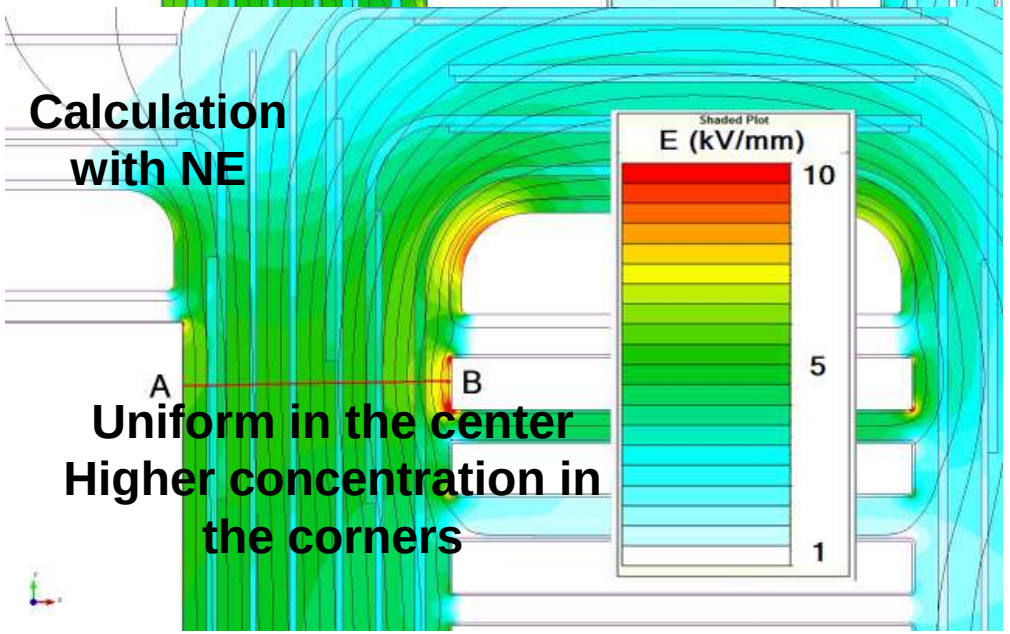


Permittivity affects field distribution

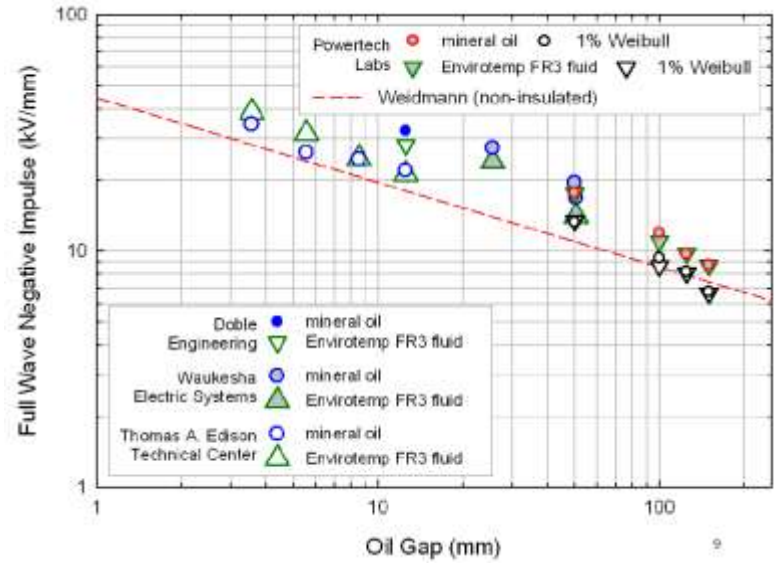


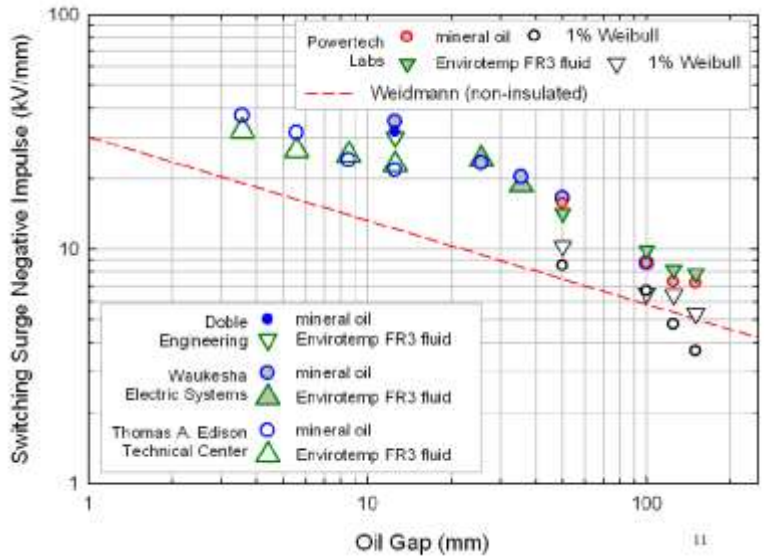


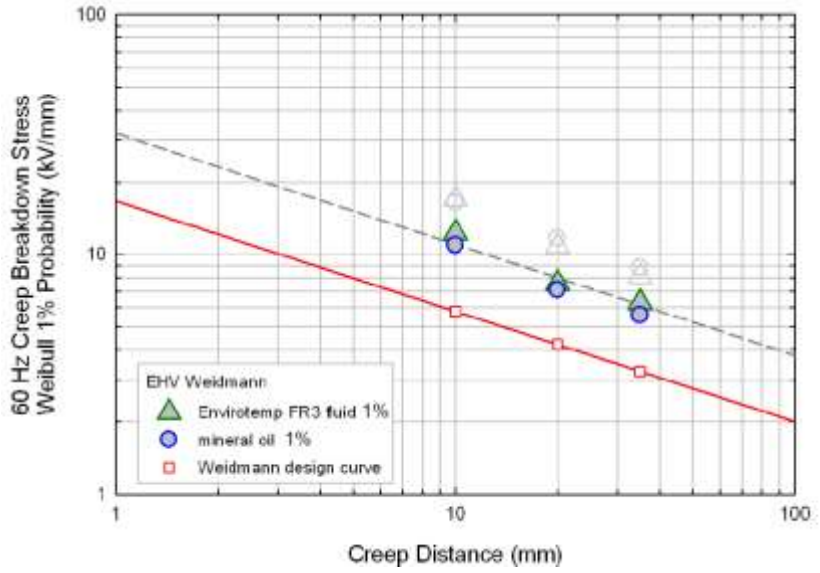


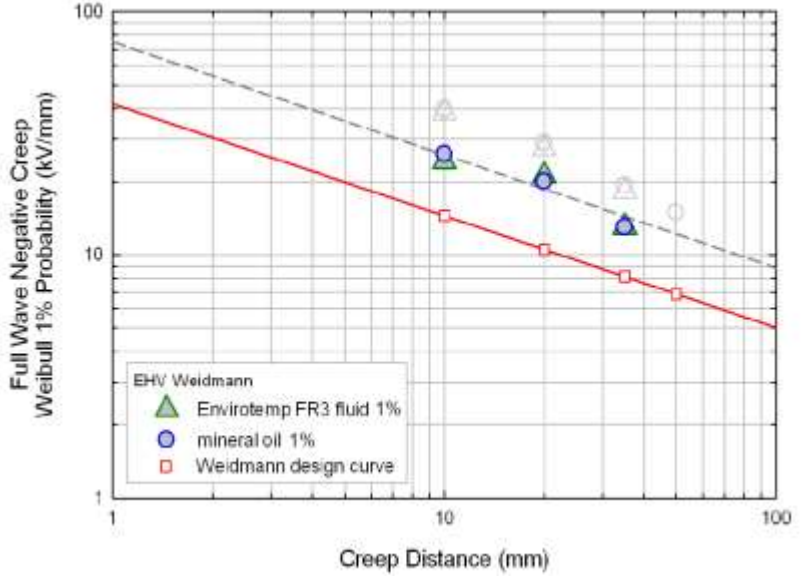


Dielectrics of FR3 fluid and Mineral Oil were equivalent

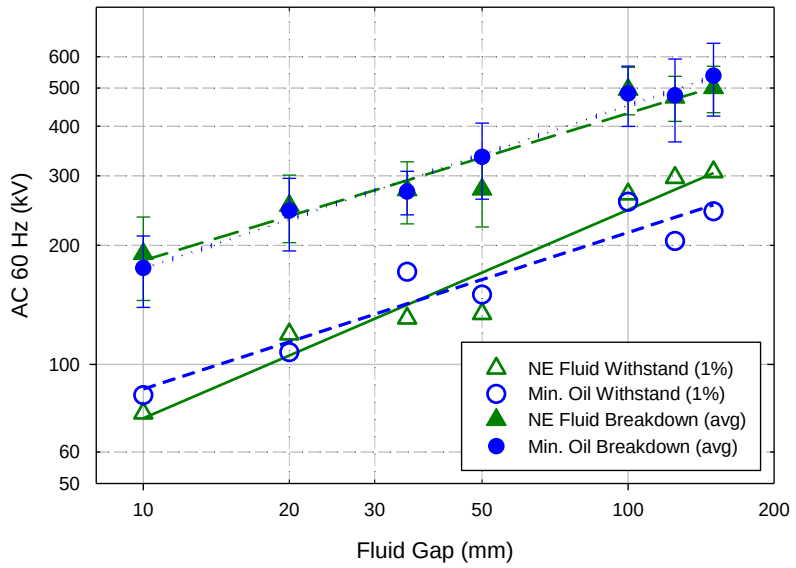




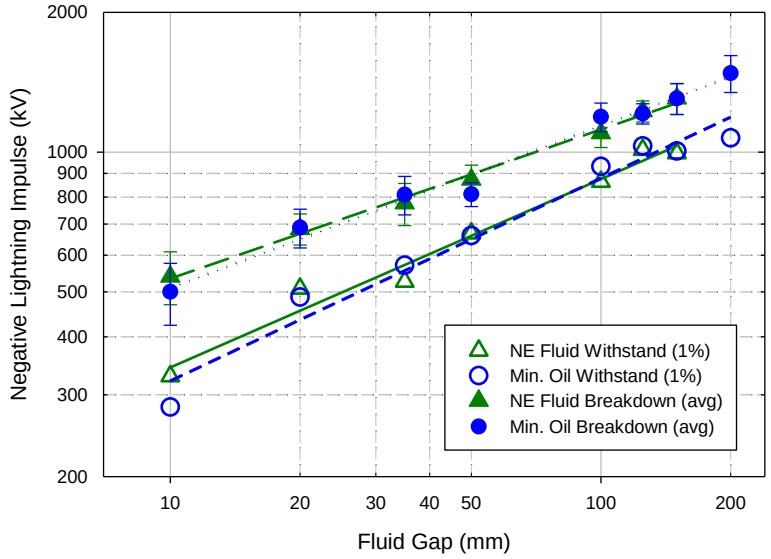


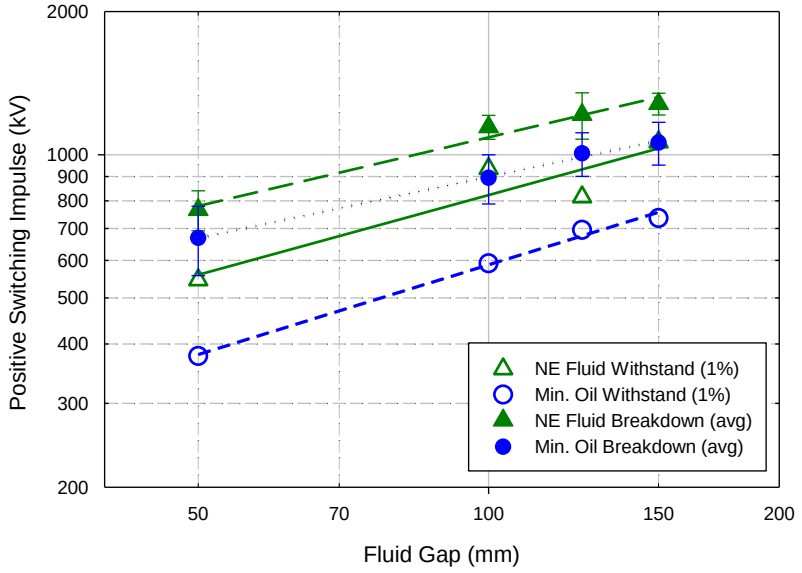


Long gap tests confirmed equivalent breakdowns

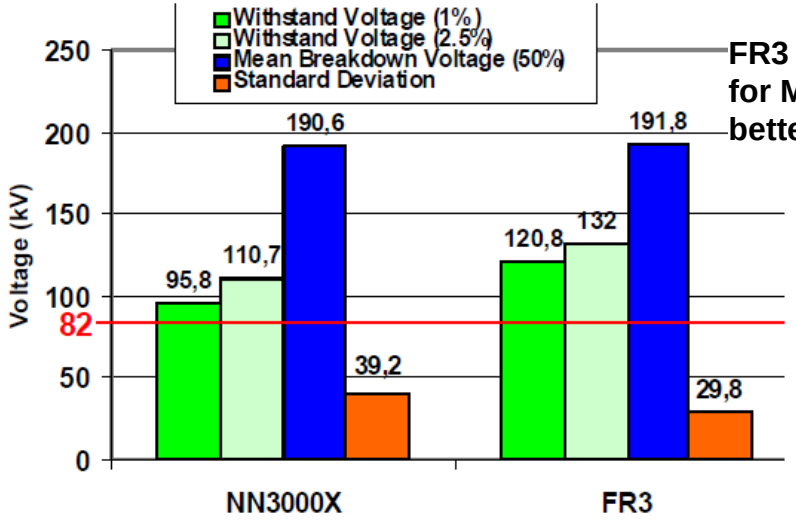


LI 1.2µs x 50µs – negative polarity



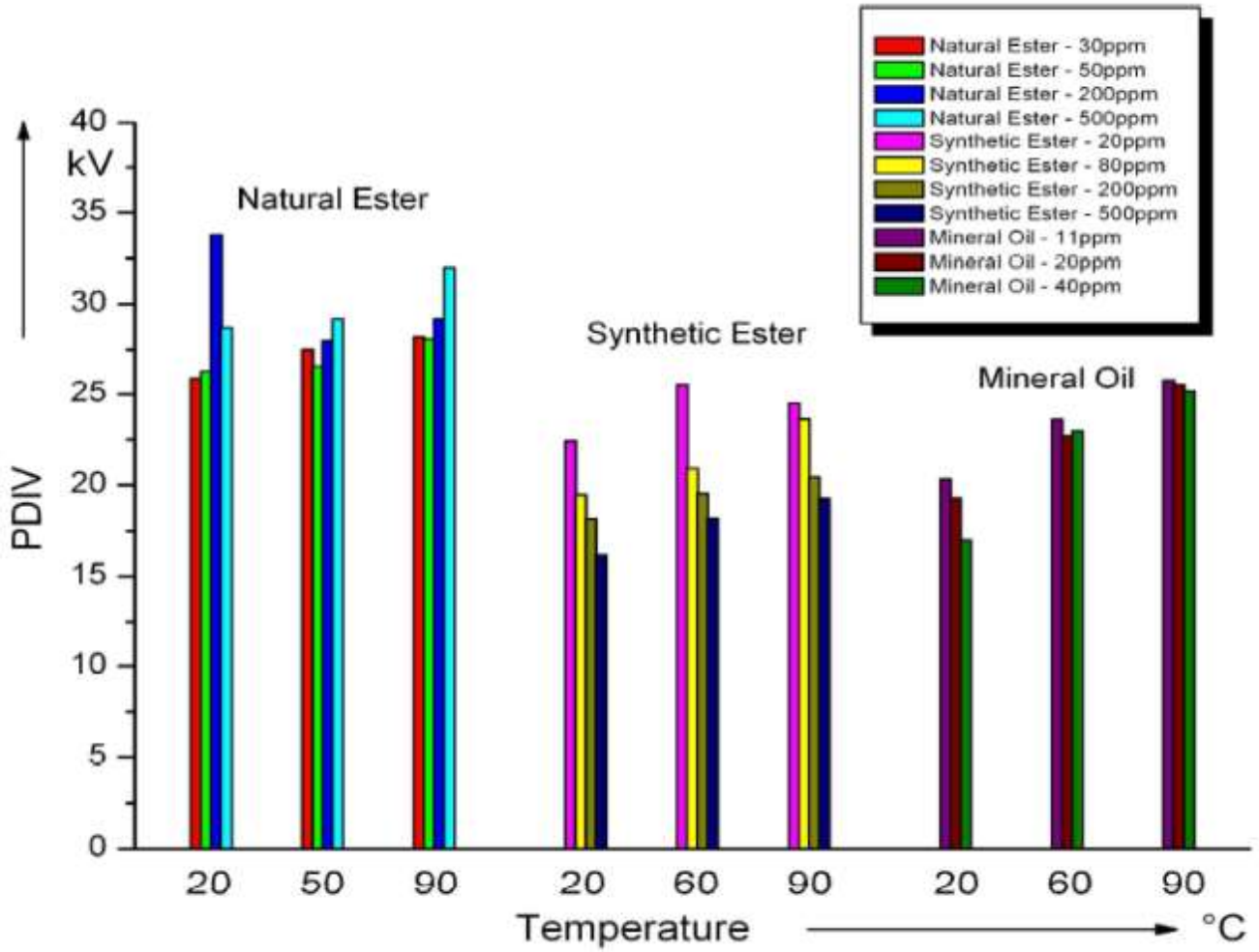


Stress between Tap Changer contacts



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.

Institute of Electric Power Systems
Division of High Voltage Engineering
Schering-Institute
University of Hanover

Authors:
Prof. Dr.-Ing. E. Gockenbach
Prof. Dr.-Ing. habil. H. Borsi
Dipl.-Ing. B. Dolata

Thank You

Email: Kevin_Rapp@Cargill.com